SIAPARTNERS

Chemical recycling of plastics: is industrial maturity within reach?

With 800,000 tonnes of capacity already installed or under development across Europe, driven by new European legislation around recycling packaging, **chemical recycling could supply up to 6.6 million tonnes of recycled plastics needed for new packaging in Europe by 2040.**

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Climate Analysis Center | CONSULTING FOR GOOD

Executive Summary

Market overview

In 2022, the EU generated 33.2 million tonnes (Mt) of post-consumer plastic waste, of which only 11.3 Mt (29%) have been recycled. To enhance plastic recycling rates, the **EU has established a new regulatory framework.** This includes a target of **55% of all packaging to be recycled by 2030** (EU Directive 2018/852) and a mandate for manufacturers to incorporate **between 50 to 65% recycled raw materials (RRM) in new packaging by 2040** (provisional PPWR, 2024)**. Additionally, forthcoming regulations are expected to facilitate the certification of chemically recycled polymers** through the recognition of the mass-balance approach.

Focus on initial projects

The study identified more than 51 projects currently operational or announced, representing **a combined capacity of ~0.8 Mt/year. Most of these projects (62%) utilise pyrolysis technology,** designed to process **blended polyolefins resins (PE, PP, and PS/EPS). The industry has experienced a slowdown in new project announcements since 2022, primarily due to heightened financial and regulatory risks and increased competition from energy recovery sectors** (SRF and incineration), particularly following the energy crisis in 2022. **Key players in this sector,** notably **refiners and petrochemical companies, are showing a strong interest** in chemical recycling to bolster their supply chains. Meanwhile, manufacturers**, under regulatory pressure, are forming partnerships** to secure volume and drive demand for chemically recycled resins.

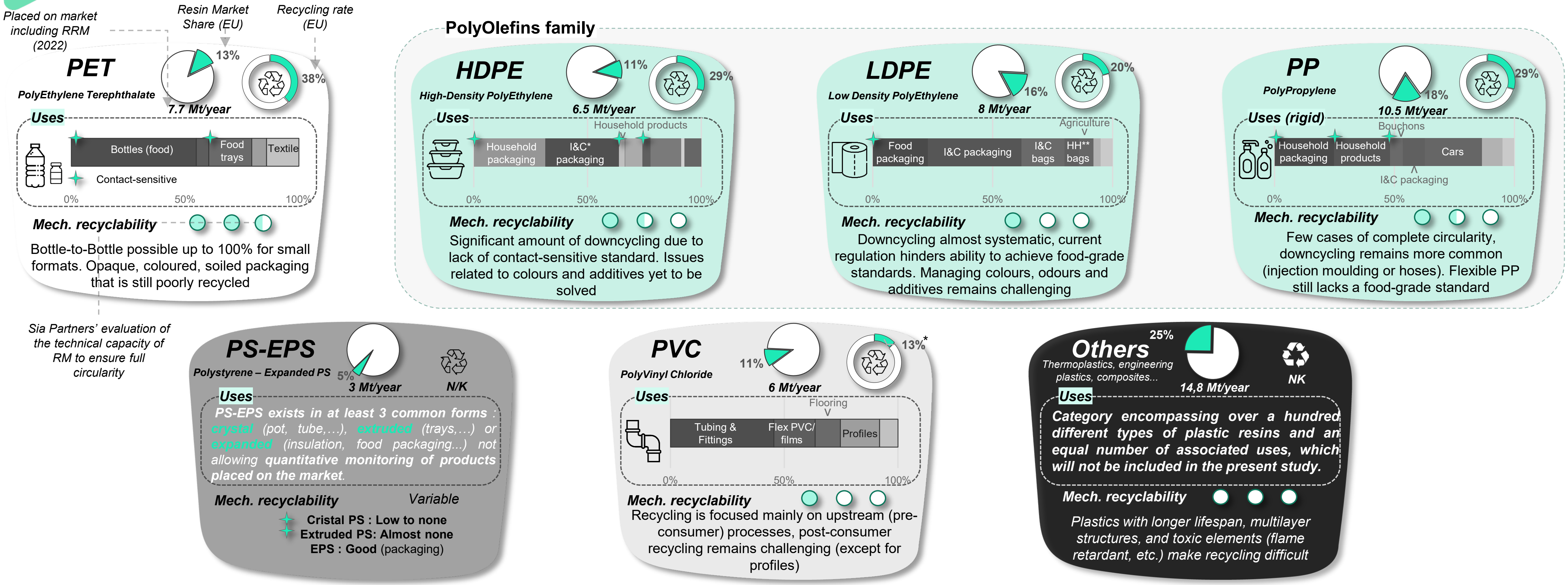
2030-2040 Trends

Ultimately, chemical recycling is expected to target polyolefin resins and PET (excluding bottles) impacted by the new packaging regulations and is projected to provide **between 1.5 and 6.5 Mt of RRM by 2030 and 2040, respectively**. This anticipated production will necessitate the **establishment of new chemical recycling facilities** categorised into two main processes: pyrolysis and/or gasification and solvolysis and/or enzymolysis. This cumulative capacity is estimated to reach **~2.5 Mt** by 2030, scaling up to **~9 Mt** by 2040. This would see chemical recycling **achieve a 15 to 40% market share compared to mechanical recycling in the packaging sector**. Overall investments for these facilities ("core-process" only) **are estimated to exceed €5 billion by 2030 and €14 billion by 2040**.

0. Introduction

Mapping plastic production and recycling in Europe

INTRODUCTION | Plastics production and recycling in Europe, 2022



Placed on market including RRM (2022)

Resin Market Share (EU)

Recycling rate (EU)

Sia Partners' evaluation of the technical capacity of RM to ensure full circularity

PET
PolyEthylene Terephthalate

7.7 Mt/year – 13% – 38%

Uses

Mech. recyclability

Bottle-to-Bottle possible up to 100% for small formats. Opaque, coloured, soiled packaging that is still poorly recycled

PolyOlefins family

HDPE
High-Density PolyEthylene

6.5 Mt/year – 11% – 29%

Uses

Mech. recyclability

Significant amount of downcycling due to lack of contact-sensitive standard. Issues related to colours and additives yet to be solved

LDPE
Low Density PolyEthylene

8 Mt/year – 16% – 20%

Uses

Mech. recyclability

Downcycling almost systematic, current regulation hinders ability to achieve food-grade standards. Managing colours, odours and additives remains challenging

PP
PolyPropylene

10.5 Mt/year – 18% – 29%

Uses (rigid)

Mech. recyclability

Few cases of complete circularity, downcycling remains more common (injection moulding or hoses). Flexible PP still lacks a food-grade standard

PS-EPS
Polystyrene – Expanded PS

3 Mt/year – 5% – N/K

Uses

*PS-EPS exists in at least 3 common forms : crystal (pot, tube,…), extruded (trays,…) or expanded (insulation, food packaging...) not allowing **quantitative monitoring of products placed on the market**.*

Mech. recyclability Variable

Cristal PS : Low to none
Extruded PS: Almost none
EPS : Good (packaging)

PVC
PolyVinyl Chloride

6 Mt/year – 11% – 13%*

Uses

Mech. recyclability

Recycling is focused mainly on upstream (pre-consumer) processes, post-consumer recycling remains challenging (except for profiles)

Others
Thermoplastics, engineering plastics, composites...

14,8 Mt/year – 25% – NK

Uses

Category encompassing over a hundred different types of plastic resins and an equal number of associated uses, which will not be included in the present study.

Mech. recyclability

Plastics with longer lifespan, multilayer structures, and toxic elements (flame retardant, etc.) make recycling difficult

The **Polyolefins** family (HDPE, LDPE, PP) **account for 45% of the plastics in the European market**. **Whilst PET only account for 10% of EU plastic, it has a much higher recycling rate than other resins (38%, excluding textiles)** with a circularity close to 100% (eg. bottle-to-bottle). **Increasing recyclability** via mechanical or chemical recycling **will therefore be specific to each resin and** its intended application (food packaging, construction, cars...) and will require coordination of the right waste flows towards the most suitable technology.

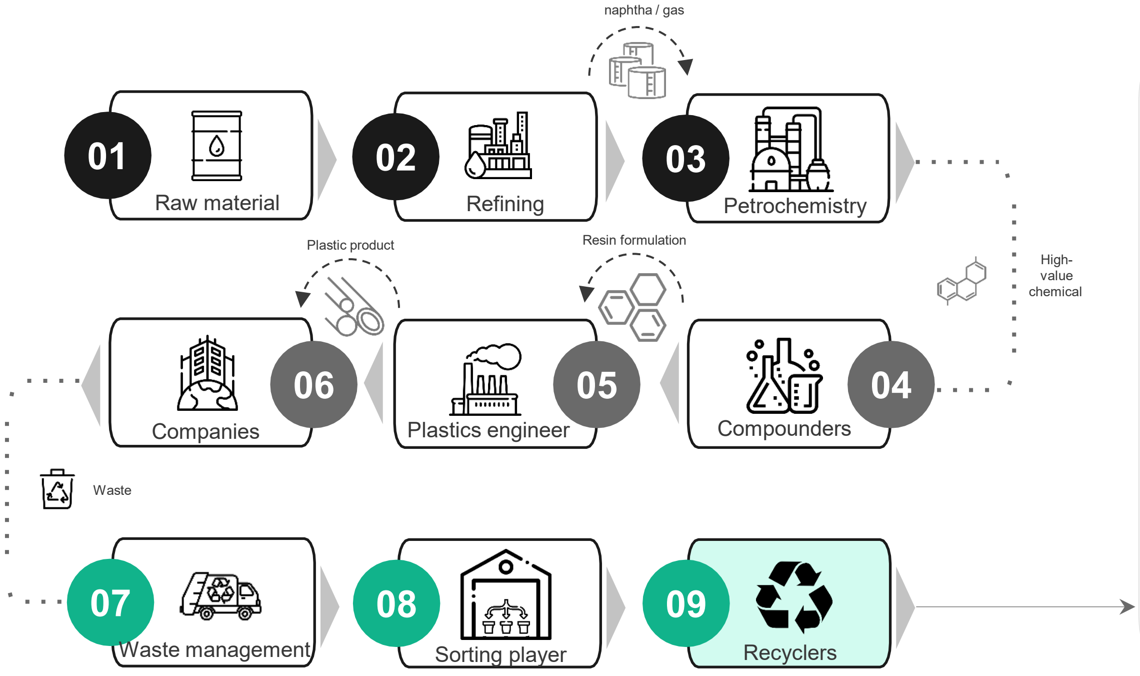
* **RRM / quantity on the market**. Does not consider the long life of some products (>50 years) | **Sources**: Plastics Europe, Plastics Recyclers, Vinylplus, Sia Partners Analysis & Research

01. Market overview

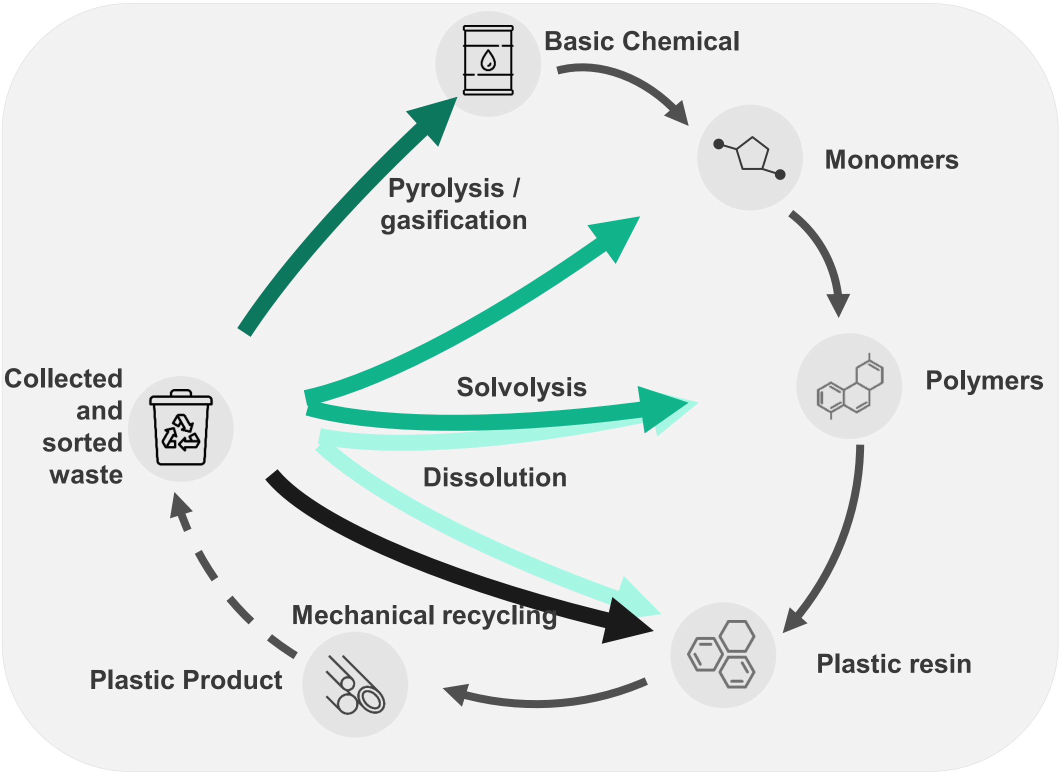
The development of chemical recycling, alongside mechanical recycling, is critical to achieving the objectives outlined in European regulations.

MARKET OVERVIEW | Plastic lifecycle and the different recycling pathways

PLASTIC PRODUCTION LIFE CYCLE



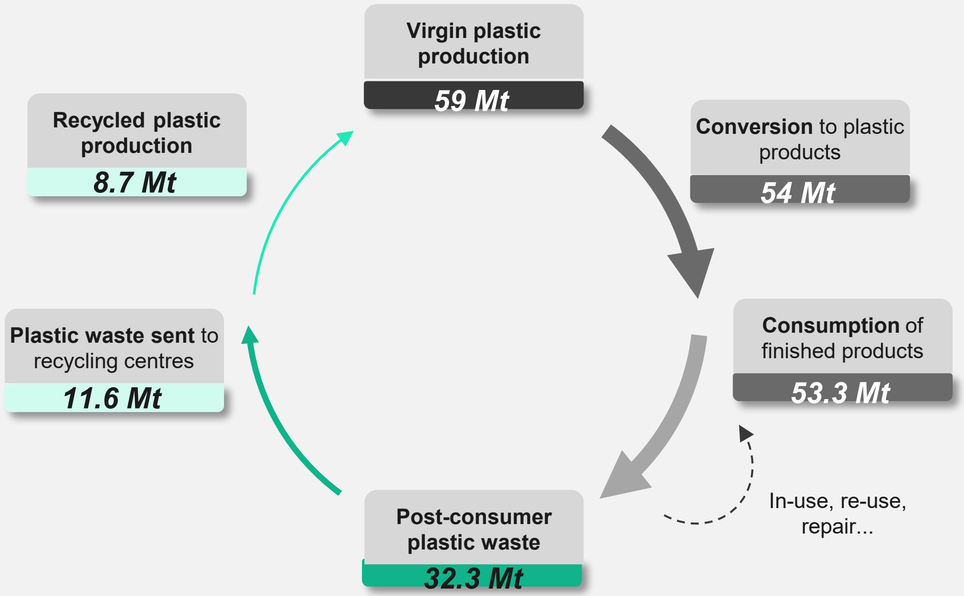
PLASTICS RECYCLING VALUE CHAIN



The long and complex plastics value chain is currently dominated by mechanical recycling, accounting for 98% of recycled plastics. However, two distinct chemical recycling pathways are emerging: solvent depolymerisation (solvolysis) and thermal depolymerisation (pyrolysis/gasification). Unlike mechanical recycling, chemical recycling allows for the processing of plastic waste materials earlier in the production chain, thereby expanding potential applications and enhancing the quality of the resulting plastics produced.

<u>**Sources**</u> : Plastics Europe "Circularity Report 2024" , Sia Partners Analysis & Research

MARKET OVERVIEW | In Europe, 32.3 Mt of plastic waste are generated annually, yet only 11.6 Mt are directed towards recycling processes and only 27% are actually recycled.



Virgin plastic production
59 Mt

Conversion to plastic products
54 Mt

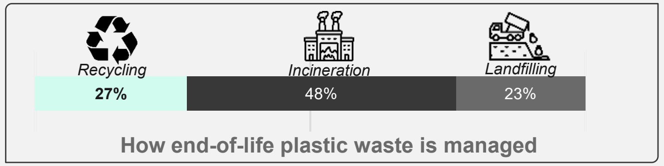
Consumption of finished products
53.3 Mt

In-use, re-use, repair...

Post-consumer plastic waste
32.3 Mt

Plastic waste sent to recycling centres
11.6 Mt

Recycled plastic production
8.7 Mt



How end-of-life plastic waste is managed

- **European plastic production has plateaued in recent years at 59 million tonnes per year (Mt/year)**, impacted by high energy costs and increased competition from abroad, particularly the Asia-Pacific region.
- **"Post-consumer" plastic waste accounts for 32.3 Mt/year** representing an 11.4% increase compared to 2020. This waste is primarily directed towards **incineration** (16 Mt, a **15% increase** from 2020), **recycling** (11.6 Mt, **+14%**) and **landfilling** (7.6 Mt, **-3%**).
- A significant proportion of **waste sent to recycling centres ends up in the disposal sector** (3.6 Mt/year, 30%) **due to insufficient quality for recycling.**
- At the end of the value chain, **7.8 Mt/year of plastics are recycled, reflecting a** +13% increase compared to 2020, **almost exclusively through mechanical recycling** (98%). These recycled materials are then reincorporated into the **manufacturing process of new products, like for examples** building materials (2.8 Mt – 22.7% rate of incorporation of RRM), packaging (2 Mt – 9.7%) and garden tools and equipment (0.9 Mt – 37.5%).

**According to Plastics Europe, these inputs could be suitable for chemical recycling if the proportion of inerts, metals and organic matter (water, food, etc.) are compatible with the process*

Despite progress in recent years increasing the proportionality of plastic waste recycled, a significant gap remains to achieve the level of circularity required to meet European targets. Improving the quality of recycled plastic will be essential for facilitating a greater incorporation of recycled raw materials (RRMs) into a wider range of finished products, such as "bottle-to-bottle" recycling, which remains underdeveloped.

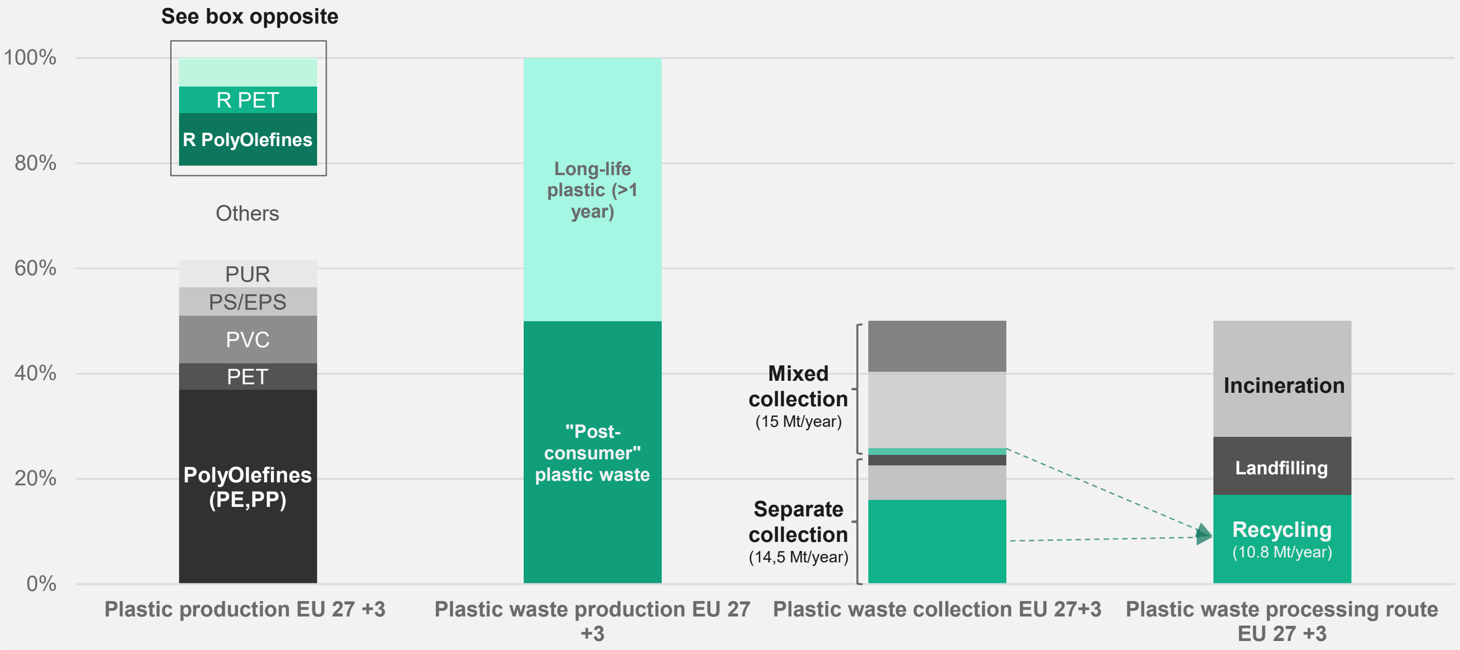
Sources : Plastics Europe "Circularity Report 2024", Plastic Recycler "State of play Flexible – 2022", "State of play Rigid HDPE & PP", Sia Partners Analysis & Research

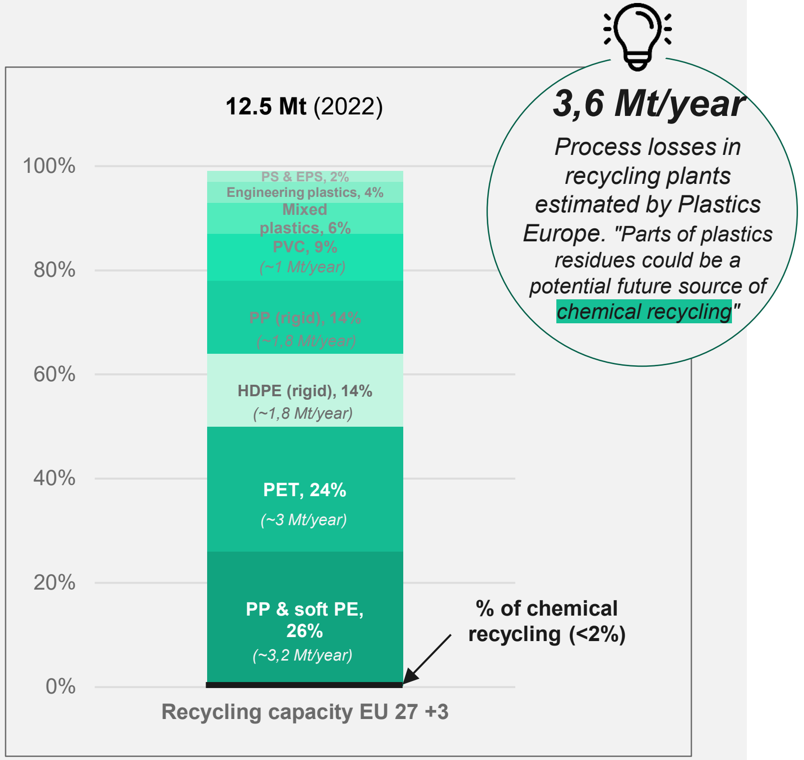
Focus

MARKET OVERVIEW | Recycling capacity is increasing, with a growth of +14% over the past 2 years, predominantly focused on polyolefins (54%) and PET (24%)

Almost half of the total plastic production (32.3 out of 59 Mt/year) is classified as **"post-consumer" waste in the same year it is produced** and collected by waste management services. Significant variation presents in the level of recyclability of post-consumer waste pending collection mechanism. Mixed collection techniques result in a 3.8% recycling rate, whereas **separate collection achieves a 49.4% recycling rate**. Collection mechanism remains a key lever to meet the European target of recycling 55% of packaging by 2030.

Production and processing methods of plastics in Europe (27 + 3) - 2020





3,6 Mt/year

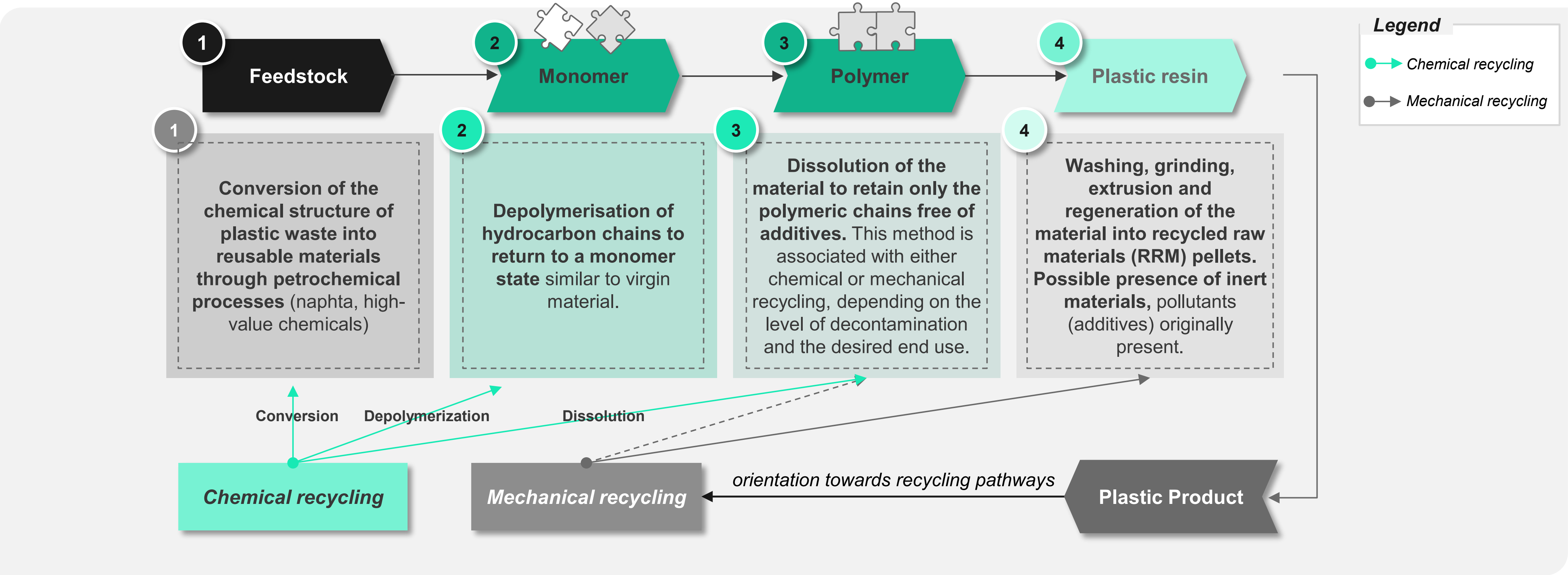
Process losses in recycling plants estimated by Plastics Europe. "Parts of plastics residues could be a potential future source of chemical recycling"

% of chemical recycling (<2%)

Sources : Plastics Europe "Circularity Report 2024", Plastics Recyclers European data 2022, Sia Partners Analysis & Research

MARKET OVERVIEW | Chemical recycling enables advancement up the plastic production chain, yielding recycled material of quality comparable to virgin resources

Chemical recycling of plastics is defined according to ISO 15270 as the process of converting waste into a monomer or the production of new raw materials by changing the chemical structure of plastics (cracking, gasification or depolymerisation). It is intended to complement mechanical recycling where traditional processes cannot be administered to certain waste inputs, such as mixed and soiled plastic deposits . A key advantage of chemical recycling is its ability to achieve final product quality comparable to virgin materials, whereas the mechanical recycling process degrades the material properties.



1 **Feedstock**

2 **Monomer**

3 **Polymer**

4 **Plastic resin**

1 **Conversion of the chemical structure of plastic waste into reusable materials through petrochemical processes** (naphta, high-value chemicals)

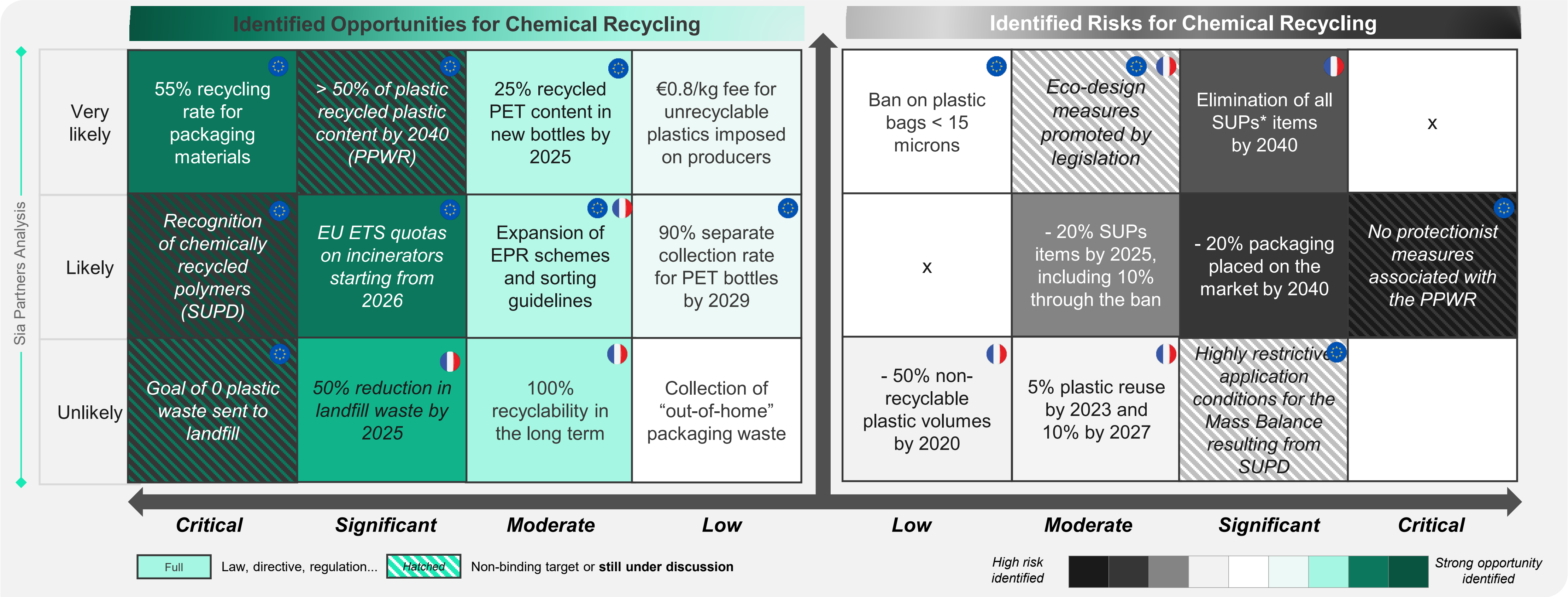
2 **Depolymerisation of hydrocarbon chains to return to a monomer state** similar to virgin material.

3 **Dissolution of the material to retain only the polymeric chains free of additives.** This method is associated with either chemical or mechanical recycling, depending on the level of decontamination and the desired end use.

4 **Washing, grinding, extrusion and regeneration of the material into recycled raw materials (RRM) pellets. Possible presence of inert materials,** pollutants (additives) originally present.

Sources : Plastics Europe 2024, Sia Partners Analysis

MARKET OVERVIEW | Chemical recycling benefits from a supportive regulatory environment that is facilitating sectoral growth (PPWR, establishment of EPR schemes, mass-balance)



Sia Partners Analysis

Identified Opportunities for Chemical Recycling

	Critical	**Significant**	**Moderate**	**Low**
Very likely	🇪🇺 55% recycling rate for packaging materials	🇪🇺 *> 50% of plastic recycled plastic content by 2040 (PPWR)*	🇪🇺 25% recycled PET content in new bottles by 2025	€0.8/kg fee for unrecyclable plastics imposed on producers
Likely	🇪🇺 *Recognition of chemically recycled polymers (SUPD)*	🇪🇺 *EU ETS quotas on incinerators starting from 2026*	🇪🇺 🇫🇷 Expansion of EPR schemes and sorting guidelines	🇪🇺 90% separate collection rate for PET bottles by 2029
Unlikely	🇪🇺 *Goal of 0 plastic waste sent to landfill*	🇫🇷 *50% reduction in landfill waste by 2025*	🇫🇷 100% recyclability in the long term	Collection of “out-of-home” packaging waste

Identified Risks for Chemical Recycling

	Low	**Moderate**	**Significant**	**Critical**
Very likely	🇪🇺 Ban on plastic bags < 15 microns	🇪🇺 🇫🇷 *Eco-design measures promoted by legislation*	🇫🇷 Elimination of all SUPs* items by 2040	x
Likely	x	- 20% SUPs items by 2025, including 10% through the ban	- 20% packaging placed on the market by 2040	🇪🇺 *No protectionist measures associated with the PPWR*
Unlikely	🇫🇷 - 50% non-recyclable plastic volumes by 2020	🇫🇷 5% plastic reuse by 2023 and 10% by 2027	🇪🇺 *Highly restrictive application conditions for the Mass Balance resulting from SUPD*	

🟩 Full: Law, directive, regulation...
▨ *Hatched*: Non-binding target or **still under discussion**

High risk identified ■■■□□□■■■ *Strong opportunity identified*

The various **regulations introduced in France and Europe concerning the collection and recycling of plastic waste present significantly more opportunities than identified risks for chemical recycling**. Although the recognition of the "mass-balance fuel-exempt" has been approved in the new SUPD directive, the operational implementation details, particularly regarding the use of credits by chemical recycling operators, remain unclear.

SUP : single use plastics

Sources: Sia Partners analysis based on various legal texts from European and French regulations.

Focus

MARKET OVERVIEW | Chem. recycling possesses a technical competitive advantage, but lags behind in terms of economic and environmental performance

Mechanical recycling currently accounts for 98% of installed capacity. As part of its circular economy strategy, Europe has set ambitious targets to recycle 55% of all packaging by 2030, up from 29% today. **This target entails not only increasing existing mechanical recycling capacity but also paving the way for chemical recycling, which can address the challenges of incorporating recycled raw materials (RRM) introduced by the provisional agreement on the PPWR regulation, particularly concerning contact-sensitive standards.**

Criteria	Mechanical recycling sector			Chemical recycling sector		
	+	-		+	-	
Ability to address all plastic streams	› Addresses the main plastic deposits resulting from effective upstream separation	› Restrictive separation and upstream sorting steps required to limit contamination (Material purity >98%) › High *in-situ* loss rate (35%)* › Low tolerance for contamination	●●○	› Addresses all types of plastics (excluding PVC and plastics containing hazardous chemical materials) › Less stringent material purity constraint (>92%)	› Significant process loss rates remain poorly assessed (pollutants… etc)	●●●
Technology Performance	› Robust, reliable and easily scalable technology	› No return to food-grade (exc. PET clear bottles), no removal of dyes › Degrades polymers' chemical structures limiting the number of recycling cycles	●○○	› Process versatility (can return to either polymers or monomers) › Decontamination of processed plastics › No premature aging of the polymer structure	› Limited industrial experience to date › Fairly low process efficiency in some cases (<60%)	●●●
Economic competitiveness	› Competitive prices compared to virgin material for many resins	› Overall cost can escalate to achieve high quality products – costs will strongly depend on the intended lifecycle (eg: bottle-to-bottle)	●●●	› Directly delivers the highest quality at no extra cost	› Very high cost of produced materials (2 to 3 times the price of virgin materials) › Production remains in its early-stage (<100kt/year in the EU)	●○○
Environmental performance	› Lowest emission and best Life Cycle Assessment (LCA) among all recycling technologies	› Water consumption can be significant (washing)	●●●	› Scale effects of the projects could lead to an improvement in LCA › Many manufacturers aim to reduce reaction temperatures to achieve economic and ecological gains	› Energy-intensive thermal processes (pyrolysis, gasification) › Associated emissions and potential toxic releases	●○○
Enables compliance with regulations	› Recycling target of 55% of packaging by 2030 › RRM incorporation rate for PET bottle	› No return to contact-sensitive plastic (excluding PET), partly due to the lack of a standard (EFSA)	●●○	› New targets for RRM incorporation rates expected through the provisional PPWR, including targets related to *contact-sensitive* materials (see trends)	› Uncertainties regarding *mass balance* recognition › Uncertainties regarding the implementation of protectionist measures alongside the PPWR	●●○

Competitiveness of the sector according to the criterion: ●○○ *Low* ●●○ *Average* ●●● *High*

Sources : Sia Partners Analysis based on data : PIE 2022 et Plastic Portal, JRC Report *"Environment and economic assessment of plastic waste recycling"* 2022, ADEME 2022

MARKET OVERVIEW | Chemical recycling will not replace mechanical recycling, rather complement existing capacity by addressing "hard-to-recycle“ plastics and materials

Chemical recycling is intended to complement existing recycling capacity, particularly in areas where current channels are limited, to facilitate the achievement of EU recycling targets and improve the circularity of plastics. Mechanical recycling will retain its advantage in well-defined streams, such as PET bottles, industrial films and non-food grade PS/EPS. However, chemical recycling will addres the "hard-to-recycle” segments, enabling the processing of "contact-sensitive" materials, including those used in food, cosmetics, medical applications and hazardous waste.

Comparative table of the main polymers placed on the packaging market (~21 Mt EU)

Polymers / *Criteria*	PET			Multi-layer trays	HDPE		LDPE		Rigid PP		Flexible PP	PS / EPS
	Clear	Coloured / Opaque	Monolayer		Bottles / PTT*/ caps	Transport packaging	Industrial films	Household flexible packaging	Bottles / PTT*/ caps	Transport packaging	Household flexible packaging	
EU volume (Mt/year)	3.1	1.4	0.5	N/A	3.4	0.7	4.3	2.5	3.2	0.3	~1	~0.4
State of recycling	+++	+	++	-	++	++	+++	-	++	++	+	-
Return to contact-sensitive	✓	✗ *Excl. white milk bottle*	✓	N/A	✗	N/A	N/A	✗	✗	N/A	✗	✗
Limits	Contaminants / sorting issues Supply tensions depending on virgin prices / need for RRM	Little/not collected	Non-recyclable lids and sealants	Little/not collected	No return to contact-sensitive			Soiled, presence of organic, mixture of materials	No return to contact sensitive		Soiled, presence of organic, mixture of materials Small packages	Brittle materials (<5 cm) with limited current outlets
Main outlets	Food packaging	Textile	Food packaging		Non-food items		Plastic bags, garbage bags, tubes		Non-food items	Plastic bags, garbage bags, tubes		Flower pots, hangers
Best recycling pathway *(Sia Partners hyp.)*	Mechanical	Chemical	Mechanical	Chemical	Mechanical	Mechanical	Mechanical	Chemical	Mechanical	Mechanical	Chemical	Chemical

20.8

+++ Efficient recycling stream in place ++ Recycling stream in place with potential for improvement + Suboptimal recycling stream - No functional recycling stream

Mechanical recycling ■ ■ 50- 50 ■ ■ *Chemical recycling*

Sources : Sia Partners analysis, Strategy (2021), Container & Packaging 2022, Eunomia 2018, Citeo 2022, SNEP

MARKET OVERVIEW | Preliminary summary of the plastics recycling market in Europe

Current Market and Trends

- **The EU produces ~60Mt of plastics per year, with two-thirds originating from four main families**: PET, Polyolefins, PVC and PS-EPS. **Mechanical recycling accounts for 98% of installed capacity in Europe** owing to its low cost[1], reliability, scalability and its ability to process major plastic waste families (under specific conditions).
- However**, only 29% of end-of-life plastics are recycled in Europe**, partly due to insufficient collection but also to a lack of outlets for recycled plastics from the mechanical sector, which face a market with lower added value and higher prices than virgin material.
- **The recycling rates of plastic waste vary significantly between different resins**: >60% for PET (bottles), but <10% for PVC.
- **Achieving full circularity of plastics requires the development of alternative technologies** to address the limitations of current recycling practices.

Regulatory Outlook

- The key European regulations **promoting plastic recycling pertain to packaging** (~19 Mt/year) include: the EU Directive 2018/852 **aiming to recycle at least 55% of packaging by 2030,** and the provisional agreement on the PPWR (with a final vote expected in autumn 2024) **targeting an incorporation rate of recycled raw materials of 50 to 65%** for new packaging by 2040.
- **The update of the Single-Use Packaging Directive (SUPD) voted in 2024 also paves the way for the certification of recycled polymers produced** through recognition in the Mass Balance.
- In France, significant **measures have been implemented to reduce landfilling by 50% by 2025, alongside the development of EPR sectors** (especially for ICP), thereby fostering better circularity better of plastics through improved collection and sorting processes.

Recycling channels

- **Chemical recycling offers at least two competitive advantages over mechanical recycling,** both regarding the **types of materials processed –** such as its ability to handle mixed plastics (polyolefins) and reduced constraints on the purity of incoming materials **–** and in terms of **technological benefits,** including the decontamination of treated plastics, the prevention of premature aging of polymers, and no limitations on the reincorporation of recycled raw materials (RRMs).
- While mechanical recycling currently demonstrates better **economic and environmental outcomes,** the anticipated scale-up of chemical recycling projects could see this gap in performance closed.

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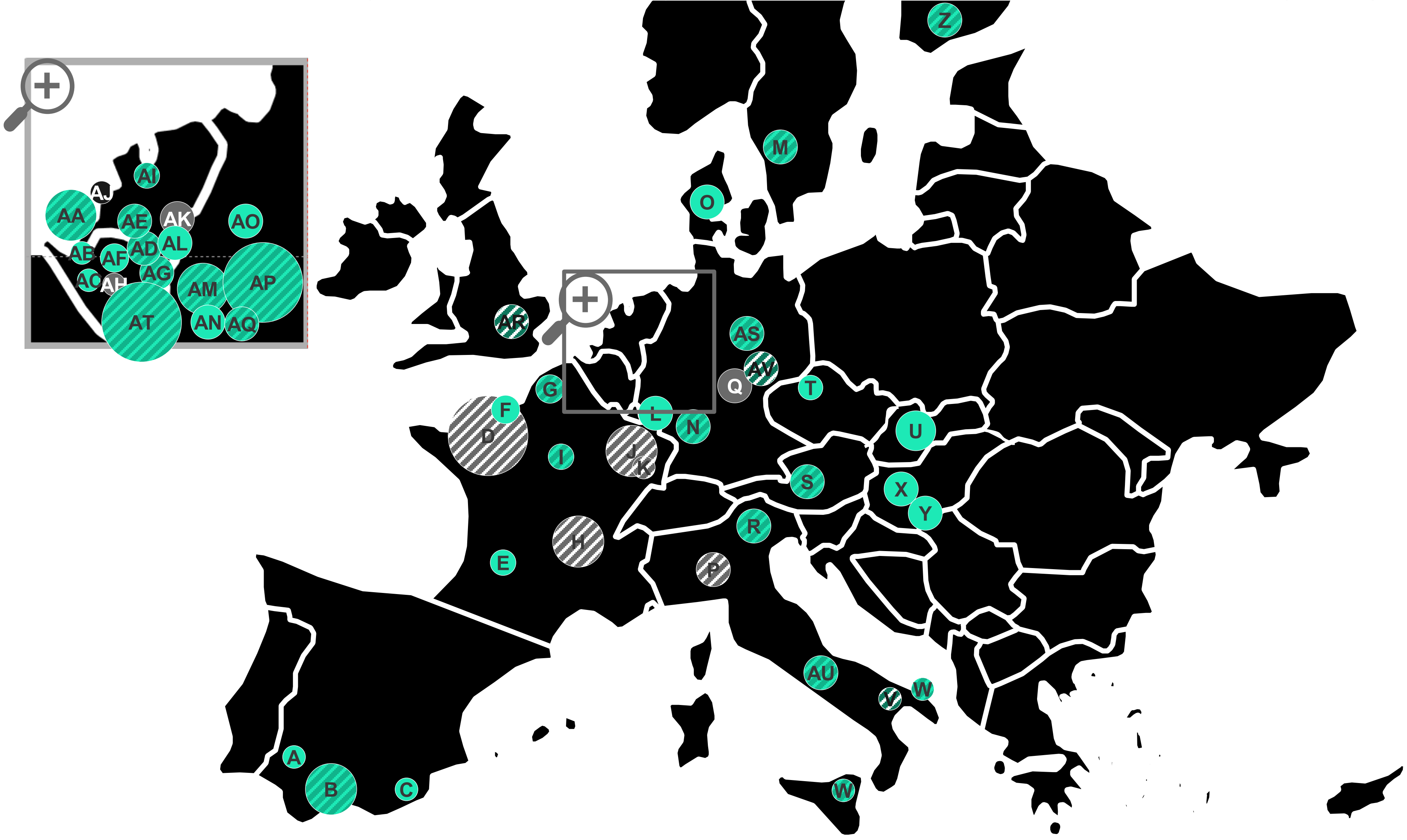
[1] : Plastics Europe estimated in Oct-23 at €1,125/t the cost of recycling a tonne of plastic compared to €1,395/t for the production of virgin resins

02. European benchmark

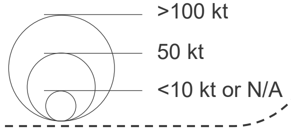
Over 50 projects have been identified, mainly in France, Germany and Belgium; however, their competitiveness is constrained by technological, economic and environmental barriers

EUROPEAN BENCHMARK | 51 projects are currently operational or announced in the EU, with a total capacity of 0.8 Mt, compared to 12.5 Mt for mechanical recycling

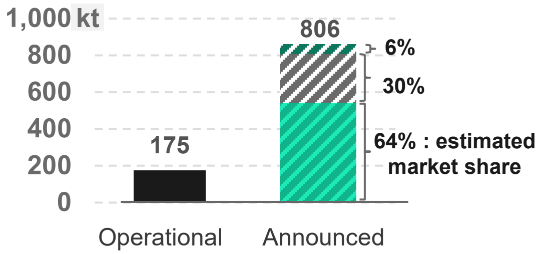


Legend

Pyrolysis	●	Operational
	▨	Announced / in development
Solvolysis	●	Operational
	▨	Announced / in development
Gasification	▨	Announced / in development
Dissolution	●	Operational



Processing Capabilities



Note: *18 June 2024

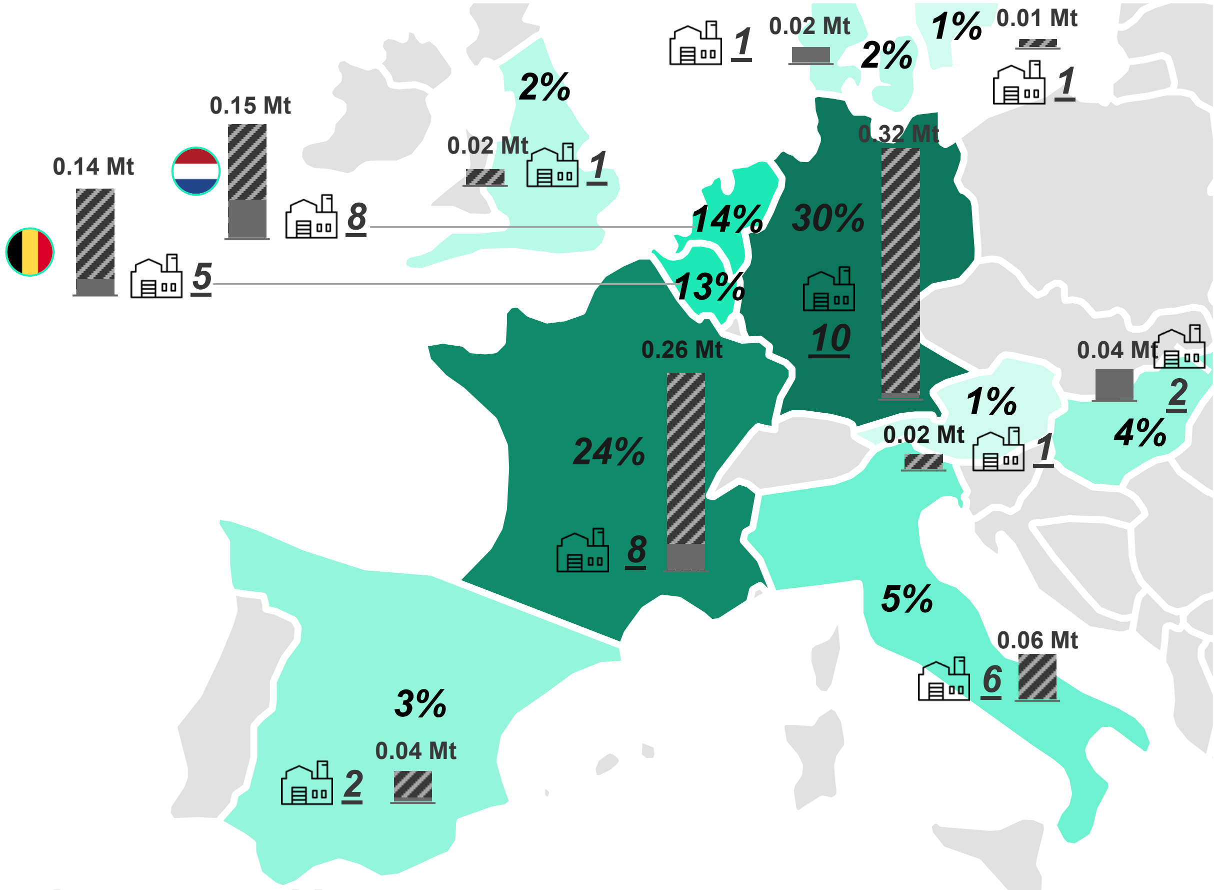
The full list of projects is available in the annex

Sources : Sia Partners Analysis & Research according to press releases and specialist press articles

Focus

EUROPEAN BENCHMARK | Chemical recycling projects are predominantly located in France, Germany, Belgium and the Netherlands (68% of announced capacity)

Chemical recycling projects are experiencing significant development and are the subject of numerous announcements. **Germany and France particularly stand-out with announced capacities** of 324 kt and 230 kt respectively, far exceeding the current operational capacity of 175 kt. Technology developers are prominently represented across these projects, driven by the need to scale their innovations to industrial levels. They most often partner with a petrochemical player for the value recovery of produced polymers and to target "contact-sensitive" markets. The primary feedstock used is post-consumer household plastic waste, indicating an integration of advanced sorting processes within the projects. In France, the focus is predominantly on PET, particularly through solvolysis technology.



COUNTRIES WITH THE MOST SIGNIFICANT CAPACITIES (>10% market share)

1	**GERMANY**	42% PE, PP, PS	58% Mixed waste*
2	**FRANCE**	70% PET	30% Mixed waste
3	**NETHERLANDS**	13% PET	87% Mixed waste
4	**BELGIUM**	86% PS	14% Mixed waste

**Mixed waste : Blend of post-consumer waste from PO resins (PE,PP)*

Legend

Country market share (total capacity): 0% 15% 30% — 24%

Total number of projects 8

Existing Capabilities ■

Announced Capabilities ▨

Total Capacity **0.3 Mt**

Capacity: 1 cm = 100 kt

Sources : analysis and calculations by Sia Partners based on public project data

Focus

EUROPEAN BENCHMARK | Many projects rely on partnerships both upstream and downstream of the value chain to de-risk investments

Projects are commonly announced in partnership with **various stakeholders,** including raw material suppliers (mechanical waste collectors and recyclers), plastic waste processors (technology providers), petrochemical producers, and industrial users of recycled plastics. These collaborations are often formalised through memoranda of understanding, joint investments, or letters of intent to ensure the supply of produced plastics.

PARTNERSHIPS EXAMPLES

Upstream partnership: **securing inputs**

Project : Eastman (Port-Jérôme, France)

Technology: Solvolysis

80% of the input supply secured through partnerships with waste management players

Downstream partnership: **valorisation of outgoing materials**

Project : CARBOLIQ (Frankfurt, Germany)

Technology : Pyrolysis

Transformation into **PA**

Transformation into **PE**

Use of processed polymer for its new packaging

***Finished products** (polymers, pyrolysis oil) **recovered by specialised companies, preventing a significant increase in project costs** (post-treatment)*

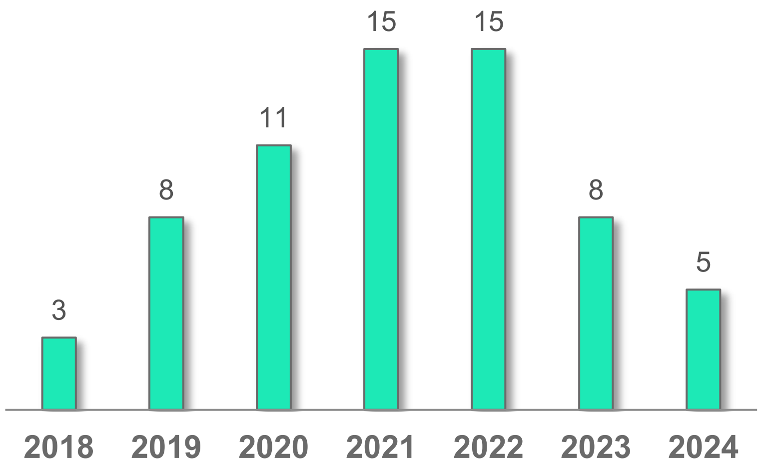
Sources : Sia Partners Analysis & Research from project development data

Focus

EUROPEAN BENCHMARK | The increase in financial and regulatory risks has led to a slowdown in the initiation of new projects since 2022

Chemical recycling projects are confronted with a range of significant risks (technological, economic, societal, etc.) that can hinder their development. Despite an increase in the number of projects since 2019, Europe experienced a notable declined in new project announcements in 2023, with a 50% decrease compared to 2022. This slowdown is largely attributed to the challenges that recycling projects face. **Sia Partners has identified several projects commissioned that have had to halt operations due to profitability and operational reliability issues.** However, these barriers could be mitigated through the implementation of a comprehensive regulatory framework.

Number of new projects announced per year



Following two dynamic years (2021 and 2022), **the number of new projects is decreasing,** with 8 projects announced in 2023 and 5 projects announced by June 2024. This decline is largely attributed to the emergence of several new risk factors (see adjacent).

Different risks identified in the implementation of projects

Technological risk

Reliability of technologies, complexity and multitude of processes within the value chain (upstream/downstream)

Economic risk

Rising required investments levels and high interest rates, coupled with low virgin material prices

Regulatory risk

Regulatory uncertainty regarding future directions prior to the PPWR and SUPD

Environmental and societal risks

Increasingly challenging environmental impact and social acceptance

Competition between sectors

Advocacy for mechanical recycling to maintain status quo, while the EU aims to reduce plastic use and promote reuse

Project shutdowns and company bankruptcies

🇸🇪	STENA RECYCLING BOREALIS	Postponed start: feasibility study inconclusive and lack of investments despite support from the EIB and the Swedish Energy Agency
🇬🇧 🇳🇱	Recycling Technologies Umincorp	Suspension of operations in the chemical recycling sector
🇫🇷	EASTMAN	Announced one-year delay announced: challenges in securing sorted PET inputs

The full list of projects is available in the annex

Sources : Sia Partners analysis based on public project data

EUROPEAN BENCHMARK | Summary of chemical recycling project developments in Europe

State of play of the CR in Europe

- Chemical recycling projects are actively developing across Europe, with **Germany and France standing out in announced capacities (324 and 230 kt), together representing more than half of the total announced capacity.**
- The pioneering countries exhibit at least one of two key dynamics: a **very high collection rate of plastic waste** (Germany, Netherlands, and Belgium) **resulting in significant waste streams that are often poorly captured by mechanical recycling,** and/or a **plastic recycling rate considerably lower than the EU average** (France, Hungary) which eco-organisations aim to improve by supporting and financing innovative projects.

Technologies and resins processed

- **Pyrolysis is the most widely deployed technology** (64% of capacity) to process **"post-consumer" household plastic waste and polyolefin residues** (LDPE, flex. PP). Although gasification technologies show promise, they are yet to be implemented at scale in the EU.
- Developments in France focus on **solvolysis technologies, with 200 kt/year of announced processing capacity allocated to** PET waste.
- Concurrently, various **“satellite” initiatives are emerging, both in relation to the recycling of new waste streams** (Source One, Interzero in Germany for the treatment of selective recycling residues) and in **pyrolysis oil processing** (Neste, Finland).

Partnerships

- **Projects are typically developed via multi-stakeholder partnerships, allowing for "de-risking" through the provision of know-how** (waste managers, petrochemists), **capital** (manufacturers) **and technology** (developers). In contrast, mechanical recycling projects are typically developed by a single entity.

Current dynamics

- **Despite an increase in chemical recycling project announcements between 2019 and 2022 within the EU, there has been a significant slowdown in 2023 (-50% compared to 2022), with a similar level expected in 2024** (5 projects announced in the first-half of the year). These new projects face a number of risks: financial (rising CAPEX and credit costs), as well as regulatory, with the anticipated European deliberations on the recognition of chemical recycling within mass-balance framework (SUPD) and the required rate of RRM in new products (PPWR).

03. Ecosystem of market participants

Refiners and petrochemical companies are demonstrating strong interest in chemical recycling to enhance their supply, while industrial manufacturers, facing regulatory pressure, are increasingly forming partnerships to secure volumes

ECOSYSTEM | The chemical recycling sector is driven by plastic resin producers and manufacturers seeking solutions for needs not currently met by mechanical recycling

(REMINDER) PLASTIC LIFE CYCLE

PROS & CONS FOR "HISTORICAL" PLAYERS

\+
- **Greening and diversifying their business model**
- **Securing "non-fossil" carbon sources**
- **Ensuring long-term business model sustainability** (improved recycling could boost plastic production, leading to rebound effects)
- **Improved margins** (Certificate Sale/Premium)

\-
- **Significant investments and high operational risks for currently low quantities** (before 2030)

\+
- **Manufacturers: strong interest in addressing the regulatory challenges regarding RRM incorporation and marketing arguments**
- **Production of resins with improved physicochemical properties** (non-degradation of polymer chains), thereby limiting waste disposal (incineration, landfilling)

\-
- **Purchase price of chemically recycled resins remains too high to address the mass market** (2 to 3 three times virgin materials' prices)
- **Significant uncertainties regarding the traceability of products brought to market and their carbon footprint**

\+
- **Waste managers: have "control" over the waste streams** (possible price wars)
- **Diversification of activities** (sort -> over-sort; mechanical + chemical recycling...)

\-
- **Significant threat to mechanical recyclers: risk of loss of waste streams (especially PET)**
- **Substantial investments are required to improve source collection and adapt sorting centres** (for limited and dispersed quantities)

EXAMPLES

NESTE	Pyrolysis oil refinery up to 450 kt/year, Porvoo site, €111M investment
DOW	Pilot project (20 kt/year waste), use of pyrolysis oil by Dow for PP and PE

See dedicated focus

lyondellbasell	Post-Consumer waste recycling unit to produce LDPE (40kt) with APK
TRINSEO	PS depolymerisation pilot plant (15kt waste)

See dedicated focus

Siemer DIE ENTSORGER	Collaboration with Plastic Energy and Sabic to source plastic waste
suez	Development of a Suez/Loop Industries plant in 2025 (solvolysis)

See dedicated focus

Sources : Sia Partners benchmark, Polyvia "Recyclage chimique : où en sommes-nous ?" 2022

ECOSYSTEM | Analysis of the plastics manufacturing and recycling value chain (1/3)

Historical oil and gas companies, along with resin producers, are at the forefront of developing chemical recycling projects

Mining and primary manufacturing industry

Market participant and position within value chain	Added value	Examples of market participants involved in C.R	Upcoming transformations and opportunities within the chemical recycling stream	Examples of achievements	Sia Partners Analysis
01 Refiners	Refinery input production	ExxonMobil NESTE TotalEnergies petroineos	› Production of pyrolysis oil from plastic waste › Pyrolysis oil refinery › "Greening" and "premiumisation" of the petroleum outputs produced › Securing the long-term use of hydrocarbons (increased recycling = outlets for hydrocarbons)	NESTE: Pyrolysis oil refinery up to 450kt/year, Porvoo site, €111M investment ExxonMobil: Production of pyrolysis oil, partnership with Plastic Energy, Le Havre	› Parent model (refinery) – daughters (pyrolysis oil production) relevant › Complex and costly process to transform existing installations › The "first-movers" (ex Neste) will be rewarded (securing feedstock) + support from European funds)
02 Petrochemists	Formulation of monomers and polymers	LYB LyondellBasell versalis BOREALIS DOW NEXTCHEM BASF The Chemical Company INEOS STYROLUTION	› "Greening" and "premiumisation" of plastic resins produced (to support the objectives of RRM production) › Preparing for the "post-fossil" era › Improving the competitiveness of recycling by addressing new markets (ex : contact-sensitive)	BASF The Chemical Company: Waste Tire Recycling Plant, 4 kt/year pyrolysis oil with NewEnergy DOW: Pilot project (20 kt/year waste), use of pyrolysis oil by Dow for PP and PE	› Central role of petrochemical manufacturers in achieving the objectives of incorporating RRM for all resins and improving the competitiveness of chemical recycling (better technicality of resins produced via recycling / economic: competition with virgin products)

Refiners and petrochemists are making significant investments in advanced technologies through strategic partnerships. These players **are also actively supporting R&D** to secure a technological edge and mitigate future regulatory risks, **particularly concerning potential reductions in the plastic quantities placed on the market.** Additionally**, the importance of branding and marketing cannot be overlooked,** as these players aim to expand their portfolio of "greener" products, while awaiting the commercialisation of synthetic fuels, which offer higher profit margins.

Sources : Sia Partners benchmark based on data from players in the value chain, Polyvia "Recyclage chimique : où en sommes-nous ?" 2022

ECOSYSTEM | Analysis of the plastics manufacturing and recycling value chain (2/3)

Regulatory pressure surrounding plastic market players will drive demand both upstream (resins) and downstream (product recyclability)

Secondary manufacturing industry and Marketing

Activities (usually) shared

Market participant and position within value chain	Added value	Examples of market participants involved in C.R	Upcoming transformations and opportunities within the chemical recycling ecosystem	Examples of achievements	Sia Partners Analysis
04 Compounders	Resin formulation	lyondellbasell CLARIANT RTP Co. Imagineering Plastics BASF The Chemical Company سابك sabic	› Production of new resins › Innovative product development › Diversification of raw material sources › Sales at premium prices › Competition among various inputs (virgin vs recycled)	lyondellbasell Post-consumer waste recycling unit to produce LDPE (40kt) with APK	› Compounders and plastics manufacturers are less likely to benefit from the transition to chemical recycling. However, there are opportunities in developing new types of resins for a broader range of applications, such as food-grade. › This shift could lead to a rebound effect on plastic consumption, increasing circularity resulting in higher plastic production › Resin formulations are dictated by the characteristics of "downstream" product and must comply with regulations, regardless of the upstream sector
05 Plastics manufacturer	Plastic products manufacturing	Plasturgia Plastisem FORVIA faurecia TRINSEO Plastipak	› Processing of previously unrecyclable plastic resins › Securing other raw materials and potential competitive advantage › Increased final product optionality › Competition between different inputs (virgin / recycled)	TRINSEO PS depolymerisation pilot plant (15kt waste) Ravago Construction of a 55kt and 200kt unit in the long term with Neste	
06 Marketer	Placing products on the market	P&G MICHELIN Knorr L'ORÉAL LVMH Gutfried DANONE ONE PLANET. ONE HEALTH	› Potential for recycling previously non-recyclable plastics (contact-sensitive) › Shift in applications from virgin to recycled plastics › Moving towards 100% recycled packaging for all packaging placed on the market (in premium sectors most likely)	Knorr 5kt Mixed PE, PP, PS Recycling Plant with Plastic Energy MICHELIN Industrial demonstrator on Michelin sites operational in 2021 (50 kt/year of post-consumer PET waste)	› Compliance with upcoming regulations › Minimisation of carbon footprint and compliance with CSR expectations › Enhanced brand image and integration of stakeholder claims › Potential access to cheaper polymers in the future and financial incentives

Plastics manufacturers and compounders are less involved in chemical recycling projects, apart from a few large players (Sabic, LyondellBasell and BASF), because of a lack of certainty regarding the current regulatory framework.

Sources : Sia Partners benchmark based on data from players in the value chain, Polyvia "Recyclage chimique : où en sommes-nous ?" 2022

ECOSYSTEM | Analysis of the plastics manufacturing and recycling value chain (3/3)

The availability of input-material will be crucial to underpin new developments. Meanwhile, established recyclers are concerned about emerging threats to their operations

Waste management and recovery industry

Activities (usually) shared

Market participant and position within value chain	Added value	Examples of market participants involved in C.R	Upcoming transformations and opportunities within the chemical recycling ecosystem	Examples of achievements	Sia Partners analysis
07 **Waste manager (collection & sorting)**	**Management, waste separation**	PAPREC suez DERICHEBOURG multiservices Siemer DIE ENTSORGER VEOLIA	› Increased value of waste › Assigns value to previously low-value waste (coloured plastics, with additives, etc.) › Development of new sorting and over-sorting lines › Reduction of residual waste, increase in the selective collection of plastics	Veolia and Nestlé partnership to reduce plastic waste and develop recycling programs Collaboration with Plastic Energy and Sabic to source plastic waste	› The players involved in collection and sorting hold control over the waste streams/ deposits, making them critical to the development of new projects › They can invest in sorting and over-sorting capacities to enhance chemical recycling projects and limit landfill disposal, thus achieving significant cost savings
08 **Recyclers**	**New resins**	DENTIS Recycling ITALY suez TERRACYCLE PLASTIC ENERGY PAPREC	› Aiming for 100% circularity of common plastics › Recovery of mechanical losses (~30%) for chemical recycling › Diversification of existing players › Synergy between mechanical recycling combined with chemical recycling (over-sorting chain in particular)	Development of a Suez/Loop Industries facility in 2025 (solvolysis) Partnership with Eastman for the treatment of waste collected by Paprec (100 kt – 200 kt in the long term)	› Established mechanical recyclers may be the most threatened by the emergence of chemical recycling › Enhancing the sector's competitiveness is essential to prevent a decline in their market share, (i.e. increase in RRM by mech. recycling in new products,…)
Other actors	**Organization of the sector, lobbying**	CITEO ISCC International Sustainability & Carbon Certification PLASTICS EUROPE PLASTICS RECYCLERS EUROPE	› Development of the regulatory framework and harmonisation of standards › Development of certification and traceability processes › Structural support provided to achieve regulatory objectives (funding, visibility, networking)	2021 : Call for tenders for the supply of deposits (52 kt/year flexible plastics) Certification of chemically recycled polymers	› Eco-organisations are key drivers in the development of chemical recycling, as they believe it will facilitate the achievement of national recycling targets › Associations of plastics producers are strongly in favour of chem. recycling, viewing it as a valuable opportunity to secure and enhance the sustainability of their business

Waste managers, through their control over plastic streams and deposits, will be key players in chemical recycling. Historical recyclers stand to lose the most from this transition towards chemical recycling.

Sources : Sia Partners benchmark based on data from players in the value chain, Polyvia "Recyclage chimique : où en sommes-nous ?" 2022

ECOSYSTEM | Preliminary analysis of the interplay of the actors in the plastic value chain

Value Chain

Interest

Mining and primary manufacturing industry

●●●

High

- **Refiners and petrochemists are primarily engaged through two approaches**: acquiring stakes in technology developers (Ineos with Plastic Energy; Shell with BluAlp) and/or participation in the establishment and development of projects (TotalEnergies, Exxon)
- For the latter, chemical recycling presents an **opportunity to access new markets, enhance their "sustainable" image by promoting a low-emission carbon source,** and "premiumise" the supply of recycled plastic resins which offer higher margins

Secondary manufacturing industry and marketing

●●○

Moderate

- **Plastic manufacturers and compounders are less involved in the sector's development, as they are minimally affected by impending transformations,** given that the resins produced are equivalent to virgin materials. Only a few petrochemical-linked players, such as Sabic, LyondellBasell and BASF are represented.
- **In contrast, the industry is observing significant involvement from manufacturers especially within the agri-food, cosmetics and automotive industries.** The regulatory pressure arising from the upcoming PPWR compel them to promptly secure volumes. However, they remain **highly vigilant regarding traceability, carbon footprint and recycled products' pricing, which currently limits the development of recycled products**. Nonetheless, recycled products increasingly serves as a differentiating factor that can influence consumer purchasing decisions.

Waste management and recovery industry

●●○

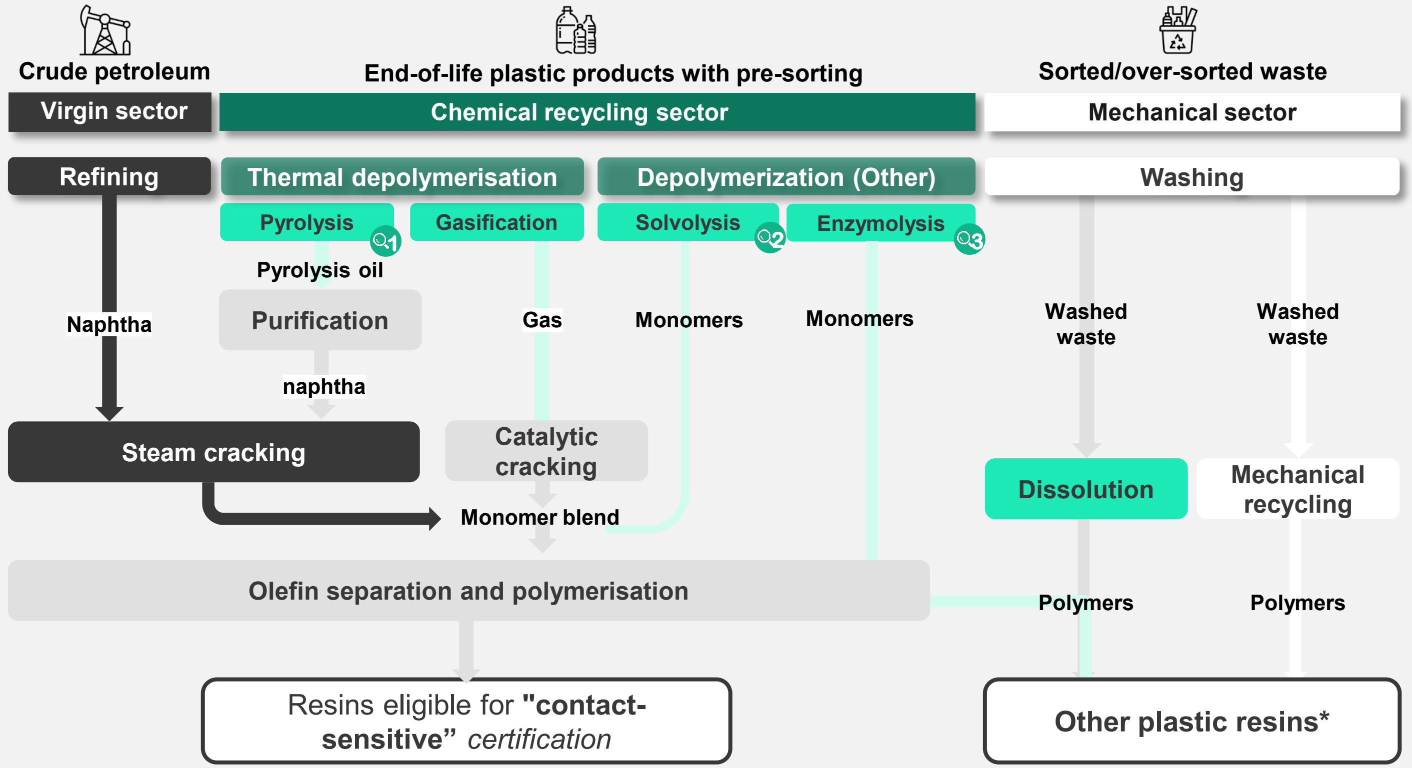
Moderate

- **Waste management actors play a pivotal role in nearly all projects.** Their ability to supply materials **in both quantity and quality** through the installation of dedicated over-sorting lines, along with their control over **resource pricing,** are decisive factors in project selection.
- **Established mechanical recyclers regard chemical recycling as a significant threat to their operations**, particularly concerning the supply of specific plastic streams, such as PET. However, opportunities for synergies exist, both in recovering materials from the ~30% of incoming volumes that are typically rejected in mechanical recycling processes, and in enhancing sorting capacities, which would benefit both recycling pathways.

04. Technology overview

Chemical recycling will process plastics currently not addressed by mechanical recycling into resins with superior physicochemical properties. However, high costs and lower environmental performance continue to pose challenges to its development.

TECHNOLOGY OVERVIEW | A diverse array of plastic recycling technologies is emerging, primarily driven by the potential to produce "contact-sensitive" recycled plastics



Crude petroleum

Virgin sector

Refining

Naphtha

Steam cracking

End-of-life plastic products with pre-sorting

Chemical recycling sector

Thermal depolymerisation

Pyrolysis ①

Gasification

Depolymerization (Other)

Solvolysis ②

Enzymolysis ③

Pyrolysis oil

Purification

naphtha

Gas

Catalytic cracking

Monomers

Monomers

Monomer blend

Olefin separation and polymerisation

Resins eligible for **"contact-sensitive"** *certification*

Sorted/over-sorted waste

Mechanical sector

Washing

Washed waste

Washed waste

Dissolution

Mechanical recycling

Polymers

Polymers

Other plastic resins*

	PP	*PE*	*PET*	*PVC*	*PS*
Pyrolysis	◉	◉	○	○	◉
Enzymolysis	○	◎	◉	●	○
Gasification	◎	◎	○	○	◎
Solvolysis	●	●	◉	●	◎
Dissolution	○	○	○	○	○

◉ Optimal technology
○ Limited technology
◎ Adapted technology
● Unsuitable technology

This simplified map **presents the different recycling and production channels of plastic resins**. To date, **no chemical recycling technology has managed to gain a competitive advantage over the production of virgin resins or mechanical recycling**. The latter are differentiated by their **processing capacities at the input** (mixture of polyolefin resins, coloured PET, etc,...) **and according to the type of molecule sought at the output** (monomers vs polymers vs resins) **with or without a return to "sensitive contact"**.

**Except for clear PET bottles and opaque PET (milk bottle type) which currently have contact-sensitive approval*

Sources : Sia Partners analysis from RECORD 2022 – chemical and physico-chemical recycling of plastic waste

Focus

TECHNOLOGY OVERVIEW | Pyrolysis

Key information

TRL
7-8

Processed inputs
PO, PS, tyres, PMMA (rare)

Incoming material purity requirement[1]
90-95%

Contaminants
PVC, PET, metals

Factory capacity of 70kt/year – mixed plastics waste (PO) – USA[2]
CAPEX : ~ $M 100
OPEX : ~ $M 89 (of which 50% inputs)

EU Facility Capacities

Existing projects	**Announced projects**
1-20kt/year	**30-100kt/year**

Process description

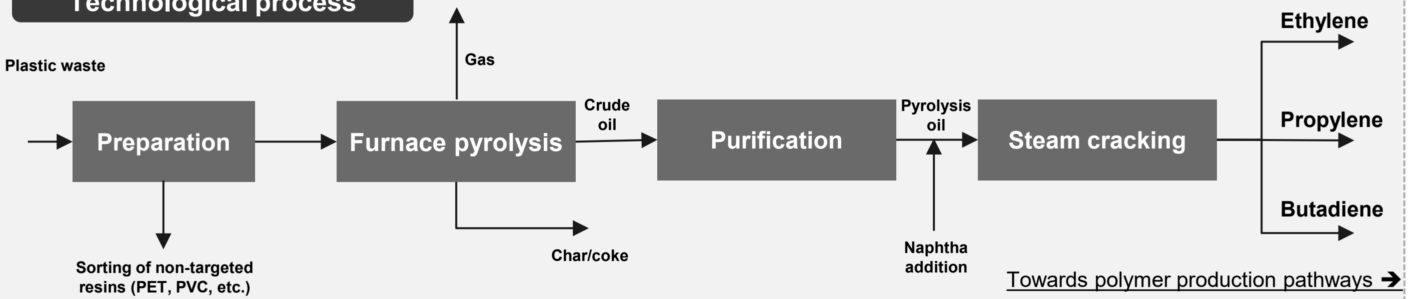
Operating principle

Operating conditions

350-800°C **STP[3]**

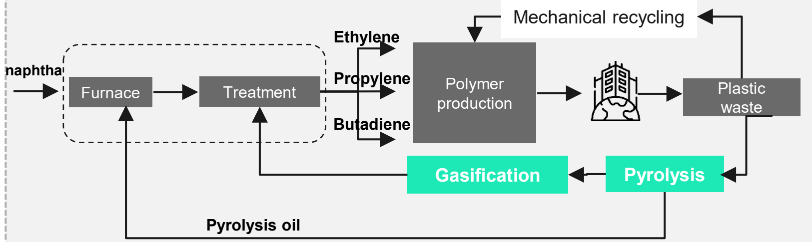
- Pyrolysis is a **thermal decomposition** process conducted in an oxygen-free environment
- **Pyrolysis yields a mix of oil,** gas, and char (solid residue) comparable to the outputs obtained through distillation in petrochemical processes.
- The pyrolysis oil (which accounts for 55 – 80% by mass of outputs) can subsequently be refined to produce various products used by the chemical, plastic or petrochemical industry. It can also be used as fuel.

Technological process



Towards polymer production pathways ➔

Chemical recycling of plastics by thermal depolymerisation



- **Pyrolysis oil** produced from plastic waste is introduced into the furnace of the steam cracker following hydrotreating and purification.
- This oil is typically diluted with fossil naphtha to enhance the input mixture, which often lacks sufficient "light" aromatic compounds (short CxHy chains)[4] facilitating the production of "alkenes".
- **Gasification processes operate similarly[5] to steam cracking.** After an initial pyrolysis stage, the oil undergoes gasification at very high temperatures to generate a gas mixture, of which the lighter fractions[6] can be reused in plastics production. As this process is less mature (TRL 3-4), there are currently no industrial facilities in operation.

Synthesis

Strengths / Opportunities

- *Suitable for food use*
- *Treats waste streams with impurities*
- *Inclusion of a catalyst reduces the heat requirement and offers better selectivity of the final products.*

Weaknesses / Threats

- *Material yield (40 to 60% of the incoming mass)*
- *GHG emissions / other pollutants*
- *Fragility of the process (production of tank, tar, blockage)*
- *High energy consumption compared to other recycling processes*

Technology providers

PLASTIC ENERGY
VALOREGEN Advanced Recycling
NEWENERGY First Hungarian pyrolysis plant
ExxonMobil
PYRUM innovations
ORLEN Unipetrol
BASF The Chemical Company
QUANTAFUEL
LUMMUS TECHNOLOGY

Innovative processes
Gasification

versalis
bobine.
NEXTCHEM

1: confidential data EPC over-sorting centre chemical recycling projects
2 : NREL, 2022, Techno-Economic Analysis and Life Cycle Assessment for Pyrolysis of Mixed Waste Plastics
3: excluding the Mura technologies process, which uses a pressurized supercritical water reactor (210 bar)
4 : A comprehensive experimental investigation of plastic waste pyrolysis oil quality and its dependence on the plastic waste composition
5: verbatim exchange with Bobine Chemistry
6: ethylene, styrene...

Sources : Sia Partners analysis from RECORD 2022 – chemical and physico-chemical recycling of plastic waste

Focus

TECHNOLOGY OVERVIEW | Solvolysis

Key information

TRL
7-8

Processed inputs
PET (majority), PA, PC

Incoming material purity requirement[1]
92-95%

Contaminants
PVC, PO, fibers, metals

CAPEX :
Project Eastman[1] : € 1,000M (100kt)
Project Loop[2] : €450M (70kt)

EU Facility Capacities

Existing projects	**Announced projects**
40-60kt/year	**200-300kt/year**

Process description

Operating principle

Operating conditions

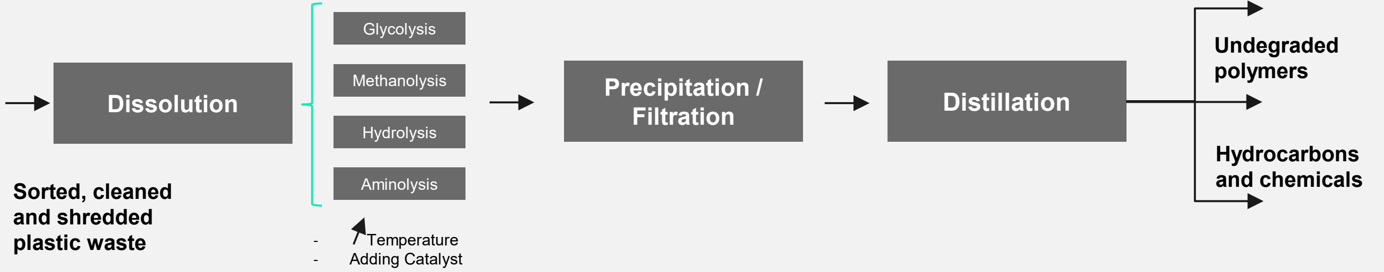
150-300°C **STP**

"**Solvolysis**" is a chemical process used to degrade polymers, involving a reaction **between polymer bonds and a solvent.**
This reaction, coupled with a catalyst, leads to the formation of monomers that can subsequently be repolymerised into high-quality resins. The solvent is also recycled and reinjected into the process.

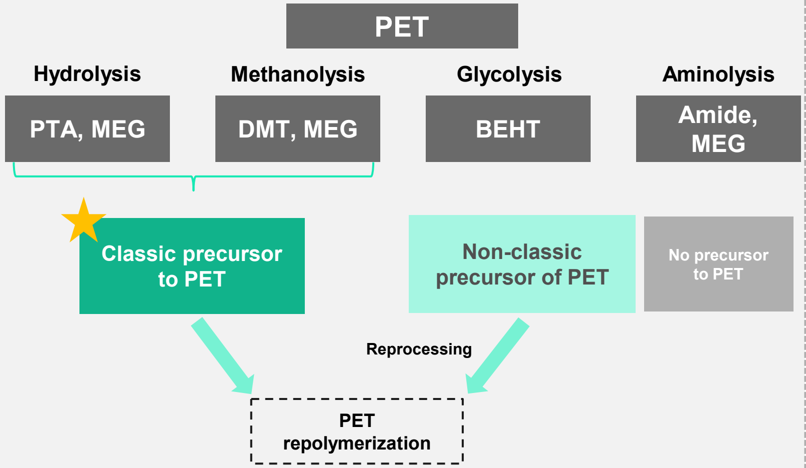
Solvents used

- **Glycolysis - Ethylene Glycol**
- **Methanolysis - Methanol**
- **Hydrolysis – Water**
- **Aminolysis - Amine**

Technological process



PET solvolysis value chain



Technology providers

EASTMAN
loop INDUSTRIES
suez
SK geo centric
JEPLAN We circulate our world
POSEIDON PLASTICS
Emery Oleochemicals
CuRe Polyester Rejuvenation
ioniqa

Synthesis

Strengths / Opportunities

- *Production of food-grade plastic*
- *Processing of thermosetting resins and cross-linked polymers*
- *Process for the selective production of monomers*

Weaknesses / Threats

- *More drastic operating conditions (high temperature and pressure) for resins that are more difficult to recycle*
- *Important upstream sorting of polymers so as not to obtain mixtures of monomers*
- *Purification step necessary in order to obtain sufficiently clean monomers before repolymerisation*

1: Entretien avec la société Pellenc ST
2: « *Eastman va investir au moins 1 milliard d'euros pour recycler des plastiques en France* » l'UsineNouvelle, 2023
3 : Suez.com, 2023

Sources : Sia Partners analysis from RECORD 2022 – chemical and physico-chemical recycling of plastic waste

Focus

TECHNOLOGY OVERVIEW | Enzymatic technology overview

Key information

TRL	Processed inputs	Incoming material purity requirement	Contaminants	CAPEX + OPEX :	EU Facility Capacities: Existing projects	EU Facility Capacities: Announced projects
7	**PET** (all types)	**No minimum level required**[1]	**None**	**N/A**	**0 kt/year**	**50 kt/year**[2]

Process description

Operating principle

Operating conditions

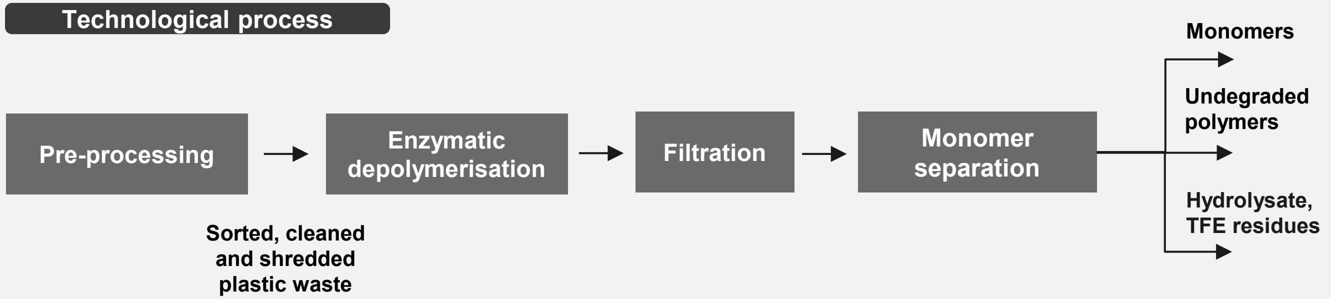
72°C **STP**

Enzymatic recycling **is a chemical process for the depolymerisation of polymers, achieved through the cleavage of polymer bonds through enzymes.**

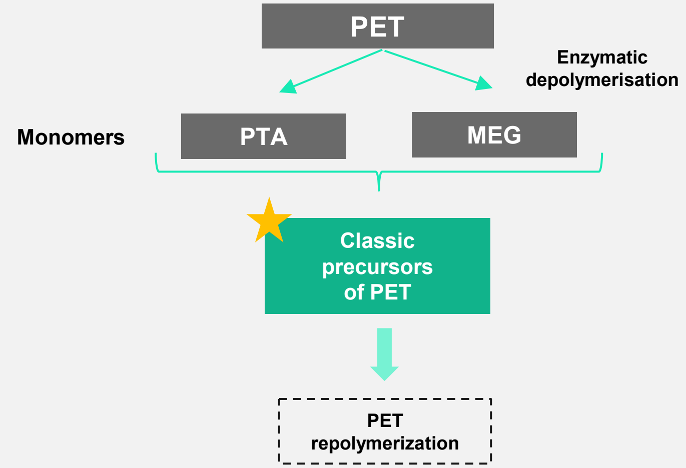
This reaction leads to the formation of monomers which are subsequently purified before being repolymerised into high-quality resins.

In the case of chemical PET recycling, cutinase is the enzyme used, following the optimisation of its binding site. **The enzyme exclusively degrades PET for recovery, while other polymers and resins are removed at the end of the process.**

Technological process



PET Enzymatic Recycling Value Chain



Technology providers

CARBIOS Enzymes powering the Circular Economy

INDORAMA VENTURES

PETROBRAS

Enzycle

Synthesis

Strengths / Opportunities

- *Back to food quality and transparency*
- *Solvent-free and low-temperature process*
- *High selectivity of monomers*
- *Large number of recycling cycles possible without altering quality: 100% recycled and recyclable products*
- *Textile recycling possible*

Weaknesses / Threats

- *High cost*
- *Non-mature technology (advanced development only for PET)*
- *Competition with mechanical recycling on clear and transparent flows*

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1 : but impact on the yield, the size of the plant and the cost of the final waste to be disposed of

2 : Carbios.com

Sources : Sia Partners analysis from RECORD 2022 – chemical and physico-chemical recycling of plastic waste

TECHNOLOGY OVERVIEW | Comparison table of the different plastic recycling routes

	Technologies	Input	Output and valorisation	Benefits	Drawbacks	EU Capability Actual / *Announced*
TRL = 9	Mechanical recycling	***All plastic types***	**Pellets** ***New plastic products*** *(Same characteristics)*	➢ **Robustness and reliability** ➢ **Scalability of units** (10 to over 100 kt/year) ➢ **Lower environmental footprint** (no solvent or heating required) ➢ **Price and costs** (compared to chemical recycling)	➢ **Increased upstream sorting of incoming materials** (purity >98%) ➢ **Degradation of the physicochemical structure of polymers** ➢ **No return to food safety nor elimination of dyes/additives** (with some exceptions)	**12,500 kt/year**
TRL = 7-8"	Pyrolysis	***PO / PS***	***High Value Chemicals*** ***Other plastic and/or combustible resins***	➢ **Market size** (PO + PS/EPS account for about half of the plastics placed on the market) ➢ **Waste streams can be processed with a higher tolerance to impurities** (>90% purity materials) ➢ **Versatility** (ex : Polyolefins -> Polystyrene, PP rigid -> HDPE…)	➢ **Sorting and over-sorting must be carried** (less than mechanical recycling) ➢ **High energy consumption** (heating) ➢ **Low material yield** (30 to 40% losses on average) ➢ **Numerous post-production intermediate steps** (hydrotreating/purification, steam cracking...) ➢ **GHG emissions / air pollutants**	**30 – *400 kt/year***
TRL = 7-8	Solvolysis Enzymolysis	***PET***	**Monomers** ***Plastic resins of the same family*** *(designed for all applications)*	➢ **Addresses all waste within the same family** (including coloured, with additives, in different forms – textile fibres, etc.) ➢ **Process selectivity in obtaining monomers** ➢ **Resin with superior physicochemical properties** (vs. mechanical recycling)	➢ **Currently addresses a limited market (PET), already well recycled mechanically** ➢ **Requires stringent upstream waste sorting and over-sorting as** any other resin can contaminate the process ➢ **Involves multiple purification steps**	**200 – *300 kt/year***
TRL = 5-7	Dissolution	***All plastic types***	**Polymers** ***New plastic products*** *(Same characteristics)*	➢ **In principle, applicable to all types of resins** ➢ **Some demonstrated ability to return to contact-sensitive** (eg: PureCycle –USA-, Polystyvert –Canada) ➢ **Resins with superior physicochemical properties** (vs. mechanical recycling)	➢ **Similar sorting and over-sorting constraints as mechanical recycling, but for a more expensive process** (increased purification costs) ➢ **High costs** compared to mechanical recycling ➢ **Limited industrial outlets,** final products do not demand require price premia	***1 – 15 kt/year***

Chemical recycling processes offer the advantage of processing plastics that conventional mechanical recycling cannot, while producing "*contact-sensitive*" quality, characterised by superior physicochemical properties. However, the high costs and comparatively lower environmental performance of these chemical recycling technologies pose substantial challenges to their widespread adoption and development.

TECHNOLOGY OVERVIEW | Preliminary synthesis of current chemical recycling technologies

Strengths

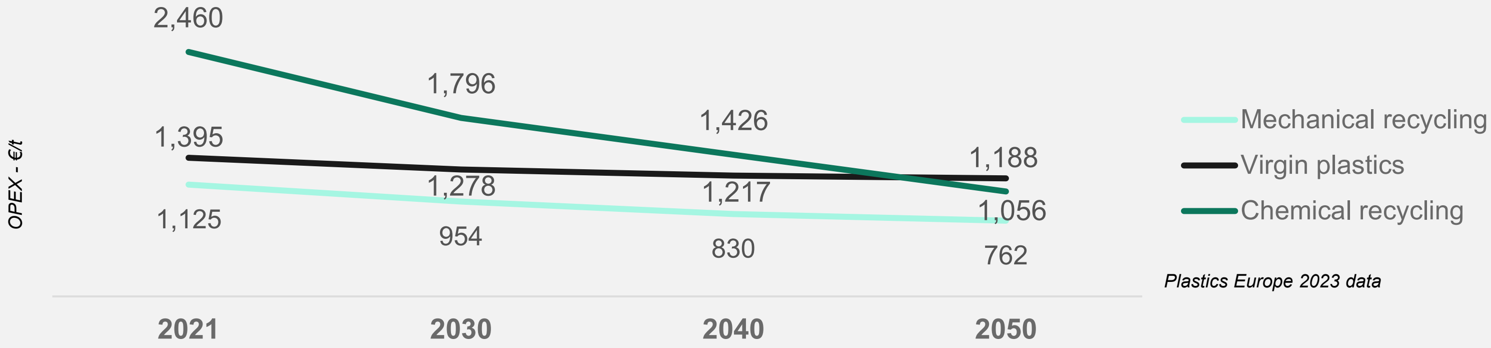
Chemical recycling and its various processes offer numerous technological advantages :

- **Reduced material input requirements** (lower purity thresholds for feedstocks, enhanced diversity of resins, minimal contamination)
- **High-quality end products** (preservation of polymer integrity, return to food-grade use, and removal of contaminants)
- **Selective and versatile monomer production**
- Increased recyclability cycles without compromising the quality of the resin

Challenges

Nevertheless, the chemical recycling sector continues to face several challenges:

- None of the chemical recycling technologies are currently economically competitive compared to mechanical recycling or virgin recycling



Plastics Europe 2023 data

- The operating conditions of **solvolysis** and **pyrolysis** have a significant **environmental impact**
- The use of solvents and enzymes generates **chemical waste** that poses risks to air, soil and water quality
- Not all sectors have achieved **industrial maturity yet**

05. 2030-2040 Trends

The development of chemical recycling in Europe is projected to result in a 3.5-fold increase in installed capacity by 2030 (reaching 2.4 Mt/ year) and a 13-fold increase by 2040 (9.3 Mt/year), to achieve the incorporation rates set out in the provisional agreement of the PPWR.

TRENDS | The rate of chemical recycling development will be subject to regulations on packaging recycling and targets for recycled plastics incorporation

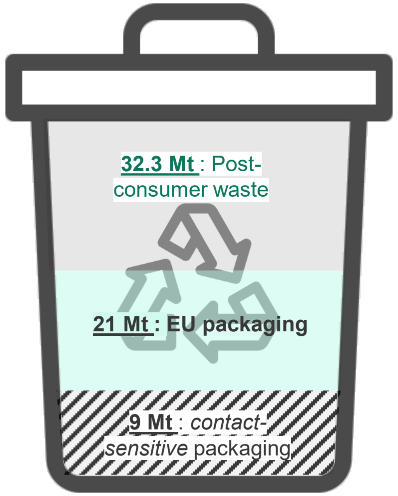
PPWR : Recycled plastics incorporation rates

The table below outlines the **minimum incorporation rates of recycled plastics** for the manufacture of new packaging

	Règlementation PPWR	
	2030	**2040**
Contact-sensitive PET packaging	30%	50%
Contact-sensitive packaging (except PET)	10%	50%
Single-use plastic beverage bottles	30%	65%
Others plastic packaging	35%	65%

"Contact-sensitive" includes packaging intended for food, animal feed, cosmetics, hazardous materials, medical devices and pharmaceuticals for human and animals

/!\ Note: these values were validated at the conclusion of the European trilogue on 4 March 2024; however, their **implementation has been delayed pending the establishment of import clauses for overseas' recycled raw materials (RRMs) . Furthermore, these targets may be revised downwards if RRM supply is deemed insufficient.**



32.3 Mt : Post-consumer waste

21 Mt : **EU packaging**

9 Mt : *contact-sensitive packaging*

Plastics Europe 2022 data

Assumptions and implications for recycling capacities

- The direct translation of these thresholds alongside market data on plastic packaging, specifies **the minimum quantities required for incorporation into the production of new products.**
- **In 2022**, the total output of plastic packaging across all resin categories **reached 21 million tonnes (Mt) in the EU.**
- The production **of new plastic packaging is expected to stabilise between 2022 and 2040** due to emerging **regulatory frameworks** governing eco-design and virgin plastic production likely offsetting each other.
- In contrast, **the generation of "post-consumer" plastic waste** is projected to follow an **upward trend** (CAGR : +3.2%), driven by sectors **such as automotive and construction**.
- **The proportion of "contact-sensitive" packaging, subject to more flexible RRM incorporation criteria** (see adjacent), is delineated as follows and is expected to remain stable throughout the period:
  - *Food-grade* : **~4 Mt**
  - *Others contact-sensitive* : **~5 Mt**

The development of chemical recycling will be supported by at least two strong regulatory measures: the requirement for European countries to **recycle 55% of packaging by 2030** (EU Directive 94/62/CE) and the provisional agreement reached between the European Council and Parliament on the new **Packaging and Packaging Waste (PPWR)** regulation, which mandates a minimum incorporation rate for new plastic packaging placed on the market.

Sources : Plastics Europe, Plastics Recycler, Vinylplus, Dow Chemicals, European commission, Sia Partners Analysis

TRENDS | Chemical recycling will primarily target polyolefin resins & PET, yielding between 1.5 Mt and 6.5 Mt of RRM by 2030 and 2040, respectively

Recycling rate: 🏭 *Installed fleet 2020* · ⚙ *Recyclate prod 2020*

	Volume on the market, EU (Mt)	Packaging share, EU (Mt)	Recycling rate	PPWR Impact: *need for RRM* *2030*	PPWR Impact: *need for RRM* *2040*		Impact of chemical recycling 2030/2040
PET	7.7 Mt/year	~5 Mt/year	38% *🏭 3 Mt* *⚙ 1.9 Mt*	**~1,5** Mt/year (~**0.45** Mt/year excl. bottles)	**~3** Mt/year (~**0.75** Mt/year excl. bottles)	*Low* ● ○ ○	Chemical recycling of PET will primarily target **opaque packaging, trays and other non-mechanically recycled materials (~1.5 Mt/year EU). Only ~18%** of this waste stream was collected separately in 2022. To meet the criteria set by the PPWR, this figure will need to increase significantly. Nevertheless, the available **source of PET could increase,** driven by a growing PET market and the capacity of **chemical recycling to process other materials** (textiles,…).
PP	10.5 Mt/year	~3.5 Mt/year	29% *🏭 3.4 Mt* *⚙ 2 Mt*	*All polyolefins* ~1 Mt/year	*All polyolefins* ~5.8 Mt/year	*Moderate* ● ● ○ *Rigid* *High* ● ● ● *Flexible*	**The amount of PP used in packaging production is estimated at ~3.5 Mt** comprising ~2.5 Mt rigid PP and ~1 Mt flexible PP. This packaging is predominantly aimed at food applications and household products, where **mechanical recycling fails to restore the original physicochemical properties.**
HDPE	6.5 Mt/year	~4.1 Mt/year	29% *🏭 1.8 Mt* *⚙ 1.2 Mt*			*Low* ● ○ ○	HDPE is proportionally less prevalent in food packaging and contact-sensitive applications. **The primary challenges for HDPE lie in collection and reuse,** especially among manufacturers. **Consequently, chemical recycling is not expected to play a significant role for HDPE,** except for plastics not suitable for mechanical recycling
LDPE	8 Mt/year	~5.6 Mt/year	20% *🏭 1.6 Mt* *⚙ 1 Mt*			*High* ● ● ●	LDPE, typically found in film form, is particularly susceptible to external contamination from pollutants, additives, and dyes, making it an ideal candidate for **chemical recycling.** However, compared to other resins, LDPE faces greater constraints from the pricing dynamics of virgin resins, limiting its capacity to absorb a significant premium.

▶ *Graphical representation on next slide*

Not considered for prospective analysis

PVC

6 Mt/year — 11%

1. ***Little post-consumer waste*** *(Long lifetime of PVC products).*
2. ***No industrial chemical recycling project treating PVC waste referenced to date***
3. ***Presence of chlorine*** *acting as a poison in the various current processes (pyrolysis in particular)*

PS-EPS

3 Mt/year — 5%

1. ***Low volume placed on the market*** *(3 Mt/year) despite a high proportion of sensitive contact (trays, yoghurt pots, transport of foodstuffs, etc.)*
2. ***Diffuse deposits that are difficult to collect/sort*** *most often found in a mixture (food packaging)*
3. ***High take-back price / high cost of deposits(~400€/t)***

Other

Thermoplastics
Engineering plastics…

25% — ***14,8 Mt/year***

Diffuse, complex and very low composition of "post-consumer" waste *subject to strict recycling laws*

Among the various plastic resins available on the market, **polyolefins (PP & PE) and PET account for 90% of packaging weight, 70% of post-consumer waste, and the majority of the "contact-sensitive" market** (excluding PS/EPS and technical resins from cosmetics). Plastic waste made up of flexible PE and PP, along with coloured PET - currently under-addressed by mechanical recycling - will be key targets for chemical recycling. Meanwhile, rigid PP, HDPE, and PET bottles will continue to supply the mechanical sector.

Resin market share in referenced projects

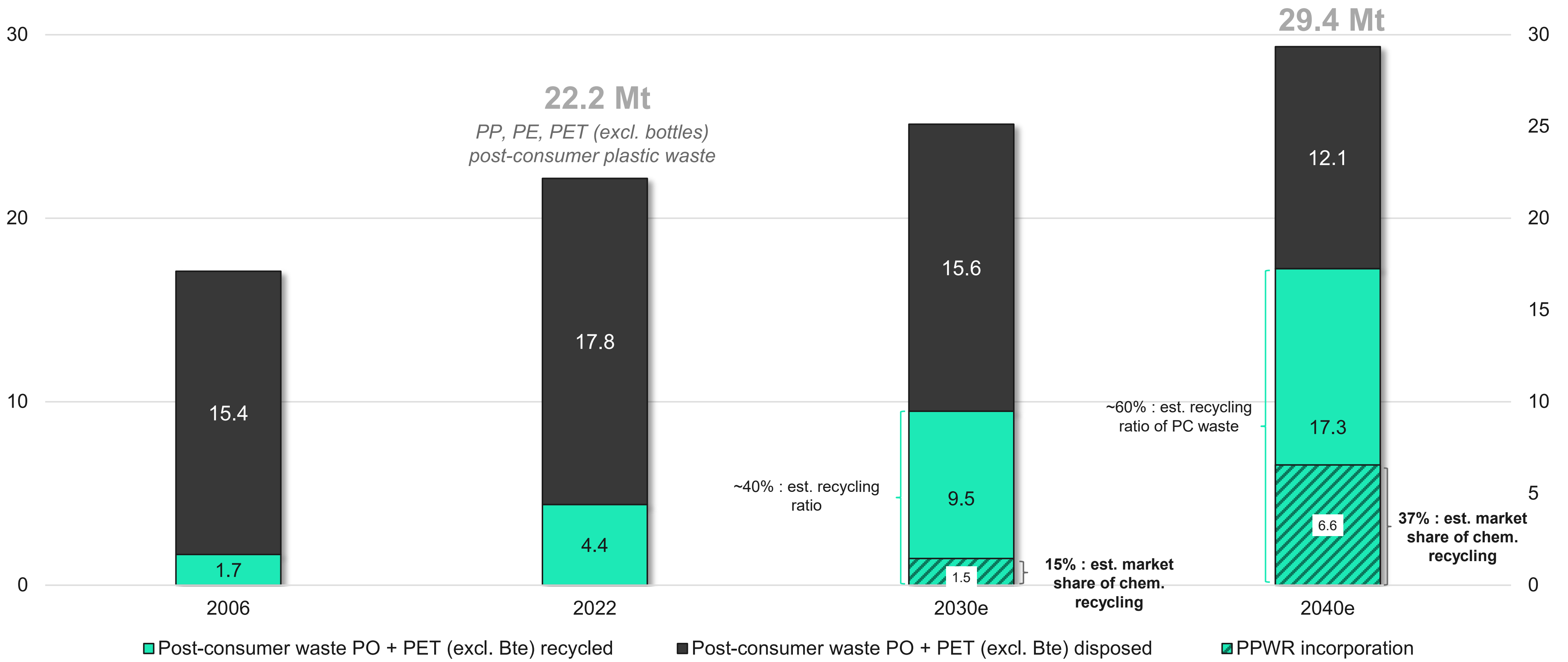
0% *10%* *20%* *30%*

*Sia Partners Estimation

Sources : Plastics Europe, Plastics Recycler, Sia Partners Analysis & Research

TRENDS | A 37% market share is projected for chemical recycling by 2040, driven by the demand for "contact-sensitive" RRM that cannot be addressed by mechanical recycling

The production of "contact-sensitive" RRM from polyolefins and PET (excluding bottles) is set against a backdrop of a steady increase in post-consumer plastic waste. This rise is primarily driven by the renewal of the automative fleet and activities in the construction and demolition sectors. Additionally, the upcoming European target of recycling 55% of all packaging by 2030 further underscores the urgency of this transition.

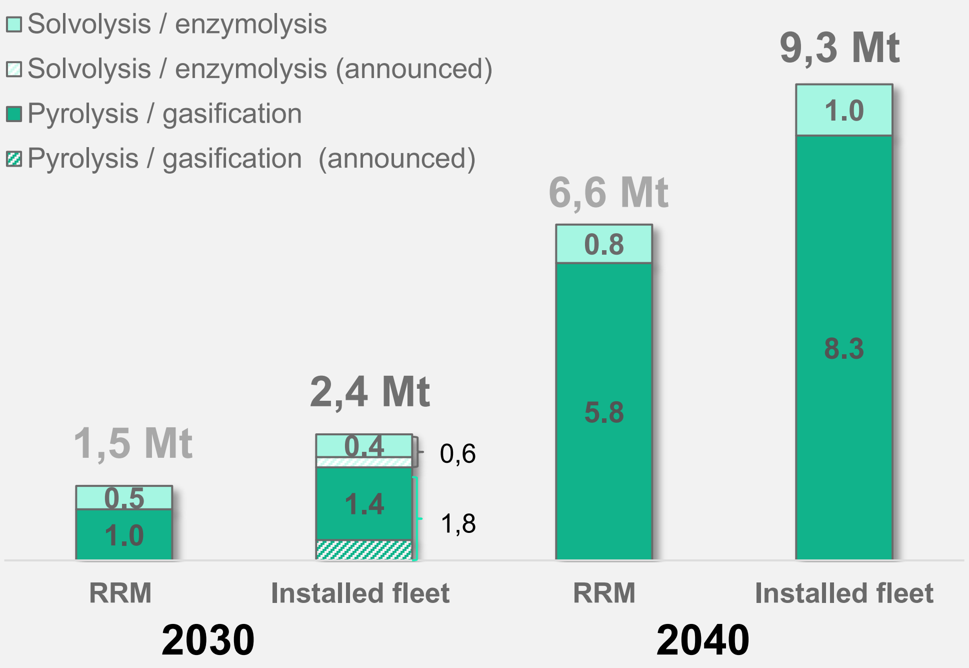


Sources : Plastics Europe "Circularity Report 2024", Plastic recycler (2022), DOW "*PO contact-sensitive market",* Sia Partners Analysis

Focus

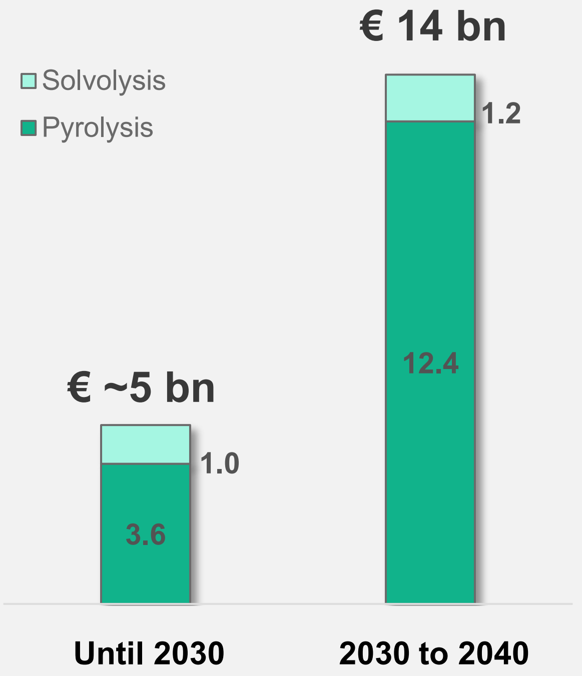
TRENDS | The chemical recycling market is projected to reach between €9 and €15 billion by 2040, with an estimated production of ~6.6 Mt of recycled plastics

RRM need and projected capacities (Mt/year)



Sia Partners analysis based on estimated yields from manufacturers for Solvolysis / Pyrolysis

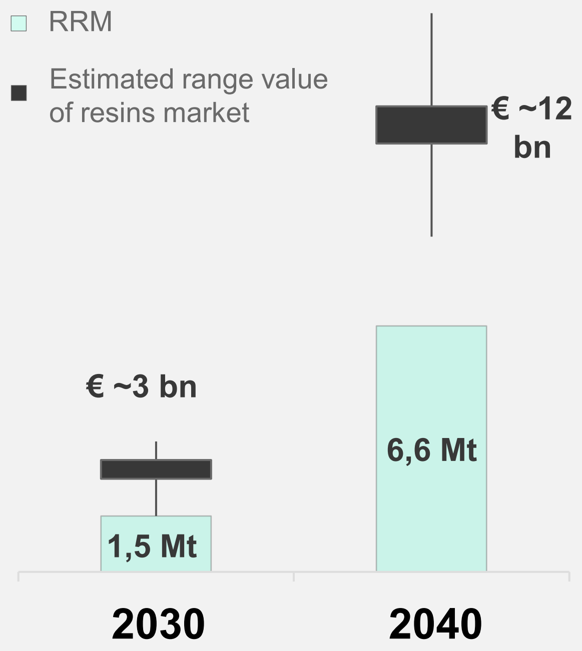
Cumulative investments (€ bn)



Investments are planned for the 'core process' only

Sia Partners analysis based on recorded investment costs for 1st industrial projects

Estimated market value (€ bn)



Sia Partners analysis based on the market value of CR resins

By 2030, to meet the EU targets for packaging recycling and RRM incorporation rates, **the chemical recycling capacity to be installed would be estimated at 2.4 Mt/year**, representing an **investment** ("Core-process" only) **of €5bn**. For 2040, driven by a strong need for PO resin (PP, PE), **the installed fleet would reach 9.3 Mt** at a cumulative cost **of €14bn**. In comparison, in 2021, a year with significant development in recycling capacities, €1.75bn was invested according to Plastics Recyclers Europe.

Sia Partners' convictions on the recovery of plastic waste

- The pressure exerted by the moderately low oil prices over the past 20 years **has hindered the competitiveness of recycling channels.**
- **It has only been through regulatory measures, such as setting more ambitious recycling rates with the emergent role of ERP and increasing taxes** (ex : *TGAP* in France), that financing for critical infrastructure has become feasible and enabled the reduction in landfilling.
- In Europe, upcoming regulations, **particularly the establishment of a minimum incorporation rate for recycled plastics in all packaging** (PPWR), are expected to drive a significant increase in recycling capacity (excluding PET bottles)
- Given the low liquidity of the market and the need for plants to operate at capacities greater than 40 kt/year for profitability, **securing supplies from waste managers will be a crucial factor** for the success of these new facilities.
- Supply tensions are likely to intensify due to the material purity requirements for chemical recycling, which must meet mechanical standards of over 92 to 95%. This will heighten competition between the two recycling sectors. Establishing a robust chemical recycling sector will require :
    1. **Enhanced sorting at the source of industrial deposits to prevent mixing, thereby facilitating higher purity levels;**
    2. **Improvements in the sorting capacities of existing facilities for mixed waste; and,**
    3. **Significant support from eco-organisations.**

- **Two significant uncertainties remain**
    1. **RRMs pricing produced by chemical recycling** estimated to be two to three times higher than that of virgin materials, which may limit market opportunities; and,
    2. **Competition from energy recovery sectors (SRF and incineration)** which shows similar growth to recycling and have been highly popular during the energy crisis.
- **Regarding traceability,** the ISCC+ certification often highlighted by project leaders does not ensure 100% circularity of the produced polymers. Furthermore, the emerging mass-balance regulations at the European level (under the "fuel exempt" approach) do not satisfy all stakeholders involved.

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Glossary

Contact-sensitive: packaging in contact with food, medical supplies and cosmetics

Depolymerization: conversion of a polymer to its monomer(s), or a polymer with a lower molecular weight

Dissolution: Process of purifying the polymer by dissolving it in a solvent, allowing it to be recovered in pure form without changing its chemical nature

Feedstock: raw material or material constituting the main input in an industrial production process

Fuel-exempt: calculation of the Mass balance exempting the use of energy fuels and co-products as fuels during the recycling process

Gasification: A process by which waste polymers are heated to produce syngas, which can be converted back into polymers

Mass Balance :a key concept of ISCC+ certification allocating specific quantities of certified raw materials and recycled products at each stage

Monomer: A molecule with the ability to chemically bind with other monomers to form a polymer

RRM: recycled raw materials

PPWR (Packaging and Packaging Waste Regulation): EU law to reduce packaging waste and promote recycling in the EU

Plastic Pyrolysis: A chemical process of heating plastic in the absence of oxygen to convert it into hydrocarbons or pyrolysis oil

Chemical recycling (CR): Recycling process to convert plastics back into chemicals by changing their chemical structure

Mechanical recycling (MR): Traditional recycling process to shred used plastic to recreate new products

EPR (Extended producer responsibility): system making producers responsible for the management of waste from their products

ICP : industrial & commercial packaging

Solvolysis: Process for dividing plastic waste into monomers using chemical solvents (glycose, methanolysis, etc.). etc.)

SUPD (Single-Use Plastics Directive) : EU Directive imposing restrictions and requirements on single-use plastic products

TGAP (*Taxe générale sur les activités polluantes* for General tax on the polluting activities) : Tax instituted by the 1999 Finance Act, payable by producers or importers of polluting products

Annexes

EUROPEAN BENCHMARK | Details of operational projects

	Players	Location	Annual capacity	Resins / Treated Waste	Year of commissioning
A C	PLASTIC ENERGY	Seville et Almería, Spain	5kt	PE, PP, PS	2015 (Almería) et 2017 (Seville)
E	VALOREGEN Advanced Recycling	Damazan, France	13kt	PET (post-consumer)	2023
F	PLASTIC ENERGY ExxonMobil	Le Havre, France	25kt, aiming to reach 33kt	PE, PP, PS	2023
L	Pyrum innovations	Dillingen, Germany	5kt	Used tires	2022
O	BASF The Chemical Company QUANTAFUEL	Skive, Denmark	20kt	Household packaging	2024
Q	APK LYB LyondellBasell KIRKBI	Merseburg, Germany	40kt	PE, PP, PS	2024
T	ORLEN Unipetrol	Litvínov, Czechia	1kt	PE, PP, PS	2020
U	LUMMUS TECHNOLOGY MOLGROUP	Slovakia	40kt	Household packaging	2023
X		Budapest, Hungary	40kt	Household packaging	2023
Y	BASF The Chemical Company NEWENERGY First Hungarian pyrolysis plant	Budapest, Hungary	10kt tires, producing 4kt of oils	Used tires	2018
AB	Renasci (Renasci)	Ostend, Belgium	20kt	Mixed waste	2020
AC	INEOS STYROLUTION INDAVER	Antwerp, Belgium	7kt	PS (yoghurt cups)	2024
AF	colruyt INDAVER	Antwerp, Belgium	26kt	PS (yoghurt cups, food trays)	2024
AH	TRINSEO	Tessenderlo, Belgium	15kt	PS	2023
AJ		Terneuzen, Netherlands		PC	2023
AK	ioniqa	Geleen, Netherlands	10kt, aiming to reach 100kt	PET	2019
AL	PLASTIC ENERGY sabic	Geleen, Netherlands	20kt	Post-consumer plastic mix	2021
AN	covestro (Covestro)	Leverkusen, Germany		PC	2023
AO	carboliq from waste to oil RECENSO Recycling and Energy Solutions	Ennigerloh, Germany	2.5kt	Mixed plastic waste	2020

● Pyrolysis ● Dissolution ● Solvolysis

EUROPEAN BENCHMARK | Details of future projects (1/2)

	Players	Location	Annual capacity	Resins / Treated Waste	Year of commissioning
🟢 B	PLASTIC ENERGY, TotalEnergies	Seville, Spain	33kt	PE, PP, PS	2025
⚫ D	EASTMAN, PAPREC	Port-Jérôme-sur-Seine, France	100kt, aiming to reach 200kt	PET	2026
🟢 G	INEOS STYROLUTION, TRINSEO	Wingles, France	15kt	PS	2025
⚫ H	CARBIOS, MICHELIN	Clermont-Ferrand, France	50kt	PET (coloured et opaque)	2025
🟢 I	PLASTIC ENERGY, TotalEnergies	Grandpuits, France	15kt	PE, PP, PS	2025
⚫ J	CARBIOS, INDORAMA VENTURES	Longlaville, France	50kt	PET	2025
⚫ K	loop INDUSTRIES, suez, SK geo centric	Saint-Avold, France	Aiming to reach 70kt	PET	2025
🟢 M	BOREALIS, STENA RECYCLING	Stenungsund, Sweden	N/A	Polyolefins	Pending
🟢 N	ARCUS, BASF The Chemical Company, سابك sabic	Frankfurt, Germany	4kt	Mixed plastic waste	N/A
⚫ P	TRINSEO	Rho, Italy	N/A	PMMA	2024
🟢 R	versalis & SRS	Mantua, Italy	6kt	Mixed plastics	2024
🟢 S	OMV	Schwechat, Austria	16kt	PE, PP, PS	2026
🔴 V	versalis, NEXTCHEM	Taranto, Italy	6kt	Mixed household plastics	Feasibility study underway (2023)
🟢 W	versalis	Brindisi & Priolo-Ragusa, Italy	6kt	N/A	2025
🟢 Z	LAMOR, RESICLO, Shell	Porvoo, Finland	10kt, aiming to reach 40kt	N/A	2026
🟢 AA	Ravago, NESTE, Alterra	Vlissingen, Netherlands	55kt	Plastic packaging waste	N/A
🟢 AD	PLASTIC ENERGY, سابك sabic	Geleen, Netherlands	20kt	PE, PP, PS	Upcoming launch (2023)
🟢 AE	Dow, fuenix Let no plastic go to waste	Eindhoven, Netherlands	20kt	At least 90% polyolefins	2025
🟢 AG	ITERO	Geleen, Netherlands	27kt	Mixed plastic waste	2025
🟢 AI	HEATHLAND, TRINSEO	Utrecht, Netherlands	N/A	PMMA, PC, ABS, PS	Heathland acquired by Trinseo (2022)
🟢 AM	LYB LyondellBasell	Wesseling, Germany	50kt	Multi-layered / mixed packaging	2025
🟢 AP	INEOS STYROLUTION, PLASTIC ENERGY	Cologne, Germany	100kt	PE, PP, PS	2026
🟢 AQ	carboliq from waste to oil	Cologne, Germany	10kt	Multilayer complex films	2025

🟢 Pyrolysis 🔴 Gasification ⚫ Solvolysis

EUROPEAN BENCHMARK | Details of future projects (2/2)

Players	Location	Annual capacity	Resins / Treated Waste	Year of commissioning
🔴 AR MURA TECHNOLOGY elite waste to resource	Teesside, England	20kt (60 kt eventually)	Post-consumer plastics	2024
🟢 AT freepoint ECO-SYSTEMS	Genk, Belgium	80kt (160 kt eventually)	N/A	2025
🟢 AS DER GRÜNE PUNKT PEPSICO	N/A, Germany	N/A	N/A	N/A
🟢 AU BLUEALP Accelerating Plastic Recycling RES RECUPERO ETICO SOSTENIBILE	Pettoranello del Molise, Italy	20 kt	Mixed plastics	2026
🔴 AV MURA TECHNOLOGY DOW	Böhlen, Germany	120kt	Post-consumer plastics	2025

🟢 Pyrolysis 🔴 Gasification ⚫ Solvolysis

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