PET recycling by depolymerisation

Position Paper by PETCORE Europe Depolymerisation WG

Introduction

PETCORE Europe, in this position paper addresses:

- The background
- Innovation & Developments
- The path forward with benefits

Which are related to the general topic of "chemical recycling" and focusing on the depolymerisation of PET (poly ethylene terephthalate) and related polyester waste products.

The evolution of the Circular Economy for Plastics fundamentally positions recycling and circular waste management systems to replace linear production and consumption patterns. The plastic industry has had to radically rethink its role in contributing to the transition from a linear to the circular model. PET is already part of a well-functioning circular economy, advancing on its circularity to meet the more stringent demands of the Single Use Plastic Directive (SUPD). Complete circular processing must be achieved to be awarded a license to operate.

Chemical depolymerisation of PET waste to its basic components (monomers – terephthalic acid and ethylene glycol), which are reused to manufacture virgin PET, complements mechanical recycling, and provides circular industry processes across the broad range of PET and Polyester Products. The Green Deal and the Single Use Plastics Directive, proposed during the previous term of the European Commission, support aspects of the Green Economy that can result in the reduction of the environmental impact of PET products by reducing unrecovered waste, greenhouse gas emissions and consumption of unsustainable raw material feedstocks.

The depolymerisation of PET/polyester participates to these objectives and complements the established recycling of PET bringing a holistic response to all stakeholders. PET use in packaging is well understood. It is also generally known that post-consumer PET bottles have been collected for more than 30 years, where they are sorted, washed, and mechanically recovered to be used in the manufacture of polyester fibre, film, sheet, and PET bottles. PET depolymerisation technology has been deployed in various forms since the dawn of PET recycling but over the past decade a new generation of technologies has emerged to further improve recycling rates and quality.

This Paper is designed to give an overview of depolymerisation and how it can contribute as a sustainable solution to end of waste through a circular economic process by regenerating raw materials.

The market situation of PET in Europe

PET bottles are a recycling success story, with the rPET market currently at 1.4 million tonnes (Mt) in the EU going into new bottles, fibres, trays and strapping. However, only 11% of collected bottles goes back into food contact bottles, and, of the total 5.5 Mt of PET packaging consumed annually in the EU, only half is suitable for bottle-to-bottle recycling. The other half are functional and non-beverage bottles as well as thermoformed trays and films, which currently are downcycled or disposed of. Consider also that globally three times as much polyester fibre is produced than PET for packaging, of which a large fraction ends up on the European market either through local production or as finished good (e.g., clothing).[1] Consequently, there remains a large portion of the total volume of PET products on the market which is not recycled today and is facing challenges in meeting the targets set for the industry.[2]

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[1] Wood Mackenzie 2017, Eunomia "PET Market in Europe, state of Play" 2020, CIRFS statistics 2020.

[2] EU 2018/852 (PPWD), EU 2019/904 (SUP directive), European Strategy for Plastics Annex III - Voluntary Pledges

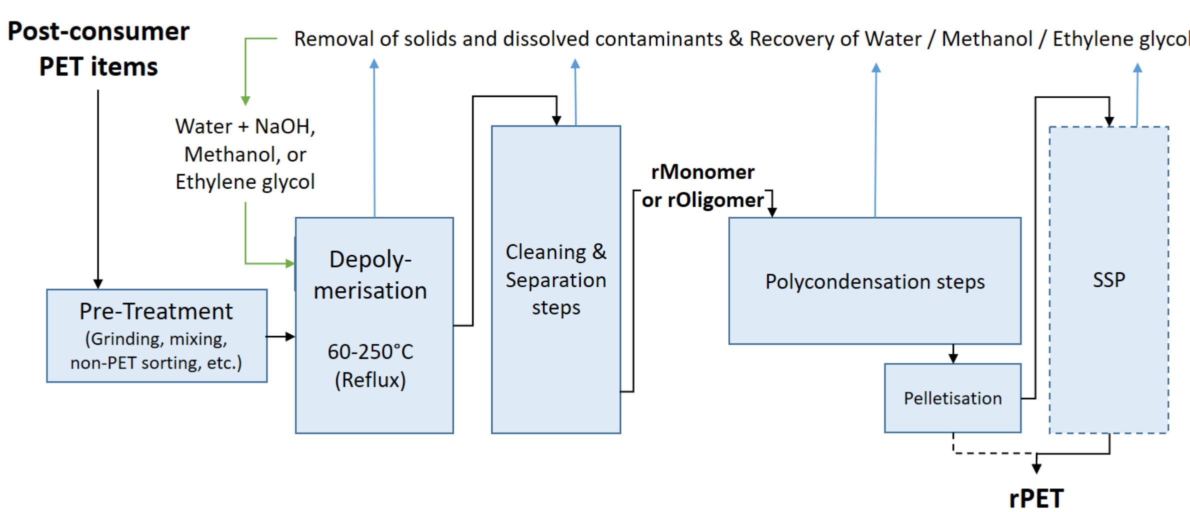
Depolymerisation recycling brings a complementary option for the more difficult to recycle items

Key approaches to improve PET recycling rates include increased collection, quality sorting, and design-for-recycling. To follow collective industry design guidelines, such as the European PET Bottle Platform (EPBP) and the PETCORE tray evaluation platform, remains the best strategy to increase PET product recycling rates. However, for some products, non-recyclable components cannot be removed without critical loss of functionality, and products passing multiple loops through mechanical recycling ultimately deteriorate in quality. For these challenges, recycling by depolymerisation provides a synergistic additional solution.

The depolymerization technology for PET

PET is a reversible polymer; it can be readily broken down back to smaller building blocks such as oligomers or monomers by hydrolysis, glycolysis, or methanolysis. Doing this enables the use of various purification techniques, amongst which those used for virgin monomers from crude oil such as distillation and crystallisation. As such, depolymerisation can be used to achieve virgin-quality raw materials for virgin-quality PET manufacturing.

Depolymerisation enables recovery of PET from poor quality waste streams; any non-PET components or substances used in packaging or fibre manufacture such as polyolefin sealant layers in trays and cotton in fibre blends can be removed in these processes, either because they do not depolymerise or because they are caught in a purification step.

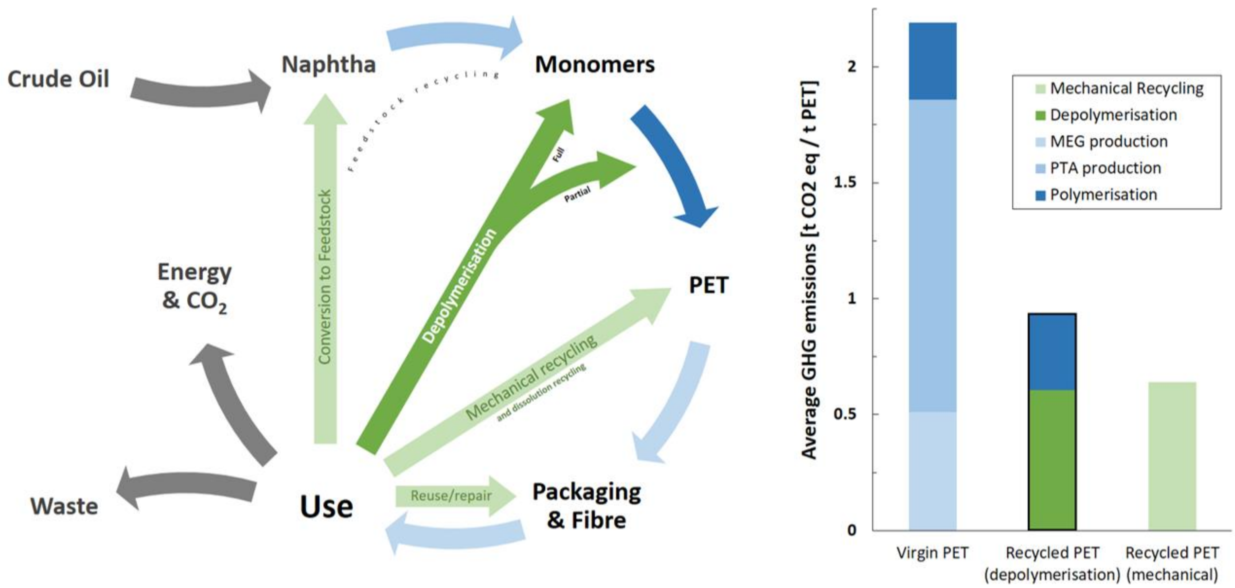


Generic PET depolymerisation & (re-)polymerisation process

Even incidental contaminants from the use phase are removed; to enable PET production all building blocks are recovered with at least 99.5% purity and the polycondensation steps in PET manufacturing remove volatile organic components.

Enabling new circular value chains

For plastics, most circular value chains that include post-consumer recovery steps yield an improved Life Cycle Analysis (LCA) compared to linear value chains, since they displace crude oil depletion and avoid waste or CO_2 emissions to the environment. However, the post-consumer recovery steps themselves may also produce CO_2 and by-product emissions. There may be reduction to intermediate products that need further reprocessing and are subject to yield losses which can negatively impact the LCA. The EU Waste Framework Directive defines a hierarchy of waste, with re-use as the most sustainable option (after prevention), followed by recycling and then by energy recovery. Building on this principle, recycling can be sub-divided in a hierarchy of mechanical, depolymerisation, and feedstock recycling.



Positioning of depolymerisation recycling in a circular value chain and greenhouse gas (GHG) emissions for PET produced via three routes in cradle-to-gate scenario, i.e., including collection, sorting and pre-treatment but excluding avoided CO_2 emissions produced by incineration. [3]

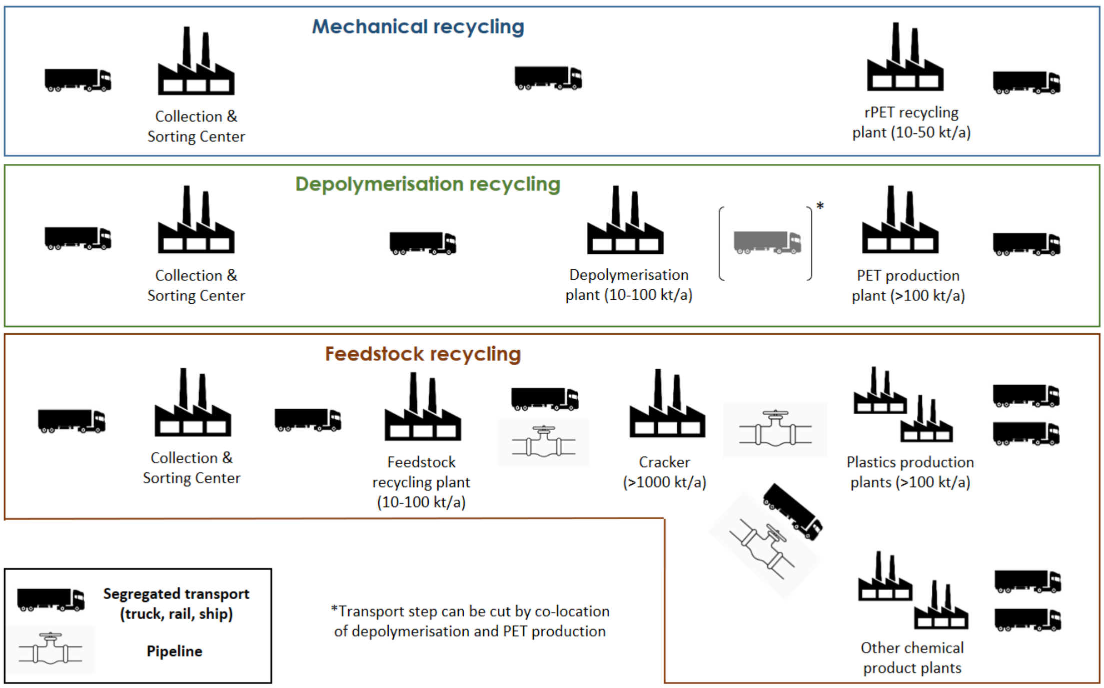
Depolymerisation requires more reprocessing steps than mechanical recycling but typically uses similar temperatures (below 300°C), and yields 76-99% monomers or oligomers that can be readily used to make PET. This translates to modelled greenhouse gas emissions between virgin PET and mechanically recycled PET, as is exemplified in the graph above. Feedstock recycling requires more reprocessing steps than depolymerisation along with high temperatures (600-1400°C) and yields lower amounts of monomers, for example pyrolysis and cracking is estimated to yield at most 19-24% ethylene and 12-16% propylene in addition to other chemicals and fuels.[4] This can reduce CO_2 emissions compared to incineration but will provide a less favourable profile relative to depolymerisation.

[3] Average from member LCA studies based on process models for industrial scale operation, PlasticsEurope Ecoprofiles (Ethylene 2012, BTX 2013, PTA 2016, PET 2017), SRP Ecoprofile 2017, CE Delft 2019

[4] Eunomia, Chemical Recycling: State of Play 2020, Petrochemicals Europe Market Overview 2021

Traceability of recycled content

The PET industry employs segregated transport and storage of monomers (e.g., PTA and MEG) for PET from depolymerisation recycling as well as for mechanically recycled PET, making traceability of recycled content in PET products relatively straight-forward. For feedstock recycling, traceability of recycled content is far more complex as recycled raw materials are fed into crackers. The cracker products ethylene and propylene are mainly fed to pipeline networks from which chemical products other than plastics are produced, these processes are more dependent on accounting using a (multi-site) mass balance approach.[5]



Simplified logistics chains for mechanical, monomer and feedstock recycling

A rapidly developing industry

Depolymerisation technologies were developed in the '90s as a direct alternative for mechanical recycling using the same clear and light blue bottle flakes as a feedstock. Today, such operations are mainly applied in existing virgin production assets with up to 30% of recycled content (50-60 kt/a on 150-200 kt/a). The process is called flake injection which by virtue of its scale enables a cost-effective approach for using recycled content. For stand-alone recycling operations at the typical scales of up to 60 kt/a, mechanical recycling has the advantage of fewer steps and lower (energy) cost.

However, over 50 companies worldwide are working on depolymerisation technologies that can use lower quality feedstocks that cannot be recycled mechanically. Lower quality feedstocks change the economic attractiveness of depolymerisation since those feedstocks are typically lower cost. Solutions for such feedstocks became a necessity due to the ambitious targets set by the EU for plastics recycling. Several announcements have been made for large scale operations in place by 2025 in partnership with multiple stakeholders along the value chain. With an investment totalling 1 billion € for installed capacity of nearly 300 kt/a. McKinsey & Co have

[5] Petrochemicals Europe flowchart, ECSSP "An overview of pipeline networks in Europe", CEFIC Chemical Recycling position paper 2020, Ellen MacArthur Mass Balance White Paper 2020

projected that by 2050 depolymerisation recycling will comprise 100 million tons per annum with a CAGR of 18% over the next 30 years.

The PETCORE monomer Working Group represents a group of companies active in depolymerisation recycling in the EU with market-ready or near-commercial technology (TRL between 5-9), to promote their common interests to policy makers and other stakeholders.

What can policy makers do to help?

- Collaborate with the industry on practical guidelines for compliance with the existing and future plastics food safety regulations.
- Minimize barriers for transport of post-consumer plastic waste within the Single Market to enable sourcing for large-scale cost and energy effective operations.
- Ensure depolymerisation recycling fits the definitions of recycling rates and recycled content when implementing directives under the EU plastics strategy.
- Economic incentives, including credits for the avoidance of CO_2 emissions.
- Place depolymerisation recycling on the agenda for development grants & sustainable financing institutions and mitigate investment risk in new technology RD&I and deployment.

Frequently Asked Questions

Q: *Why continue with PET?*

A: To achieve climate change initiative targets, continuing to make products from plastics is crucial to avoid green-house gas emissions compared to materials that are more energy-intensive to produce and transport. Importantly, PET packaging prevents vast amounts of food waste compared to not using plastics.

Q: *Why depolymerisation?*

A: By developing chemical recycling alongside the established mechanical recycling of PET, a complete package is given to handle all types of PET waste. This will give the waste management companies the incentive to collect and separate post-consumer PET products as they will have value as recycled raw materials.

Q: *Why is depolymerisation recycling taking so long to be established?*

A: The current operational practices and scale of the petrochemical industry have developed over decades and comprise hundreds of thousands of people, while feedstock-flexible depolymerisation developments started in the 2010's with smaller groups of innovators and entrepreneurs. Organising new supply chains around these technologies based on complex feedstocks and integrating with current industrial practice takes time.

Q*: Is PET recycled by depolymerisation recycling safe for food applications?*

A: In short, yes. Depolymerisation of PET yields monomers or pre-polymers / oligomers that are chemically identical to those used in virgin PET and need to be of the same high technical quality and purity to allow polymerisation. Furthermore, producers are required to do risk assessments on the presence and food safety of any impurities. As such the recycled PET complies with regulation EU 10/2011.[6]

Q: *What about dangerous chemicals/by-products?*

A: All Chemical production processes produce by-products. The hazard profile of these by-products is dependent on a particular process. Each chemical production process is managed by legislation and permitting systems at local, national and EU level. Some by-products can be used as a feed material for other processes (i.e., methanol from DMT production) and other by-products may become waste products which must be dealt with under waste legislation. Modern plants use a range of environmental measures such as carbon capture and storage, water recirculation, and heat recovery. In this way the production units become very efficient, safe, and clean.

The segregation of waste materials followed by depolymerisation, and purification steps will ensure by-products will be removed and handled separately and will ensure monomer purity comparable to today's synthesis from fossil feedstock. To ensure safety for food use, the group is conducting thorough Non-Intentionally Added Substances (NIAS) testing on Monomers and PET manufactured with monomers produced by depolymerisation processes as part of the risk assessments for compliance with EU 10/2011. Depolymerised monomers and polymer manufactured with recovered monomers will also be required to provide a Declaration of Compliance in line with Article 15 of Regulation 10/2011.

Q: *What is your opinion on mass balance?*

A: A mass balance approach may be a way to provide financial incentives for new technologies in complex supply chains and thus enable innovation, but a traceability method that includes inherent losses to non-plastic fates is required. For depolymerization recycling, the focus is on segregated monomers & prepolymers to enable controlled blending into PET with recycled contents up to 100%, therefore providing easier traceability.

Q: *What is the difference between polyester and PET?*

A: PET and polyester are products are chemically similar. Typically, PET is formed following further treatment of a polyester making it suitable for more stringent applications such as bottles. They are the same molecule with minor differences in chemical structure, PET can be used in most of the polyester applications.

Q: *Is depolymerisation recycling technology only used for PET?*

A: Depolymerisation by reaction with water or alcohols as described in this paper can only be applied to poly-condensate polymers, i.e., PET, other polyesters, and polyamides. Radical polymers can be thermally depolymerised to stable monomers if they have large side-groups i.e. PMMA and PS. However thermal decomposition of the more linear radical polymers like Polyethylene and Polypropylene will always form a mixture of hydrocarbons.

Q*: Why is textile to textile recycling necessary?*

A: the demand for recycled PET in food packaging is high and post-consumer food packaging is the ideal raw material for producing food packaging again and again, so little material is left for textile recovery. Extended Producer Responsibilities for textiles including the obligation to use recycled polyester are likely to be implemented in the future.

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[6] Commission Regulation (EU) No 10/2011 of 14 January 2011 on plastic materials and articles intended to come into contact with food

Q: *Why are economic incentives against GHG emissions of virgin necessary?*

A: The negative environmental impact of virgin PET is not implemented in the virgin price, where recycling is addressing the environmental impact of GHG and waste emissions

Q: *Why not use biodegradable polymers?*

A. Biodegradability depends not only on the properties of the plastic material itself, but also on the environmental conditions. Many biodegradable plastic products only actually biodegrade in certain specific environments, or only in industrial composting facilities, rather than in the open environment. The SAPEA opinion[7] published in December 2020 recommends limiting the use of biodegradable plastics to specific applications for which reduction, reuse, and recycling are not feasible, rather than as a solution for inappropriate waste management or littering. Biodegradable polymers can become a contaminant in the PET recycle streams and as such may lead to degradation of the quality and quantity of PET that can be recycled for this reason the EPBP Design Guidelines places biodegradable polymers in the red category.

Q: *What is the difference between recycling and circular economy?*

A: The definition of recycling is "the action or process of converting waste into reusable material." This means that a recycle material can be downcycled or upcycled to product which is different from the starting product i.e., a PET bottle recycled to a tee shirt. This process is part of a circular economy but is not the full picture. A true circular economy deliberately aims to reduce the demand for raw material inputs and natural resources by recovering, reuse, and recycle of those inputs and resources as an integral part of a production process, ideally back to the principal article.

Finally, depolymerisation and monomer synthesis works alongside mechanical recycling to ensure PET becomes infinitely recyclable and circular. This combination ensures that degraded PET through repetitive mechanical recycling will be replaced by the renewable sourcing of virgin quality raw materials through the depolymerisation balancing process.

Q: *What are the target feedstocks for PET Depolymerisation operations?*

A: PET Depolymerisation targets converting waste streams which are difficult to recycle with mechanical operations. Waste streams which can be efficiently handled by mechanical recycling should be kept out of scope for chemical recycling operations. Chemical Recycling is not intended to withdraw high quality feedstock for mechanical recycling operations.

[7] https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/0c0d6267-433a-11eb-b27b-01aa75ed71a1