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Economic viability of chemical recycling

Current and future perspectives

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Contents

Abstract

Chemical recycling refers to a family of processes that breaks down waste such as plastics into its chemical building blocks, which may then be used to produce new plastics. The report provides an overview of the current (2025) state of the economic viability of chemical recycling of plastics in the European Union, highlighting the key challenges and opportunities in this field. The report discusses different types of chemical recycling technologies and focusses on the economic viability of solvolysis and pyrolysis, currently the most prominent chemical recycling pathways. It considers production and investment costs, as well as the maturity and limitations of these technologies. The report concludes that although chemical recycling in the EU does not achieve cost parity with virgin plastics, it could have a significant role to play in supplying markets with recycled plastics that are required for compliance with the Packaging and Packaging Waste Regulation and Single Use Plastics Directive recycled content requirements, and potential future regulation of a similar nature.

Foreword

The present report was prepared by the Joint Research Centre (JRC) of the European Commission for the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), as part of an Administrative Agreement between JRC and DG GROW (ref. PLASTICPVCRM).

This report aims to support DG GROW, and the European Commission in general, in current and future policymaking initiatives related to the recycling of plastics, by providing evidence-based analysis of techno-economic issues in this field.

Disclaimer

The current report, and the output of any JRC scientific work, do not represent an official position of the European Commission; in addition, the fulfilment of this task by JRC does not represent a commitment from the European Commission to issue legislative proposals in this policy area nor to use or interpret the conclusions of this report and associated work in the formulation of policymaking proposals.

Please note that for the main part, the analysis presented in this report has been drafted in the course of 2025 (Q1-Q3) based on information collected in Q3 2024-Q1 2025. Punctual data updates have been included but recent (Q2 2026) information at the date of publication may not be fully reflected.

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Organisations (in alphabetical order):

- Axens
- BASF
- BDE
- Carbios
- CEFLEX
- Chemical Recycling Europe
- CURE
- Eastman
- ERFO
- ExxonMobil
- FEAD
- GR3N
- INEOS
- LyondellBasell
- MURA
- NESTE
- OMV
- OVAM
- Plastic Energy
- PRE Plastic Recyclers Europe
- Quantafuel (now Viridor)
- Repsol
- SABIC
- Zero Waste Europe

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Executive summary

Policy context

This report contributes to the EU's ongoing efforts to reduce plastic waste and promote a circular economy. The EU's Single-Use Plastics Directive (SUPD) and the Packaging and Packaging Waste Regulation (PPWR) set targets for the recycling of plastic waste, including a minimum of 30% of recycled plastic in polyethylene terephthalate (PET) beverage bottles and 10% in non-PET contact-sensitive plastic packaging by 2030, thereby fostering market demand for recycled material. Chemical recycling represents one supply channel for such materials. The report provides an analysis of the current state of chemical recycling of plastics in the EU from an economic perspective, including the key challenges and opportunities for the most relevant processes.

Key conclusions

The report concludes that although chemical recycling in the EU does not achieve cost parity with virgin plastics, it can play an instrumental role in supplying markets with recycled plastics that are required for compliance with the PPWR and SUPD recycled content requirements, and potential future regulation of a similar nature. However, there are several challenges that need to be addressed, including the structurally high costs of chemical recycling processes and the uncertainties regarding potential demand for chemically recycled materials, especially of EU origin.

Main findings

The report first provides an overview of the different types of chemical recycling technologies, including solvolysis, pyrolysis, and gasification. It then examines the economic viability of chemical recycling, with a focus on costs (e.g. capital costs, operating costs), for the two currently most prominent technologies (pyrolysis and solvolysis), based on stakeholder input and published literature (other technologies e.g. gasification main gain prominence in future, however information collected on operational facilities, especially regarding costs, was insufficient to derive conclusions regarding economic viability).

The report finds that chemical recycling produces high-quality plastics (comparable to virgin plastics) at generally much higher costs than those of primary plastics.

Thermochemical recycling and solvolysis are the two most common families of chemical recycling processes, which apply to different polymers:

- Thermochemical recycling (pyrolysis and hydrothermal liquefaction) mainly treats plastic waste consisting of polyolefins (polyethylene PE, polypropylene PP) or styrenics (polystyrene PS) and follows a co-production business model. That is, PE, PP and PS are not the only outputs, and the industrial processes are geared towards the maximization of the joint value of all their different outputs.
    - The cost modelling in a baseline scenario[2] shows a cost for pyrolysis[3]-derived naphtha that is 1.5 to 3.5 times higher[4] than that of virgin naphtha, leading to a **cost per tonne of chemically recycled polymer that is 1.4 to 3.7 times**

[2] Estimating realistic values with scaled-up processes in the short to midterm, with existing technology (not assuming any breakthrough but rather incremental improvement of current performances towards industrial-scale operations).

[3] In this report we have modelled thermochemical liquefaction at a high level encompassing pyrolysis and related processes e.g. hydrothermal liquefaction; "pyrolysis" is used as the reference archetype.

[4] N.B. Strict mass-balance allocation rules could further widen this cost gap, to 10 times higher and beyond.

higher than that of virgin polymer, depending on virgin fossil fuel prices. This translates to recycled polymer prices of around 3000 €/tonne in a baseline scenario (1500 to over 4000 €/tonne under varying assumptions).

- Physicochemical constraints and relatively low material recycling yields (typically ~30-50% relative to plastic waste feedstock) contribute to the higher costs of chemical recycling via pyrolysis compared to virgin polymers. Incremental innovation, economies of scale and efficiency savings are not expected to significantly alter these fundamentals in the near foreseeable future.

– Solvolysis processes currently focus on recycling of plastic waste containing PET polymers, known as polyester in textiles, but could also be applied to polyamides and polycarbonates.

- Solvolysis processes report material recycling yields of 90% and above. The data received by the JRC shows, in the EU, total **costs per tonne of chemically recycled PET output in the range of EUR 2,150±500,** to be compared to EU prices for food grade virgin and mechanically recycled PET fluctuating between EUR 1,500 and EUR 2,000 (years 2021-22), and between EUR 1,000 and EUR 1,700 (years 2023-24)[5].

As costs for chemically-recycled polymers are set to remain high, and given upcoming legal obligations on plastic recyclate uptake, this creates an opportunity in the market where alternative solutions may be sought to achieve compliance at lower cost.

The report notes that there are significant knowledge gaps and uncertainties in the field, including on the supply side, the lack of data on the operating costs of full-sized chemical recycling facilities; and on the demand side, the extent to which recycled content obligations for plastics will affect the willingness to pay for recycled material in the future.

Related and future JRC work

The JRC has conducted several studies on the topic of chemical recycling of plastics, including a study on the environmental impacts of plastic recycling (García-Gutiérrez et al. 2023). The JRC will continue to monitor developments in the field and provide support for the development of chemical recycling technologies and associated policy initiatives.

[5] Some studies exhibit lower costs, however these are focused on the US and Canada, and are not fully comparable with the present study.

1. Introduction

The European Union (EU) has made reducing plastic waste and transitioning to a circular economy a central pillar of its environmental policy agenda. The 2019 Single-Use Plastics Directive (SUPD) and the 2025 Packaging and Packaging Waste Regulation (PPWR) establish binding targets to increase the use of recycled materials, including a minimum of 30% recycled plastic in PET beverage bottles and 10% in non-PET food contact material by 2030. These policies aim to foster higher market demand for recycled materials and thus to reduce reliance on virgin plastics and mitigate environmental impacts. Chemical recycling - processes such as solvolysis, pyrolysis, and gasification - are increasingly seen as complementary to mechanical recycling, particularly for complex or contaminated plastic waste streams that cannot be efficiently processed through mechanical methods. However, the economic feasibility of chemical recycling remains an area of uncertainty, motivating the present analysis to inform policy and industry stakeholders.

This report has been developed to address the knowledge gaps surrounding the economic viability of chemical recycling in the EU. It evaluates the current state of chemical recycling technologies, their costs, and their potential to contribute to the EU's circular economy goals. The study was commissioned to support the European Commission's (EC) understanding of the structural challenges—such as high capital and operating costs, limited data on large-scale operations, and uncertain market demand.

The specific objectives of this study are to:

1. assess the economic viability of key chemical recycling technologies (pyrolysis and solvolysis) by analysing capital and operating costs, as well as potential revenue streams;
2. discuss challenges hindering the deployment of chemical recycling, including costs, technological uncertainties, market risks and regulatory constraints.

These objectives are directly tied to enabling the EU to achieve its plastic recycling targets while fostering a competitive and sustainable industry sector. Additionally, the report contributes to the broader JRC research on circular economy technologies, supporting the EC's efforts to transition toward a resource-efficient and climate-neutral economy.

Quick guide

The report is structured as follows: Chapter 1 introduces the technoeconomic and policy context and the importance of chemical recycling in the European Union's transition to a more circular economy. Chapter 2 provides an overview of the current state of chemical recycling technologies, including solvolysis, pyrolysis, and gasification, with a focus on technical constraints and material yields of each technology. In Chapter 3, we discuss methodological aspects and the meaning of economic viability in the present context. Chapter 4 presents the data and wider evidence base. Chapter 5 carries out the analysis of the economic viability of chemical recycling processes, focussing on pyrolysis and solvolysis. Chapter 6 discusses market and regulatory issues that can influence the economic viability of chemical recycling. Finally, Chapter 7 draws conclusions and outlines avenues for further research.

2. Background and scope

2.1. Focus on chemical recycling

In plastics recycling, mechanical recycling has been the dominant technology in the past decades. According to Plastics Europe (2024), of the 54 million tonnes of plastics produced in Europe (EU27+3), about 7.1 Mt came from mechanical recycling of post-consumer plastics and 3.1 Mt from mechanical recycling of pre-consumer plastics. This contrasts with less than 0.1 Mt that came from chemically recycled post-consumer plastics.

Nonetheless, there has been growing interest in chemical recycling for a number of reasons. These include increased ambition to recycle plastic waste into high-value applications (including hard-to-recycle plastic waste), export restrictions on plastic waste, a further push to reduce incineration and landfilling of plastic waste, new quality requirements on recycled plastics and mandatory recycled content requirements for a variety of plastic products. Moreover, current recycling rates vary considerably between polymers and even within the same polymer group, as shown in **Table 1**, suggesting a potential for increasing the recycling rate for many polymer streams and sub-streams.

Table 1. Overview of recycling rates by polymer and polymer sub-stream.

Polymer/sub-stream	Recycling rate (%)
HDPE	32
PP	30
PVC	24
PET overall	20
PET packaging	41
PET beverage bottle	53
PET non-beverage bottle	32
PET trays	19
PET polyester fibre	<1
LDPE films and flexibles	15
PS, XPS, EPS	4

Source: Systemiq (2023) and Plastics Recyclers Europe personal communication; 2023 data for EU27+UK, Norway & Switzerland; figures include post-consumer and pre-consumer waste; recycling rate is calculated as the ratio of amount sent to recycling divided by generated waste amount.

In mechanical recycling, the polymer embedded in the plastic remains largely unaffected by the recycling process. A more recent development in plastics recycling is solvent-based recycling, also called dissolution recycling or solvent-based purification[6], where the polymer backbone is separated from the other plastic constituents like additives or fillers (Ragaert et al. 2023) but not brought back

[6] Note that dissolution recycling is also referred to as 'physical recycling' by many industry actors, whereas others consider mechanical recycling (including advanced mechanical recycling) and dissolution recycling separate branches of physical recycling.

into monomeric or smaller molecular forms. These processes are thus different from chemical recycling processes (such as solvolysis) where the polymers, and possibly other plastic constituents, are broken down into smaller molecular fragments. These fragments can then be further treated and used to resynthesize new molecules, including new polymers. In the context of EU legislation, it is important to note that the term *recycling* only applies to the share of the input material that is not converted into energy or fuels.

Typical advantages of chemical recycling, compared to mechanical recycling, include its versatility with regard to the inputs it can process, as certain mixes of plastics or plastics with non-plastic materials (e.g. polyester with cotton in textiles) can be treated together. Chemical recycling can also treat thermoset polymers (in particular polyurethane) which constitute about 16% of the European plastic converters demand (Plastics Europe 2022) and cannot be recycled mechanically into new polymers (Plastics Europe 2022a). In addition, the quality of the chemical recycling output is a major advantage, as most processes can produce virgin-like and food-grade quality.

Table 2 shows the possible recycling pathways and recyclate uses of chemical recycling and mechanical recycling, distinguishing between food-contact and non-food-contact input and output quality. The table reveals that, in principle, mechanical recycling and chemical recycling can treat many of the same polymers, but with chemical recycling consistently achieving virgin and food grade quality, in contrast to most mechanical recycling routes.

According to ICIS Recycling Supply Tracker - Mechanical[7], 28 % of global PET (mechanical) recycling capacity is for food grade, but this number is much smaller for polyolefins (PE and PP), around 3 %[8]. The imbalance between supply and demand for food-contact recycled polymers has been driving up their price, with recycled food-contact PET prices consistently topping their virgin equivalents since 2016 (ICIS 2026).

Moreover, chemical recycling produces fewer greenhouse gas emissions than incineration (García-Gutiérrez et al. 2023), which makes it a relevant option for plastics that cannot be recycled mechanically and would otherwise be disposed of, often at considerable fees for incineration or landfilling.

Typical disadvantages of chemical recycling are its higher technical complexity and resulting higher cost, compared to mechanical recycling. These technical and economic differences between mechanical recycling and chemical recycling are the reason why the technologies are typically presented as complementary to each other (Plastics Europe 2022b). Chemical recycling may have the best chances of success when its relatively higher cost can be compensated by a lower feedstock cost, due to unsuitability of the feedstock for mechanical recycling, in addition to sale-price premiums, thanks to virgin-equivalent and food-contact quality of the produced recyclate.

[7] https://www.icis.com/explore/services/recycling-supply-trackers/

[8] essentially through FDA certification for food-contact material.

Table 2. Recyclability and food-contact potential of plastic waste streams. (FC= food contact, PET= polyethylene terephthalate, PP= polypropylene, PE= polyethylene, PS= polystyrene, PMMA= poly(methyl methacrylate), PA= polyamide, PC= polycarbonate, PU= polyurethane, PVC= polyvinyl chloride)

		Mechanical Recycling		Chemical Recycling	
Resin identification code [9]	**Waste plastic polymer type**	**Can be recycled ?**	**Recyclate widely suitable for food-contact ?**	**Can be recycled ?**	**Recyclate widely suitable for food-contact ?**
1	PET-FC	☑	☑	☑	☑
1	PET-non FC	☑	☒	☑	☑
5	PP	☑	☒	☑	☑
2, 4	PE	☑	☒	☑	☑
6	PS	☑	☒	☑	☑
7	PMMA	☑	☒	☑	☑
7	PA	☑	☒	☑	☑
7	PC	☑	☒	☑	☑
7	PU	☒	☐	☑	☑
3	PVC	☑	☒	☑*	☑

* PVC-containing waste streams pose additional technical challenges for pyrolysis-based recycling due to chlorine release and corrosion risks. While technically feasible, PVC is therefore often restricted or limited in current commercial pyrolysis plants for economic and operational reasons.

Source: own elaboration

2.2. Scope of the study

While chemical recycling is predominantly discussed in the context of plastics, there are other materials and industries where chemical recycling processes are being applied or explored. These include non-plastic textiles (e.g. cotton), metals and even organic waste. Nonetheless, the present study focuses entirely on chemical recycling of synthetic polymers encountered in plastics, including those used in textiles. This is also in line with the input that JRC received from stakeholders, which predominantly related to plastics.

2.3. Chemical recycling technologies

2.3.1. General overview

It is important to understand that chemical recycling does not refer to a single technology or process, nor is the scope unambiguously defined; there is, however, broad consensus on the relevant technologies. The main chemical recycling technologies are categorised according to the extent to which they break down the polymer molecules (Liu, Q. et al. 2024, Martínez-Narro et al. 2024, Liu, Y. et al. 2024, Jiang et al. 2022, Solis and Silveira 2020, Biessey et al. 2023, Klotz et al. 2024). They are graphically depicted in **Figure 1**.

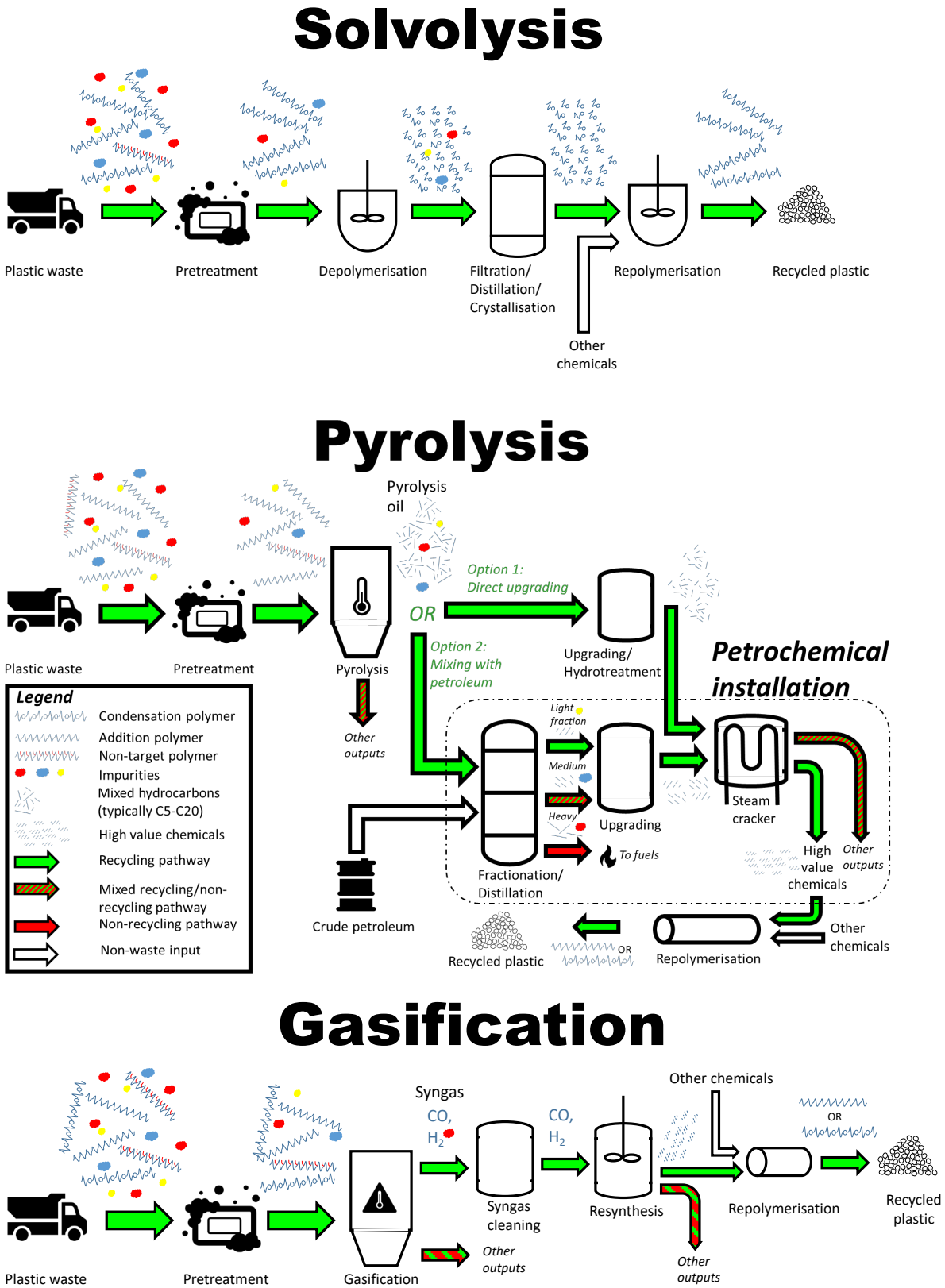
- *Solvent depolymerisation* or *solvolysis*: this category refers to chemical processes where polymers are broken down into oligomer or monomer building blocks, by means of a solvent under relatively mild reaction temperatures of typically 80 to 300°C. The obtained oligomers and monomers are then purified and can be resynthesised into new polymers, typically

[9] 97/129/EC: Commission Decision of 28 January 1997 establishing the identification system for packaging materials pursuant to European Parliament and Council Directive 94/62/EC on packaging and packaging waste

after addition of virgin monomers and other chemicals. The depolymerisation may also yield other chemicals, which can be used either for repolymerisation or in other chemical synthesis processes. The most common processes of the solvolysis category are hydrolysis, methanolysis, glycolysis and aminolysis, which differ by the chemical agent used to split the polymers. Combinations of these processes have also been reported (Umdagas et al. 2025). The process should not be confused with dissolution recycling, or solvent-based purification, in which polymers are recovered from a plastic matrix without breaking down the polymer structure, and which is thus not considered chemical recycling.

- *Pyrolysis*: this category refers to thermochemical decomposition processes that break down polymers under high temperatures (typically 300 to 700°C) in the absence of oxygen. For many polymers, the result is a heterogeneous mixture of predominantly liquid hydrocarbons, some gases and solid residue (char). Pyrolysis processes are therefore also referred to as thermochemical liquefaction processes. The liquid mixture is called pyrolysis oil, which can be further processed into chemicals and fuels. Generally, the pyrolysis oil will not be of sufficient quality for standalone downstream processing. There are two main options to address this: i) diluting the pyrolysis oil with crude oil before fractionation or ii) upgrading the pyrolysis oil by hydrotreatment so that the quality is sufficient for direct use in a steam cracker. The high value chemicals coming out of the steam cracker can be used to synthesise new polymers, including polymers that differ from those used to produce the pyrolysis oil, and other chemicals. For some types of polymers, pyrolysis can also produce a very high level of monomers, such as for PS or PMMA (Godiya et al. 2019). In that case, the output from the pyrolysis process is separated into fractions, with the target monomer sent for repolymerisation, typically after mixing with virgin monomers.
- *Gasification*: like pyrolysis, gasification is a thermochemical process. It converts polymers into a gas mixture called syngas (synthesis gas) through the application of very high temperatures (typically 700 to 1200°C) in the presence of a controlled amount of oxygen or steam. The syngas, after cleaning, can be used for direct energy production or for the synthesis of new polymers and other chemicals, including fuels.

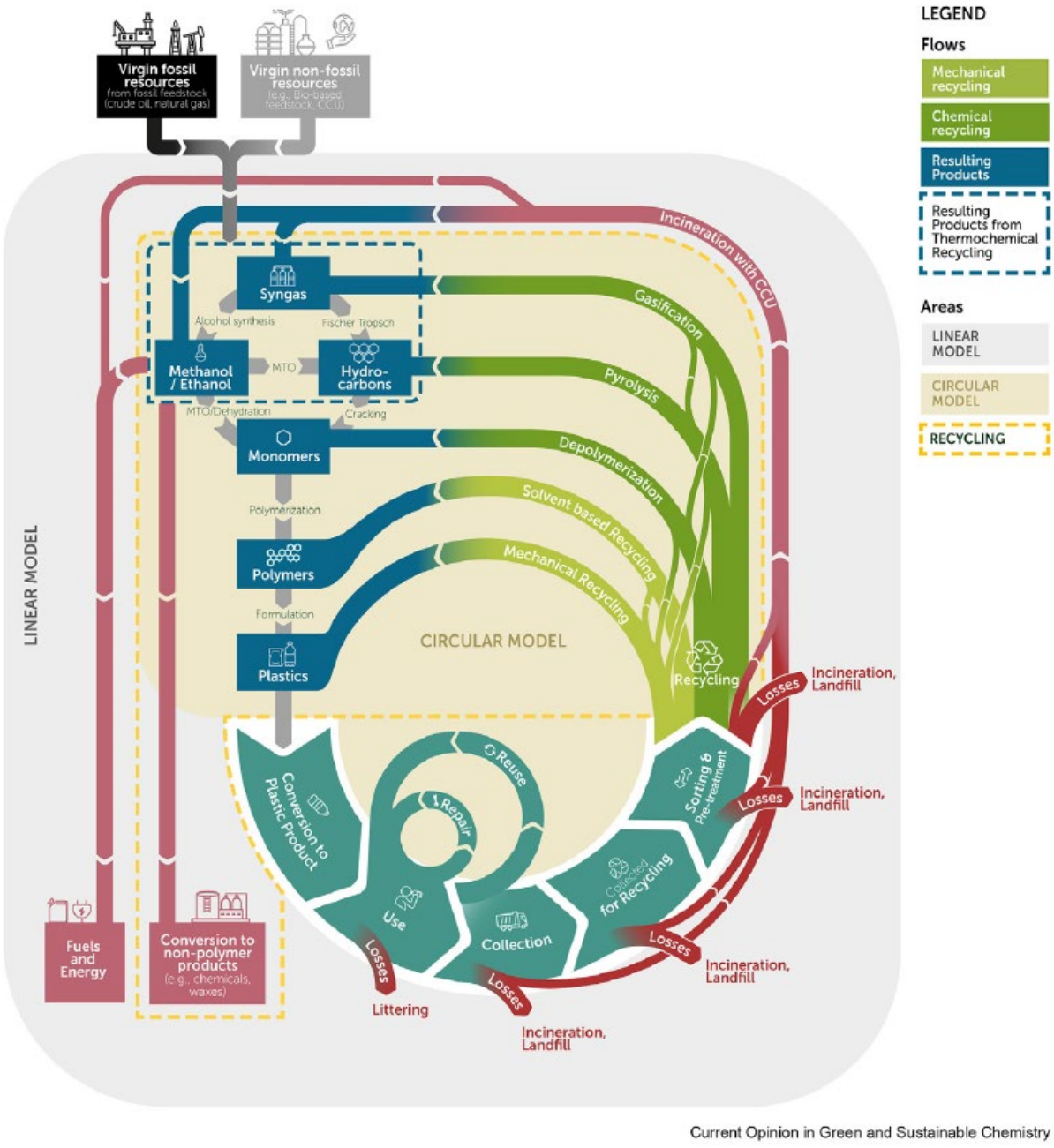
Figure 1. Schematic representation of typical solvolysis, pyrolysis and gasification recycling pathways for plastic waste (the legend applies to all technologies; for simplicity reasons not all detailed steps, inputs, outputs, emissions or losses are shown, nor any specific variations on the processes).



Source: own elaboration

A schematic overview of how the different chemical recycling processes compare to mechanical recycling and energy recovery is given in **Figure 2**.

Figure 2. Schematic overview of different plastic recycling and recovery processes.



Source: Ragaert et al. (2023a).

Although the present study does not aim to provide a full technical discussion of chemical recycling technologies, it is important to take into account the following observations for later discussion:

- *Like any recycling process, chemical recycling does not convert all of the input into recycled material output.* The flows in **Figure 2** highlight an important point with regard to the various plastic waste management processes. Depending on the ultimate fate of the outputs

and the applied processes, some of the chemical recycling technologies in fact combine energy recovery (including fuels production) with recycling operations. This is the case when part of the material is directly converted to energy during the treatment, or is ultimately used for the production of fuels. The distinction between recycling and recovery is made by the Waste Framework Directive 2008/98/EC[10], where 'recycling' is defined as any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. The definition of recycling includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. This is particularly relevant for pyrolysis and gasification processes. On a more fundamental note, the question of whether chemical recycling processes can, in fact, be considered as primarily recycling and not energy recovery, hinges on the proportion of input material actually ending up as recycled material, rather than being converted into energy or fuels.

- *Not all technologies work for all polymers*. Cleavage of polymers into identical monomers is possible where certain chemical bonds in the polymer are more reactive than others. This is the case for so-called condensation polymers,[11] where solvent depolymerisation can break specific types of bonds. These include ester bonds (e.g. PET, PC), amide bonds (e.g. PA) and carbamate bonds (e.g. PU) (Yeung et al. 2021, Cirujano et al. 2024, Vollmer et al. 2020). Decomposition into monomers also works for certain carbon-carbon bonds (e.g. PS or PMMA), where a tailored pyrolysis process affects the more reactive bonds while leaving the other bonds intact (Ragaert et al. 2017). Yet, it typically does not work for polymers where the atomic bonds are of comparable reactivity across the polymer, as in most polyolefins (e.g. PE, PP), an important category of so-called addition polymers[12]. On the other hand, processes like pyrolysis require to minimise the presence of certain polymers containing atoms other than carbon and hydrogen in their input streams (e.g. oxygen in PET, chlorine in PVC), because of these polymers' negative impacts in the process or downstream uses. A schematic overview of which technologies are suitable for which polymers is given in **Figure 3**.

- *Many technology variations exist*. Apart from the broad categorisation provided above, other subvariants of chemical recycling technologies exist, and continue to emerge, reflecting that this still is an evolving field. An example is enzymatic depolymerisation (Arnal et al. 2023), where enzymes are used to help depolymerise PET polyester. Another example is hydrothermal conversion, also called hydrothermal upgrading or hydrothermal liquefaction, which may either be seen simplistically as a hybrid variant of pyrolysis using supercritical water under high temperature and pressure (350-500 °C, 230 bar), or more accurately as a dis-

[10] Article 3, points (15) and (17) of the Waste Framework Directive provide the definitions of recovery ('recovery' means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfil a particular function, or waste being prepared to fulfil that function, in the plant or in the wider economy. Annex II sets out a non-exhaustive list of recovery operations) and recycling ('recycling' means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations)

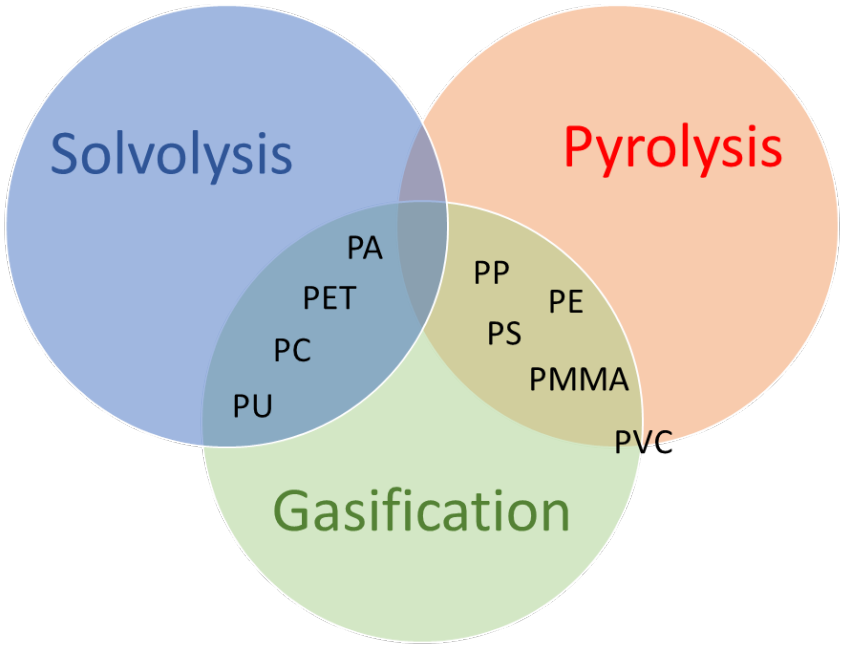
[11] Condensation polymers are formed through a polymerisation process where monomers link together, releasing a small molecule like water.

[12] Addition polymers are formed through a polymerisation process where monomers, typically containing double bonds, simply add to each other without the loss of any atoms.

tinct process with characteristics of both pyrolysis (high temperature) and solvolysis (dissolution) (Ozoemena and Coles 2023)[13]. Moreover, many of the chemical recycling technologies described above use specific catalysts to improve the overall process in terms of reaction time, energy consumption or uniformity of the outputs. Therefore, while for the practical purpose of this study, technologies are grouped into a few broad categories, one might say that almost all specific industrial facilities of chemical recycling are 'one-of-a-kind', with their own benefits and drawbacks in terms of cost, yield, output characteristics, integrability in established processes, etc.

- *Several denominations are in use throughout the literature:* The terminology applicable to chemical recycling varies and may be confusing, on top of the technical nuances between processes (Harasymchuk et al. 2024). Ragaert et al. (2023a) propose a review of this flourishing of new terms. Various non-standard terms are in use to describe chemical recycling in general and some of its subtypes. For instance, Closed Loop Partners (2021, 2021a) uses "molecular recycling" to refer to chemical recycling, "purification" (dissolution without altering the polymer), "depolymerisation" or "conversion" for which boundaries are less established ('partial conversion' being used to refer to pyrolysis and 'full conversion' to gasification), corresponding to "thermochemical recycling", i.e. covering pyrolysis and gasification.

Figure 3. Schematic overview of suitability of polymer types for different chemical recycling technologies, based on existing industrial applications. Note that most chemical recycling technologies tolerate limited amounts of non-target polymers. Regarding PVC, see comment in Table 2.



Source: own elaboration

[13] See Q&A on chemical recycling: https://chemicalrecyclingeurope.eu/questions-about-chemical-recycling/

2.3.2. Supply side: current and planned chemical recycling capacities in the EU

Table 3 and **Table 4** provide an overview of current and planned capacities, respectively, for chemical recycling in Europe. The figures tend to differ across sources, as some sources report plants that are planned but not yet operational, or sometimes already out of business. Nonetheless, the data reveal two main findings: i) current chemical recycling capacity is very small compared to the 13.2 million tonne mechanical recycling capacity in Europe[14] and ii) chemical recycling capacity is expected to grow substantially in the coming years.

At the global level, Europe plays a predominant role, especially when looking at the number of plants in operation. More than half of all operational chemical recycling installations are located in Europe, according to Nova Institute.[15] Nonetheless, when looking at capacity numbers, European installations only represent about a quarter of the current global capacity. Roland Berger (2024) expects global recycling capacity to grow to 20 Mt/y input by 2030 and 70 Mt/y input by 2050.

In terms of the technologies, it appears that the current distribution between solvolysis and pyrolysis will remain stable at around 20%/80%. This distribution seems to follow the relative market shares of the polymers that the respective technologies can address: according to Plastics Europe (2022), European plastic converters'[16] combined demand for PUR, PET, PA and PC (target feedstock of solvolysis) represented 9.8 Mt/y in 2021, versus a combined demand for polyolefins, PS and PMMA (target feedstock of pyrolysis) of 28.1 Mt/y, or a relative ratio of 26%/74%.[17]

ICIS reports that installed chemical recycling capacity operating in Europe in 2025 is dominated by pyrolysis (~150kt installed capacity) while other technologies add up to ~40kt (hydrolysis, glycolysis and others), in line with the distribution mentioned above (80/20). The key target feedstocks are mixed plastic waste bales with a high percentage of polyolefin content, although some projects focus on materials such as PS or PMMA[18]. Looking ahead, pyrolysis capacity under construction is roughly 90% of capacity (440kt) versus 10% (50kt) for hydrolysis[19].

Gasification does not seem to have an important share amongst chemical recycling technologies, and its relative presence could possibly even decrease further in the future, based on projection figures from **Table 4** and recent market signals[20,21].

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[14] Data for 2023 for EU27+3 (UK, Switzerland, Norway) from Plastics Recyclers Europe (2023).

[15] Summary of study "Mapping of advanced plastic waste recycling technologies and their global capacities" consulted at: https://renewable-carbon.eu/news/advanced-recycling-on-the-rise-rapid-growth-in-capacities-at-global-and-european-level/

[16] Plastic converters are companies that transform raw plastic materials (e.g. polymers) into finished or semi-finished products like plastic bottles, bags, or containers. They may use a combination of virgin and recycled polymers in the process. European plastic converter demand is as a proxy for the amount of plastics put on the European market (when excluding imports and exports) and even for the amount of plastic waste generated (assuming that most plastics, in particular packaging, are collected as waste within a short time after being put on the market).

[17] NB the direct comparison of the ratios between installed capacity and final product demand should be approached cautiously and modulated by the fact that average yields for the two families of processes differ: solvolysis normally achieves plastic-to-plastic conversion ratios that are twice as high as pyrolysis. Therefore, solvolysis installed capacities can meet more demand than equivalent figures for pyrolysis.

[18] ICIS Chemical Recycling Supply Tracker, ICIS personal communication 2026

[19] ibid.

[20] See, e.g., the news item by Joshua Dill on 'Recycling Today' website: https://www.recyclingtoday.com/news/gasification-chemical-plastic-recycling-pitfalls-investment-slowdown-icis/

[21] One exception is the company Eastman that pursues an integrated approach of employing both gasification ("Carbon Renewal Technology") and solvolysis ("Polyester Renewal Technology"). See: https://www.eastman.com/en/sustainability/environmental/circularity/circular-solutions/carbon-renewal-technology

Table 3. Overview of reported existing chemical recycling capacities in Europe

Reference year	Source	Total input capacity (ktonne/y)	Number of active plants	Geographical area	Breakdown by technology	References
2022	Plastics Europe	±100	N/A	EU27+3	N/A	Plastics Europe (2024a)
2023	Plastics Recyclers Europe	150	N/A	EU27+3	Pyrolysis dominant	Plastics Recyclers Europe (2023)
2023	Nova Institute	±100	N/A	EU27+3	20% solvolysis 80% pyrolysis <0.1% gasification*	Nova[22]
2024 (April)	ICIS	160	N/A	Europe	22% solvolysis 71% pyrolysis 7% gasification	British Plastics Federation[23]
2024 (June)	SIA Partners	260	16	EU	10% solvolysis 90% pyrolysis	SIA Partners (2024)
2026 (March)	ICIS	190	N/A	Europe	20% solvolysis 80% pyrolysis	Personal communication March 2026

*Sources: see individual references; sorted by reference year; data until 1Q 2026; * =breakdown based on installed and planned capacities*

Table 4. Overview of projected chemical recycling capacities in Europe

Target year	Source	Total capacity (ktonne/y)	Number of planned plants	Geogr. area	Planned investment billion €	Breakdown by technology	Reference
2026	ICIS	680 (input)	N/A	Europe	N/A	13% solvolysis 87% pyrolysis	Personal communication March 2026[24]
2026	SIA Partners	903 (input)	24	EU27 +UK	N/A	30% solvolysis 69% pyrolysis 1% gasification	SIA Partners (2024)

[22] Last chart shown at: https://renewable-carbon.eu/news/advanced-recycling-on-the-rise-rapid-growth-in-capacities-at-global-and-european-level/

[23] https://www.bpf.co.uk/hub/chemical-recycling-non-mechanical-capacity.aspx

[24] The data, from March 2026, refer to installed capacity and capacity under construction, including plants under commissioning. The nature of these data differs from the 2029 projections made in 2024 by ICIS, which stem from a compilation of companies' announcements, including both final investment decisions (FID) and pre-FID projects at all stages (see also footnote on the 2024 ICIS data).

2027	Nova Institute	480 (output)	N/A	EU27+3	N/A	N/A	Nova[25]
2029	ICIS[26]	3300 (input)	N/A	Europe	N/A	15% solvolyis 85% pyrolysis	ICIS (2024)
2030	Plastics Europe	2800 (output)	44	13 EU countries	8	80% pyrolysis and gasification	Plastics Europe (2024a) Plastics Europe (2022c)
2030	SIA Partners	2400 (output)	N/A	EU27 +UK	5	25% solvolysis 75% pyrolysis	SIA Partners (2024)
2040	SIA Partners	9300 (output)	N/A	EU27 +UK	14	11% solvolysis 89% pyrolysis	SIA Partners (2024)

Sources: see individual references; sorted by reference year; data projections from 1Q 2026 onwards

2.3.3. Demand side: projected demand implied by legal requirements in the EU

2.3.3.1. Regulatory context

Chemical recycling technologies are largely understood by the market not to be cost-competitive vis-à-vis virgin plastic production in current market conditions – a situation we explore in detail in the rest of the report. However, most of the stakeholder inputs received pointed to an expected baseline demand for chemically-recycled plastics, created by legal obligations such as recycled content mandates stemming from EU legislation.

In particular, markets anticipate the need to supply recycled material to meet the obligations deriving from:

- the Single-Use Plastics Directive (EU) 2019/904 (SUPD[27]): the Directive includes an obligation to incorporate 25% of recycled plastic in PET beverage bottles from 2025, and 30% in all plastic beverage bottles (PET and non-PET) from 2030;
- the Packaging and Packaging Waste Regulation (EU) 2025/40 (PPWR[28]): Article 7 of the Regulation includes obligations on minimum recycled content in plastic packaging, notably a plastic recycled content requirement of 10 % for contact-sensitive packaging made from plastic materials other than PET (except single-use plastic beverage bottles) by 2030, which further increases to 25% by 2040;

[25] https://renewable-carbon.eu/news/advanced-recycling-on-the-rise-rapid-growth-in-capacities-at-global-and-european-level/

[26] N.B. From the ICIS Recycling Supply Tracker – Chemical : based on all companies' announcements, including both final investment decision (FID) and pre-FID projects at all stages, based on installed (input waste processing) capacity. https://www.icis.com/explore/services/recycling-supply-trackers/

[27] For more information, see https://environment.ec.europa.eu/topics/plastics/single-use-plastics_en

[28] For more information, see https://environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en

- the Regulation[29] on recycled plastic food contact materials (EU) 2022/1616, applicable also to chemically recycled materials[30] (pyrolysis and gasification routes are likely to meet this requirement, but most solvent based recycling technologies are not, so must be run fully in accordance with this Regulation).
- the 2026 Regulation on circularity requirements for vehicle design and on management of end-of-life vehicles[31] includes requirements for a minimum recycled content of the plastics fraction of 15% after 6 years, increasing to 25% after 10 years, including at least 20% from end-of-life vehicles.

Note that some of these legal obligations are still undetermined[32], which creates uncertainty in industry and dissenting views about future demand and production capabilities.

2.3.3.2. Estimation of demand

According to Plastics Europe (2024a), the European (EU27+3) market for plastics as a whole was 58.8Mt (production) and 54.1Mt (consumption) in 2022 (of which about 20% of circular origin). Packaging represented 35-40% of that total market or 21.1Mt in 2022. 18.5Mt of waste plastic packaging were collected in 2022. Meanwhile, total polyolefin packaging is estimated to represent about 15Mt. Of all plastic packaging, almost half (9Mt) is estimated to belong to the categories of food-grade (4Mt) or other contact-sensitive (5Mt) packaging (SIA Partners 2024).

In a rough approximation, and all things being equal (i.e. if the market does not shift substantially to avoid noncompliance), the PPWR alone creates a demand for recycled food-grade or contact-sensitive packaging of 10% of this ~9Mt, which can only partially be met by conventionally recycled PET. Therefore, it is likely that **500kt-1Mt/y of chemically recycled plastics** would be needed. If focussing on non-PET plastics, i.e. polyolefins and potentially styrenics (treated through thermochemical liquefaction e.g. pyrolysis), with a typical process efficiency of 30-50% yield, this corresponds to an installed **input capacity of around 1-3Mt/y** of waste plastics to be chemically recycled.

This seems to concur with the calculations available from industry sources:

- According to **Plastics Europe** (2024a, p.69) "Plastics Europe's member companies announced investments of more than **8 billion euros**, in 44 planned chemical recycling projects in 13 EU countries, to produce **2.8 Mt of recycled plastics** per annum by 2030."
- Plastics Europe (2023, p.53) also mentions that the large player LyondellBasell *alone* announced 2Mt/y of capacity by 2030 (since revised to 800kt/y[33]), covering both recycled and renewable-based polymers.

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[29] Commission Regulation (EU) 2022/1616 of 15 September 2022 on recycled plastic materials and articles intended to come into contact with foods

[30] N.B. Not applicable to monomer production only if those monomers can meet the purity requirements set out in Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food.

[31] Regulation (EU) 2026/... of the European Parliament and of the Council of ... on circularity requirements for vehicle design and on management of end-of-life vehicles amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2019/1020 and (EU) 2023/1542 and repealing Directives 2000/53/EC and 2005/64/EC (Adopted by the Council on 29 June 2026; publication in Official Journal pending on date of publication of this study)

[32] For example, while SUPD rules have now been set (see footnote 98), for the PPWR, secondary legislation still needs to specify important implementation modalities (as of Summer 2026).

[33] https://www.lyondellbasell.com/en/who-we-are/updates-events/corporate--financial-news/lyb-announces-updated-2030-sustainability-goals

- CEFLEX (2025) offers similar figures: they estimate a need for between 0.7 to 1.1 Mt/y of chemical recycling capacity in the EU 27 + 3 to meet the 2030 10% recycled content target for contact sensitive flexible PE and PP packaging, assuming 3.3 Mt/y flexible plastic packaging placed on the market. For rigid PE and PP contact sensitive packaging, the need would be for an additional 0.9 to 1.4 Mt/y of chemical recycling capacity.

Market research and consulting firms (e-cube Strategy Consultants 2025, SIA Partners 2024) confirm these orders of magnitude, especially in the short term (2030): e.g. eCube identifies a shortfall in the market of around 1Mt/y installed pyrolysis capacity by 2030.

It is important to consider that the above calculations are based on current trends with assumed rigidities in the market from a technological, industrial and economic point of view: namely, the above assumes that there is little leeway in the short-medium term (5-10 years) to adapt and that the main available "solution" to the problem of supplying food-grade / contact-sensitive recycled content is using chemically recycled material, especially for non-PET plastics. This assumption and its limitations are further discussed in chapter 6 below.

2.3.4. Technical aspects that may affect the economic viability of chemical recycling

The economic viability of chemical recycling for plastics is determined by the balance between revenues and costs. Nonetheless, technical aspects play an important role in the economic balance of each chemical recycling operation, in particular two which will be further discussed here: First, material yield, which greatly determines revenues, and, second, feedstock quality requirements, which influences feedstock costs, one or *the* most relevant item in operating costs (as will be discussed in section 3.5 and Chapter 5.)

- *Feedstock quality*: lower feedstock quality may reduce the feedstock price for the recycling plant but also increases the costs of the process due to requirements for additional treatment to make the feedstock suitable for processing; this means that technologies with higher feedstock quality tolerance can improve the economic viability;
- *Material yield*: processes that achieve higher technical material yields may be able to generate higher amounts of creditable recycled material (depending, especially for pyrolysis, on the specificities of regulation, in particular mass balance rules) and thus higher overall revenues;

These aspects, which are intertwined, are discussed in the following subsections.

2.3.4.1. Feedstock quality and process tolerance

According to Eunomia (2022), both mechanical and chemical recyclers require consistent streams of feedstock with minimal contamination. The authors state that while chemical recycling should be viewed as a recycling outlet for a *different* range of materials, it should *not* be viewed as a recycling outlet for contaminated materials or unsorted materials (although it does offer the potential to treat materials difficult to recycle mechanically to a similar grade). Neither should chemical recycling be considered as a direct outlet for untreated rejects from the mechanical recycling sorting step.

As indicated above, the different types of chemical recycling processes are intended to treat different types of polymers in terms of chemical composition. This also means that non-target polymers may have a negative effect on the chemical recycling process performance. Moreover, non-polymer

components such as inorganic materials (e.g. fillers, glass), metals, organic contamination (e.g. food residues, paper) and even moisture may negatively affect the process or require additional treatment steps. N.B. The applicability and merits of chemical vs. mechanical recycling are discussed at greater length in UBA (2024), pp.179 sqq.

What is meant by contamination?

Contamination can be related to any or all of the following elements:

— non-target recyclate materials - metals, glass, paper

— non-target plastics- assuming these are for polyolefin focused chemical recycling processes - contaminants could be PVC, ABS, PU, PET.

— 'soiling' of the plastics - food residues, dirt, grit, paper labels

— other non-target materials - batteries, sharps, sanitary material, small components such as springs, nuts, bolts from rigid packaging soap dispensers

— other materials found in material recycling centres - wood, steel bars...

Each of these 'categories' creates challenges for all recycling technologies, whether chemical or mechanical, but each technology also has its own tolerance to different types of contamination with respect to:

— how they can process the material - i.e. PVC leads to the formation of hydrochloric acid in some technologies which will cause corrosion in the process (see below)

— the quality of the output - the carry-through of chemical contaminants and how a company determines whether it is e.g. preferable to exclude these contaminants or to rather post-process the outputs (e.g. hydrotreating pyrolysis oil)

— the process tolerance itself to low-levels of contaminants - such as 5-10% PVC for some gasification processes, 5-7% PET for hydrothermal treatment...

— whether the contaminant can be removed in the process and not pass through into the oils - for example, water soluble contaminants (ions such as N, S and Cl) pass into the wastewater following hydrothermal treatment of waste plastic

— the infrastructure which will process the hydrocarbon products, and the offtake specification that chemical recyclers need to meet.

For solvolysis, Arcà et al. (2025) performed a literature review and conducted interviews with industry experts. They concluded that the technology requires a purity of more than 70% to 85% of the individual target polymers as input. Moreover, their findings indicate that the process is sensitive towards non-target thermosets, heavy metals and other hazardous substances. Overall, the literature seems less clear on which processes can handle more contaminated feedstock, although a review of various processes suggested that enzymatic hydrolysis has a higher tolerance towards non-target plastics and other contaminants (Uekert et al. 2022).

For pyrolysis, Eunomia (2022) state that the key advantage that pyrolysis has over mechanical recycling from a feedstock perspective is that (a) pyrolysis feedstock can contain both PE and PP at varying levels, and (b) pyrolysis can readily accept certain films. While a broad spectrum of multi-material films cannot be accepted as pyrolysis feedstock in high concentrations, certain types of multi-material films such as those that are mixtures of PE and PP can be accepted, and it is possible to combine multimaterial feedstocks with mono-materials to meet feedstock specifications. Nonetheless, Arcà et al. (2025) indicated a required purity (% target polymers) of at least 60% to 85% of individual and mixed target polymers in the input, in particular PE and PP.

The pyrolysis process is known to be sensitive to inorganic materials and heteroatoms, especially halogens like chlorine in PVC[34] - see for instance (UBA, 2024) p. 24[35]. These halogens, and other heteroatoms like sulphur[36], may harm the catalyst performance and decrease the quality of the products (Huang et al. 2022; Franke et al. 2024). Heteroatoms may also negatively affect downstream processes, e.g. the pyrolysis oil obtained from plastic waste is seldom suited for direct use in steam crackers (Zero Waste Europe 2023) where coking is an issue, and also for catalytic processes (such as fluidised catalytic cracking). For some contaminants, this may constitute less of an actual problem because pyrolysis oil is blended with other petroleum-derived feedstock in the steam cracker. Yet, Kusenberg et al. (2022) state that the only contaminants that most likely do not require additional treatment are sulphur, sodium and silicon, because the dilution factor is sufficiently small. The authors highlight that all other contaminants such as nitrogen, chlorine, calcium, iron and lead are typically exceeding the feedstock specifications for steam crackers by a factor of up to 16, 485, 34, 7000 and 350, respectively. This implies a requirement for additional upgrading processes, such as distillation and hydrotreatment, which add an additional cost. This is also reflected in the end-of-waste criteria for pyrolysis oil that exist in France[37], which have stricter requirements on contaminants for pyrolysis oil that does not undergo further purification at the petrochemical plant than for pyrolysis oil that will be purified.

Pilot-scale incorporation of PVC in pyrolysis feedstock is currently being demonstrated: recent industrial evidence[38] shows that ARCUS Greencycling's 2024 demonstration campaign successfully processed a feed containing 10 % PVC by weight in mixed polyolefins with no conversion penalty, producing pyrolysis oil within off-taker limits for chloride and acidity[39]; in addition, other advanced pyrolysis technology providers, such as Pryme[40], Synpet[41], and Lummus (New Hope Energy), describe feedstock-robust processes capable of handling mixed plastic waste and contaminants, and based on direct industry communication and conference presentations, these technologies are understood to tolerate up to ~2% PVC by weight in their feedstock. It remains unclear what the energy consumption trade-off would be at scale for these technologies.

For gasification, Arcà et al. (2025) indicate a high tolerance to mixing of various plastics and even to the presence of materials other than plastics, such as organic waste. Nonetheless, inorganic materials and heteroatoms like chlorine in PVC negatively affect the process. Some gasification processes are being investigated to accept a few weight percent of PVC in feedstock or even pure PVC feedstock[42]. Additionally, gasification technologies are being investigated for processing a larger range of feedstock than plastics, including also other carbon-containing waste e.g. biomass from municipal waste.

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[34] There are current innovations in this field such as the process developed by Arcus Greencycling (Arcus, 2025) with increased tolerance to chlorine-containing feedstock, potentially opening the way to higher contaminant intake (or a broader range of feedstock specifications) in pyrolysis.

[35] "PE and PP are the fractions generally used. Contaminants and impurities are acceptable to a limited extent. Plastic fractions with heteroatoms (PVC, nylon, etc.) are particularly problematic." (translated from original)

[36] This would mostly relate to the use of tyres as feedstock.

[37] See information provided at: https://www.legifrance.gouv.fr/jorf/id/JORFSCTA000049241724

[38] See Arcus-Vinylplus white paper (Arcus 2025)

[39] independent review by Ghent University indicates the oil can be blended into a steam cracker at approximately 2–3 wt% based on chlorine and oxygen specifications, with hydrotreatment enabling higher rates.

[40] https://pryme-cleantech.com/chemical-recycling

[41] https://synpet.com/rd-facility/

[42] https://www.vinylplus.eu/circular-economy/recycling-options-old/feedstock-recycling/

2.3.4.2. Material yield

One of the main elements that will determine the economic viability of chemical recycling is the amount of material that ultimately comes out of the process, and more specifically the amount of material that can be classified as "recycled"[43]. Whereas energy produced during the process and chemicals used for fuels also have a certain economic value, it tends to be the recycled compounds that generate the highest revenues for each tonne of produced material. This is particularly the case where such materials provide premium features compared to mechanical recycling, e.g. food contact suitability.

Parameters that affect the overall material yield in chemical recycling include (CE Delft 2022):

- Feedstock quality: The relative material yield will be higher when the input material has a higher purity and fewer unwanted constituents need to be discarded during pretreatment.
- Technologies applied: Certain processes, like pyrolysis and gasification, will result in a wide range of outputs, including emissions, hydrocarbons that will be used as or converted into fuels, (thermal) energy and solid residues (e.g. wax, char). Other processes, like solvolysis, produce much more homogeneous outputs, with only a few reaction products.
- Operating conditions and downstream processing choices: Chemical recycling processes can be steered by adapting the operating conditions or even including additional process steps, e.g. hydrocracking to treat the heavy fraction of pyrolysis oil, which would otherwise be destined to fuel production. Moreover, the distribution of outputs can be fine-tuned in several steps by using catalysts (Ellis et al. 2021, Martín et al. 2021, Qin et al. 2025, Huang et al. 2022, Lopez et al. 2017).

Few industrial scale facilities are operational, and only limited data is available on the yields achieved beyond the lab scale. **Table 5** provides an overview of yields for industrial operations. It should be stressed that the figures in this table could not be checked independently for accuracy and seem generally high compared to values encountered in the scientific literature and shared by experts.

Table 5. Overview of reported yields for industrial chemical recycling operations.

Company	Subvariant	Input material	Yield (%)	Reference
SOLVOLYSIS				
Carbios, FR	Enzymatic hydrolysis	PET mechanical recycling rejects, trays and fibre	90	Carbios[44]
Eastman, US/FR	Methanolysis	PET packaging and fibre	>90	Eastman[45, 46]
INEOS Aromatics, BE (Infinia)	Methanolysis and hydrolysis	Difficult-to-recycle PET packaging (incl. multi-layer trays) and polyester textiles	>90	INEOS[47]

[43] N.B. as stressed elsewhere, this report does not aim to discuss "mass-balance" requirements and their impact on this parameter.

[44] https://www.carbios.com/wp-content/uploads/2024/09/carbios_investor-presentation-september-2024-web.pdf

[45] https://s29.q4cdn.com/397220757/files/doc_presentation/2024/Circular-Deep-Dive-2024-Presentation-Slides-FINAL.pdf

[46] https://www.eastman.com/en/media-center/news-stories/2022/eastman-exclusive-negotiation-site-normandy

[47] https://www.ineos.com/businesses/ineos-aromatics/sustainability/ineos-infinia/

Ioniqa, NL	Glycolysis	PET bottles	93	Thiounn and Smith (2020)
Jeplan, JP	Glycolysis	PET bottles and fibre	98	Thiounn and Smith (2020)
Gr3n, CH	Hydrolysis	PET bottles, textiles, food packaging	98-99	Hann and Connock (2020)
Two companies (undisclosed)	N/A	PET bottles, textile	97-100	CE Delft (2022)
PYROLYSIS				
Plastic to monomer				
Regenyx, US	N/A	PS	81	Hann and Connock (2020)
Pyrowave, CA	Catalytic microwave pyrolysis	PS	95	Hann and Connock (2020)
Plastic to pyrolysis oil				
Pryme One, NL	N/A	Mixed plastic waste	65	Pryme[48]
Quantafuel, NO	N/A	Mixed post-consumer plastic waste	68	Sustainable Plastics[49]
Plastic Energy, ES	N/A	Plastic waste	70	ResourceWise[50]
ReOil, AT	Non-catalytic pyrolysis	Plastic packaging, mainly polyolefins	82	OMV [51, 52]
Plastic to plastic				
Five companies (undisclosed)	N/A	Plastic films, mixed plastic waste	43-60	CE Delft (2022)
Six companies (average)	N/A	PE/PP/Mixed plastic waste/Foils	49	CE Delft (2022)
MoReTec, DE	Catalytic pyrolysis	Mixed plastic packaging and flexible polyolefins	80	ICIS[53] and LyondellBasell[54]
Plastic Energy	N/A	Mixed plastic waste	68	Plastic Energy & Sphera (2025)
GASIFICATION				
Undisclosed company	N/A	Mixed plastic waste (mainly PO)	34	CE Delft (2022)

Note that the data have been included as reported by the indicated sources but could not be verified for accuracy.

[48] https://pryme-cleantech.com/uploads/downloads/Pryme-N.V.-Trading-Update-29-October-2024.pdf

[49] https://www.sustainableplastics.com/news/proof-concept-announcement-norwegian-chemical-recycler-quantafuel

[50] https://www.resourcewise.com/blog/chemicals-blog/chemical-recycling-towards-a-circular-economy

[51] https://www.omv.com/en/media/press-releases/2021/211220-omv-scales-up-innovative-reoil-recycling-technology-at-schwechat-refinery

[52] https://www.euwid-recycling.com/news/business/chemical-recycling-omv-launches-reoil-plant-for-mixed-plastic-waste-040425/

[53] https://www.icis.com/explore/resources/news/2024/11/01/11046565/lyondellbasell-may-make-2026-fid-on-us-chemical-recycling-plant/

[54] https://www.lyondellbasell.com/en/sites/moretec/

Sources: see individual references. Data reported as plastic to plastic or monomer ready for polymerisation, unless otherwise indicated (N/A: no detailed information available).

Table 5 shows that, overall, solvolysis ranks higher than pyrolysis, which in turn ranks higher than gasification, on yielding chemicals that are not used for fuel production[55].

In solvolysis, polymers are dissociated into oligomers or monomers by means of a solvent. These monomers, after possible crystallisation, filtration and distillation can be resynthesised again into polymers (Tullo 2023, Sia Partners 2024). The conversion of polymers to monomers is a process with few losses and resynthesising the new polymers is also straightforward. This explains the overall higher yield of the process.

Based on a literature review of academic and industrial research, Kusenberg et al. (2025), using industrial, patent and lab data, reported the median yield of depolymerisation via methanolysis, glycolysis and hydrolysis processes as 94% with first and third quartile values at 88% and 99%, respectively. According to the same study, the purification efficiency had a median value of 96%, with first and third quartile values at 94% and 97%, respectively. Based on these findings, the authors estimated the overall conversion efficiency for solvolysis processes, from polymer to purified monomer, to be between 83% and 96%. CE Delft (2022) found slightly higher conversion rates, based on company data from four industrial plants, with plastic-to-plastic conversion yields of 97% to 100% for various types of PET waste.

In pyrolysis, plastic waste is turned into pyrolysis oil, gas and char. Gas and char tend to end up as fuel or residues, although some material use has also been reported (Wijesekara et al. 2021), with some recyclers pursuing End of Waste declaration for the char. The pyrolysis oil is then typically sent to large petrochemical installations, where it is mixed with petroleum-derived streams and sent to fractionation, followed by upgrading and steam cracking, or directly to steam cracking if the pyrolysis oil is of sufficient quality (e.g. following prior upgrading). The basic chemicals resulting from steam cracking can be used for production of new polymers. Nonetheless, the process is characterised by a partial conversion into energy, chemicals that will be used for fuel production and losses (e.g. emissions) along the process chain. This affects the overall achievable material yield.

Kusenberg et al. (2025) analysed the conversion rates in the various steps of a process that uses pyrolysis to create high value chemicals, including basic chemicals for polymer production. According to their analysis, the conversion rate from plastic waste to pyrolysis oil is about 85% to 92%. Subsequent fractionation showed a conversion rate of 24% to 39% for naphtha and 41% to 52% to the light/medium gasoil fraction. Whereas the naphtha fraction generally tends to be used in its entirety for steam cracking, only about 70% to 85% of the light/medium gasoil fraction may be suitable for steam cracking. Upgrading of the naphtha and light/medium gasoil fractions had a conversion rate of 90% to 95%. Finally, the conversion rate in the steam cracker was estimated to be between 66% and 71% for the production of ethylene, propylene, butadiene and BTX.[56] Assuming a fuel-use-excluded mass balance methodology, this would mean that overall about 27% to 52% of

[55] Uekert et al. (2023) question the role of thermochemical processing technologies on efficiency grounds:

"The economic and environmental metrics of pyrolysis and gasification are currently 10–100 times higher than virgin polymers due to low yields of monomers suitable for repolymerization (material retentions of 0.010 ± 0.003 to 0.14 ± 0.07) and high energy requirements for the conversion and subsequent upgrading processes (Figure S13, Table S29). Previous reports have shown that pyrolysis and gasification can be economically and environmentally competitive for the production of feedstock fuels and chemicals (e.g., benzene– toluene–xylene mixture, naphtha, or methanol) rather than plastics, although this may change with technology and policy advancements."

[56] BTX refers to the aromatic hydrocarbons benzene, toluene, and the three xylene isomers. Ethylene, propylene, butadiene and BTX are considered high value chemicals as they are typically used for the production of polymers.

the plastic waste would be converted to new chemical building blocks that can be allocated to polymer manufacturing[57]. By additionally employing a fluidised catalytic cracking unit or hydrocracking unit to treat the heavy pyrolysis oil fraction, the overall plastic waste to high value chemical yield can be increased to 31%-63% and 35%-77%, respectively, according to the authors.

Based on data from 11 different industrial plants, as indicated in **Table 5**, CE Delft (2022) reported that the plastic-to-plastic yield for various pyrolysis processes varied between 43% and 60%, while other sources even claim higher plastic-to-plastic yields. As we discuss in more depth in section 5.2.3.6, these high material yields have to be put in the perspective of a trade-off whereby additional process energy input is associated with higher costs and carbon emissions.

In gasification, polymers are decomposed through a high temperature treatment, and the resulting gas fraction can be directed to synthesise new chemicals. Nonetheless, as in the case of pyrolysis, a considerable fraction of the input material is converted into energy, chemicals that will be used for fuel production and losses (e.g. emissions). Voss et al. (2022) calculated a yield of 25.6% of high value chemicals (butadiene, butene, ethylene and propylene) for the gasification of sorted residues from light weight plastic packaging. As reported in **Table 5**, CE Delft (2022) reported a 34% plastic-to-plastic yield for the industrial gasification of mixed plastic waste mainly consisting of polyolefins while Lange et al. (2024) mentions a potential to reach 54%.

2.3.5. Scope of economic viability analysis

In this report we largely focus on two key process types which currently occupy the largest share in the landscape of chemical recycling of plastic waste, i.e. thermochemical liquefaction (pyrolysis and hydrothermal liquefaction) targeting mostly hydrocarbon waste (polyolefins and styrenics), as well as solvolysis (hydrolysis, glycolysis etc.) targeting PET/polyester. Note that other processes may also become relevant in the future and are also being investigated, such as gasification, but lack of economic data and evidence from operational facilities currently impedes an investigation of their economic viability in the context of this report. Hence, this should not be regarded as an assessment of the potential of e.g. gasification (assessed positively in, e.g., Lange et al. (2024)), but a reflection of the scarcity of representative technoeconomic data at the present stage.

[57] also consistent with UBA (2024), reporting a High Value Chemicals yield between 45% and 50%.

3. Methodological approach

3.1. Economic viability

There is no standard definition of economic viability and how to measure it. For a certain business model or technological production process, it captures a notion of being able to stay in the market with a minimum of profitability or at least breakeven. It implies, as necessary condition, the capability to generate sufficient revenues to cover costs and sustain operations. Revenues are generated from the sales of recycled plastics and other outputs, whereas costs occur through capital and operational expenses, the latter including plastic feedstock, labour, energy, raw materials, and other categories. A more comprehensive view might link economic viability to whether an economic activity generates an *Internal Rate of Return* (IRR) that is positive and commensurate with returns typically achieved in the sector.

Here, a pragmatic approach is adopted, in which as the main criterion of economic viability we compare unit production costs with expected sales prices. This approach is simple, but similar to the frequently used Minimum Sales Price (MSP) and is not least a consequence of the overall sketchy data situation, which does not allow to systematically estimate more comprehensive indicators such as IRR.

Chemical recycling operates in a specific market context, warranting some additional clarifications on how economic viability could be understood. In fact, we argue below that there are three different perspectives on the notion of economic viability of chemical recycling.

Technically, the output of chemical recycling can be considered a perfect substitute of virgin plastics, and vice-versa. This implies that under a narrow perspective, chemically recycled plastics should have the same price as virgin plastics, and economic viability would thus require that the unit production costs of chemical recycling are sufficiently below market prices observed for virgin plastics (as chemical recycling output represents a small share of the overall plastics market, it would be a price-taker). This is the first perspective, which could be called a 'hard market' view.

However, chemically recycled plastics have an attribute of environmental friendliness (being "green"), for which some plastics producers and consumers are *willing to pay* higher prices, the so-called "green premium". Recycled plastic is what economists describe as a credence good, as this property cannot be verified by buyers themselves by looking at or using the plastic, especially in the case of chemical recycling (mechanically recycled plastic may be traceable); the green claim must be believed on the basis of documentary evidence. This explains why clear rules and third-party certification is important in this sector (e.g. ISCC PLUS is a common private certification scheme for the use of alternative feedstock[58]; RSB is another standard in use[59]), and why attempts of fraudulent green claims might be likely.

In such a market setting where "green" and "non-green" grades of the same product co-exist, market demand for chemical recycling output is driven by the general plastics supply and demand combined with the extra willingness-to-pay (WTP) for the "green" attribute. Until recently, demand for recycled plastics – including mechanically recycled – was mainly linked to sustainability pledges of consumer goods producers. However, these are voluntary commitments which might abruptly

[58] https://www.iscc-system.org/certification/iscc-certification-schemes/iscc-plus/

[59] https://rsb.org/certification/

change or even disappear, e.g. in an economic recession or due to a lack of consumer interest or trust. As the second perspective on economic viability, this could be called the 'soft market' view.

The final perspective is that of a 'regulatory market', which in fact is now taking centre stage in the EU. In this regime, the use of recycled plastics becomes mandatory by regulation in several important sectors, namely through the PPW regulation and SUP directive (see following section), and potentially others (plastics in textiles is, for now, a notable exception). The demand for recycled plastics, both from mechanical and chemical processes, is set to grow several-fold as a consequence.

Moreover, the nature of the *recycled content targets* mandated by EU regulation means that in principle, there is an overall amount of recycled plastics that has to be supplied to the EU market for legal compliance - a percentage of total plastics put on the market - making demand for it less elastic to price. However, in case the price of locally supplied recycled plastics goes far above acceptable green premium levels (or in case the available quantities are insufficient), downstream users (e.g. packaging producers) could use several mitigation strategies, with different options in the short, medium and long term. For example, they could switch to other materials (e.g. non-plastic packaging), to imports, or even to lower quality grades (e.g. compromising on product protection or non-essential functionalities), as further discussed in section 7. In extremis, if recycled plastics prices unexpectedly become very high and none of these mitigating strategies are possible, the regulation could even become unenforceable (e.g. penalties for non-compliance might be lower than compliance costs) and may have to be revised.

In the short term, however, the question of economic viability is fundamentally altered by mandating recycled content because, on the compliance market, recycled plastics are no longer in competition with virgin plastics, and the green premium is largely determined by the price mark-up that recyclers require to supply the needed quantities. The green premium acceptable on a 'regulatory market' is therefore expected to be significantly higher than on a voluntary 'soft' market.

The mandatory use of recycled plastics for regulatory compliance also means that there is a certain shift of market competition: from virgin vs. recycled plastic producers to competition mostly *within* the recycling sector, i.e. which recyclers are able to produce certain qualities of recycled plastics (e.g. food grade) at the relatively lowest costs, with less importance of how these costs compare - in absolute terms – to those of virgin producers. Other competitive pressures remain (e.g. product or material substitution, imports), as well as the competition between mechanical and chemical recyclers, even though their business models are to some extent complementary.

Importantly, the price mark-up recyclers require may depend on the regulation's technical rules that define what counts as recycled plastics. Most prominently, mass-balance-allocation rules (not discussed in detail in this report, see §3.4) define the strictness applied to the crediting of recycled content in co-production processes (mostly pyrolysis) and, through this, strongly influence the required price mark-ups for each tonne of recyclate.

In sum, there are three possible views on economic viability: viable/competitive against virgin products (pure price competition), viable/competitive with respect to reasonable green premiums on a voluntary market (competition on a mix of "greenness" and costs), and viable/competitive in a regulatory context where a minimum, fixed demand for recycled plastics is imposed by regulation (with higher green premium levels than on a voluntary market).

The objective of the present study is to assess the economic viability of chemical recycling. As discussed, in the 'regulatory market' setting, the concept of economic viability is fundamentally altered and depends on several parameters enshrined in the law defining the regulation. Although a large share of the EU market for chemically recycled plastics will in fact be of this type, additional market

volume will still rely on voluntary green premiums, most notably recycled fibres and textiles. Therefore, the present study will discuss economic viability in terms of whether production costs and implied minimum sales prices are within a range that appears compatible with reasonable green premiums.

3.2. Examples of policy support to enhance economic viability

In order to 'correct' existing market dynamics toward more desired behaviour, one or several policy instruments can be put into place. Policy design may be both price-based and quantity-based, leading to a combination of market signals. We here highlight some characteristic approaches that are already observed in some jurisdictions (as the outcome of local/regional, national or EU rules):

- **Gate fee** (at waste disposal stage): this relates to the potential constraints on alternatives to (chemical) recycling as disposal routes for waste plastics, typically incineration and landfilling. If, all things being equal, waste holders are faced with negative prices for their plastic waste (they are charged a disposal fee) when landfilling or incinerating it, this creates a competitive advantage for plastic recyclers who are then operating in a market where they can also charge a fee for taking the material off the waste holder's hands. This gate fee charged by waste-treatment operation can induce a negative cost for the feedstock to chemical recycling processes, where it is seen as an input material, tilting the economics in favour of recycling. In practice, this can only exist where there are strong impediments to incineration which prevent the material being used for its high calorific value (typically >25Mj/kg for waste plastics, higher than the typical ~10 MJ/kg for municipal solid waste). Research by Tomić et al. (2024), for instance, indicate that thermochemical conversion of industrial plastic waste cannot be economically viable on a small scale without a gate fee.

- **Green premium** (at the plastic conversion stage): as discussed in the previous section, this refers to the willingness-to-pay (WTP) of downstream actors for recycled plastics in order to comply with voluntary sustainability goals or legal obligations (recycled content incorporation). This premium is likely to have a ceiling even in a setting of legal obligations, determined by non-compliance fines and the costs for substitution ('escaping regulation') with alternative materials (paper packaging, etc.). Nevertheless, there exist market conditions where paying a green premium might be the most viable strategy for plastic manufacturers and their customers (consumer goods manufacturers, etc.). The green premium might be a direct consequence of some indirect obligation, such as a mandate for the incorporation of recycled content.

- **Trade instruments**: these can typically consist of tariffs on imports or subsidies on exports, as well as non-tariff instruments such as requirements for local content incorporation. Note that those may contravene obligations assumed under the World Trade Organisation.

- **Recyclate subsidy**: for instance through eco-modulation of EPR scheme, by providing an incentive per weight of post-consumer recyclate incorporated[60].

- **Recycling subsidy**: other instruments can be devised, such as a direct subsidy of the recycling activity (based on recycling plant processing capacity, or on some metric of actual recycling throughput), levelling the playing field versus virgin materials.

[60] See example from Citeo (France) https://www.petcore-europe.org/images/2025/2025-presentation-petcore-europe-conference/940-juliette-beaulieu-citeo-petcore-thermoforms.pdf , sl. 15

In practice, it is possible that these instruments, which interfere with market pricing mechanisms at different points of the value chain, coexist and concur to push chemically recycled plastics towards improved economic viability.

3.3. Cost allocation for multiple-output processes

As described in chapter 2, some chemical recycling approaches are derived or adapted from existing processes which are conventional in the (petro)chemical industries, in particular the thermochemical processes of pyrolysis and gasification. These production pathways typically yield multiple outputs: high-value chemicals (including polymers or polymer precursors), fuels (gaseous or liquid) or solid residue (char, waxes etc.).

Each of these co-products or by-products enters in the overall economic assessment of the process and it is fundamentally impossible to assign specific costs to each output in an unambiguous manner, since a single process produces multiple outputs at the same time. Therefore, if an output-specific cost needs to be formulated, an accounting rule for the allocation of costs must be selected. Possibilities for these rules include: allocation based on weight or volume (or some other physical characteristic, such as calorific value) of the final products, allocation of the value to only one or some outputs (the rest being considered by-products or co-products), or allocation based on the expected market value / sales revenue to be derived from each product.

Accounting and business practices have been dealing with this structural issue since the beginning of trade (e.g., in the meatpacking and refining industries), and unless specific accounting constraints advocate otherwise, the most common practice is to follow the "relative sales value" method, otherwise described as the Net Realisable Value method. Note that in this case some products can be allocated negative values (e.g. hazardous co-products with disposal costs), which is not possible under a physical allocation method.

To reflect industry practice, unless otherwise specified we will consider that the *relative* sales value method is the most suitable allocation method, and thus the one we will be using. It is important to note that it is relative i.e. the *relative market prices are used proportionally* to allocate costs between products, but this does not reflect the potential market propensity to absorb products at a price equal or above that given calculated cost (i.e. minimum sales prices derived with this method may be higher than market clearing prices).

This discussion is related, but not identical, to the problems raised by the *mass balance allocation* problem which also looks at attributable metrics for certain outputs, but from the perspective of a physical characteristic (e.g. recycled content) attributable to various fractions in relative quantities.

Cost allocation happens in a market context regardless of legal obligations, as operators seek to maximise value arising from inputs and outputs and therefore attempt to optimise revenues accordingly. In contrast, mass-balance allocation is a response to an external constraint on a characteristic of one or several of the inputs and outputs, in order to fairly determine a value for the purpose of compliance: we explore below the key issues raised by mass-balance.

3.4. Mass-balance allocation and economic viability

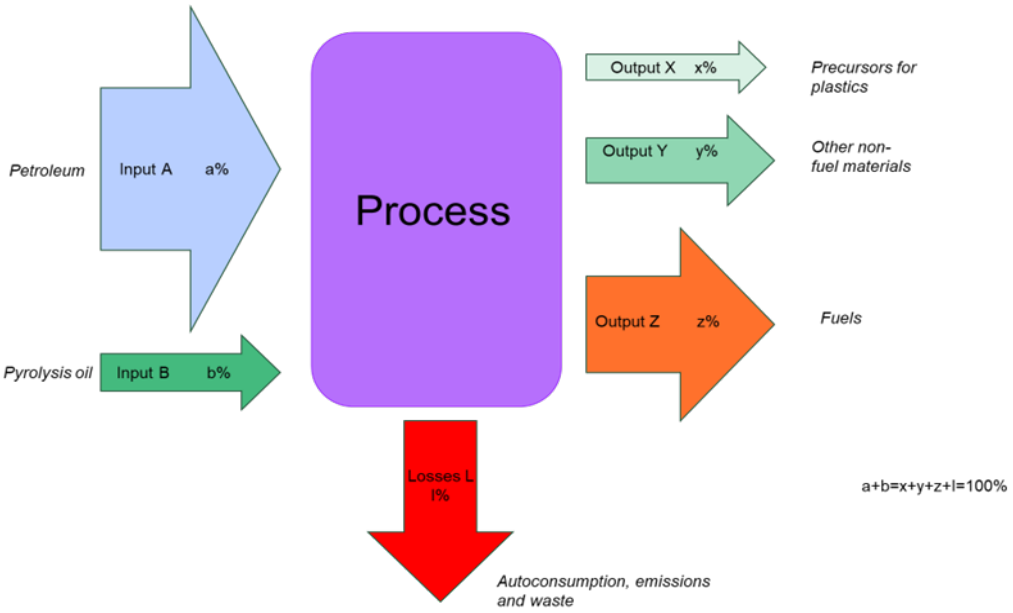
3.4.1. Introduction to mass-balance allocation

Mass-balance allocation refers to the method of accounting for a specific, non-measurable characteristic (here, the amount of recycled material, assuming it is not physically distinguishable from virgin material) in a product, typically when arising from a **multiple-input, multiple-output process.** As indicated above, a typical example is **pyrolysis** oil from plastic waste being mixed with petroleum in a petrochemical installation to produce various outputs. It involves tracking or simulating a flow of materials through a production process to determine or assign a characteristic (in this case, the amount of recycled content) to the final output, with the aim of ensuring that the claims made by manufacturers are accurate or trustworthy. It is also assumed that the specific characteristic attributed to outputs has market value (i.e. there are customers willing to pay a premium for this specific characteristic). It can be a crucial parameter for the economic viability of a complex recycling process like chemical recycling, particularly when a significant premium is associated with recycled content.

3.4.2. Mass balance: calculation principles

To introduce the concept of mass-balance allocation in chemical recycling of plastics[61] in a simple manner, we consider a multi-input, multi-output process as pictured below in **Figure 4**: Input flows A and B enter the process, and output flows X, Y, Z and L exit the process.

Figure 4. Mass balance principle (elements in italic are examples)



Source: own elaboration

[61] The methodology outlined below may also be followed in other contexts, e.g. where biobased material is used together with fossil-based inputs to produce various output products

Mass balance calculations typically aim to provide an answer to the question: when we combine two input streams A and B, **how much of the output X** (or Y or Z or L) **counts as coming from B?** For example, let's assume that for an input A of 1000 t, we produce 100 t of X (10%), 200 t of Y (20%), 400 t of Z (40%) and have 300 t of losses L (30%). In this case, the question is, when we add an additional input B of 200 t, how should we allocate the origin of B to each of the ensuing outputs X, Y, Z and L? As we mentioned before, there is no single, unambiguous answer to the question, and therefore a plausible, internally consistent, but to some extent also arbitrary allocation has to be decided upon.

In concrete terms, for the chemical recycling discussion, "A" would be fossil input (e.g. petroleum) whereas "B" would be recovered material, such as pyrolysis oil derived from plastic waste; X would be high-value materials (plastics or their precursors) and Y would be low-value materials, with both X and Y theoretically counting towards recycling for the parts derived from B. Z would be fuels, and as in the case for losses L, would never be able to claim that they contain recycled content but only recovered content[62]. We assume that the material properties of inputs A and B are the same, so that they will undergo the same transformation pathways in the process. For illustrative purposes, several lines of reasoning could be followed:

- **Proportional allocation** (physically the most intuitive): the proportions of recovered content, allocated to stemming from B, are the same in all the output fractions. That is, X, Y, Z and L all have a b% recovered content. In our example, upon adding 200 t of B to the 1000 t of input A, we will produce 120 t of high-value materials X with a 16.7% (200/1200) recovered content, 240 t of low-value materials Y with a 16.7% recovered content, 480 t of fuels Z with a 16.7% recovered content and 360 t of losses L with a 16.7% recovered content. Only in the case of the materials X and Y, the recovered content can be considered as recycled content. Beyond the strictest ***rolling average*** approach, where each and every part of X has the same recycled content of b%, there is the somewhat less strict approach that typically allows for a limited ***credit transfer*** within the output fraction produced in the same petrochemical plant. In the latter case, recycled credits can be transferred "from molecule to molecule". As a result of this transfer, b% of the entire production of X can claim a recycled content of 100% while the remaining fraction can no longer claim any recycled content. In our example, this would mean that 20 t of output X can be claimed to have 100% recycled content, while the remaining 100 t of output X would then have a zero percent recycled content. Nonetheless, contrary to the fuel-use excluded method (see below), no credit transfer is allowed between different output fractions. In our example, no credit transfer is allowed between output X and output Y.
- **Free allocation (with credit transfer)**: In this approach, there is a mandatory proportional allocation of input B to losses, whereas the remaining amount of B can be freely allocated, while no allocation can go beyond the amounts of each output fraction produced. All of B, minus the obligatory allocation to losses, can be counted as going to X, up to the amount of X produced (i.e., if $b \times (1-l) > x$, X is 100% recycled ; or, if $b \times (1-l) < x$, then a share of $b \times (1-l) / x$ of X can be declared as 100% recycled). In our example, upon adding 200 t of B to the 1000 t of input A, 30% of the input B, i.e. 60 t, has to be mandatorily allocated to losses, meaning that 140 t remains available for completely free allocation. Since only 120 t of X are produced, only 120 t from input B can be allocated to output X, which

[62] Based on the definition of recycling under the Waste Framework Directive 2008/98/EC

will thus have a 100% recycled content, whereas the remaining 20 t of input B can be allocated to output Y, which will then have an 8.3% (20/240) recycled content. For the latter, it is also possible to declare 20 t of Y as having a 100% recycled content and 220 t as having zero recycled content. In this case, the fraction Z (fuels) has no recovered content.

- **Fuel-use excluded (with credit transfer)**: In this approach, there is a mandatory proportional allocation of input B to losses and fuels, whereas the remaining amount can be freely allocated among material outputs, while no allocation can go beyond the amounts of each output fraction produced. All of B, minus the obligatory allocation to losses and fuels, can be counted as going to X, up to the amount of X produced (i.e., if b × (1-l-z) >x, X is 100% recycled; or, if b × (1-l-z) <x, then a share of b × (1-l-z) /x of X can be declared as 100% recycled). In our example, upon adding 200 t of B to the 1000 t of input A, 30% of the input B, i.e. 60 t, has to be mandatorily allocated to losses and 40% of the input B, i.e. 80 t, has to be mandatorily allocated to fuels, meaning that 60 t (200-60-80) remains available for completely free allocation. Since 120 t of X are produced, the 60 t remaining from input B can be allocated to output X, so that 60 t of X has 100% recycled content whereas the other 60 t of X has zero recycled content. In this case, none of fractions Y or Z will have any recycled or recovered content.
- Other allocation methods can be followed for more complex processes (e.g. for outputs which could potentially be used both for fuels and materials, known as 'dual-use', etc.).[63]

3.4.3. Relevance for chemically recycled plastics

In the context of chemical recycling of plastics, these considerations become important especially when processes aim to utilise existing petrochemical infrastructure to benefit from large-scale, often largely amortised processing facilities (Systemiq 2022). However, in this case both '*b*' (share of recovered input) and '*x*' (share of high-value materials) are likely to be small: typically, today in the petrochemical industry, *b*<~1% of input and *x* (plastics share) ~10% of output (Plastics Europe 2024a, Plastics Europe 2023). In that case, with stringent mass balance rules the share of plastic that can claim to be recycled becomes very low. If the extra costs for the sustainable (plastic waste) inputs have to be allocated (distributed) on a very small amount of output material, the required mark-up on the unit sales price of the recycled output can become drastic.

As an example (to illustrate a 'rule-of-thumb' of allocation), if a recovered input material costing 100€ more per tonne is fed into the process, but due to the mass balance rules only 10% of the mass of each input unit leads to creditable recycled material at the output stage, the potential extra cost carried over to the creditable recycled output material is of the order of 100€/10% = 1000€/tonne. This would represent the order of magnitude of the required price premium for the recycled vs the fossil output variant, to reflect the higher production costs.

The economic viability of plastic recycling, specifically for pyrolysis and gasification, may thus be closely tied to mass-balance allocation rules. Note that the arguments presented above are **extremely simplified** and do not take into account other constraints and characteristics of products, markets and processes, which may be relevant in implementation.

[63] More generally, in the wider context of chain-of-custody models, a variety of concepts exist, e.g. segregation or book-and-claim, as well as mass balance implementations such as batch-level accounting. These are not discussed here.

For the Single Use Plastics Directive (EU) 2019/904, mass balance calculation rules were published in June 2026[64]. Nonetheless, such rules are not yet in place for the Packaging and Packaging Waste Regulation (EU) 2025/40.

For this reason, in our cost modelling and evaluation in Chapter 5, we aim to avoid as much as possible the on-going discussions on mass-balance[65] rules, for multiple input and output processes like pyrolysis, by focusing on a largely stand-alone process. The advantage of this approach is that it reliably tracks the yields at every step in the conversion of waste plastics towards new plastics and thus presents a realistic picture of overall physical conversion efficiency and cost propagation. As such, it avoids two opposing opiniated basic assumptions with regard to the mixed use of pyrolysis oil and virgin feedstock in a petrochemical plant that would impact the calculations. The first is the amount of high-quality feedstock that may be redirected to fuel production, rather than to potential high-value material production, in real-world petrochemical plant operations, for commercial or other reasons, and which would drastically decrease the amount of recycled output under stringent mass balance rules. Some opponents of pyrolysis may argue that, in practice, this would always reduce the conversion efficiency considerably. The second is the possibility to allocate more of the pyrolysis oil to the high-value output material and less to fuels, by allocating more of the virgin input to fuels and less to high-value output materials. Some proponents of pyrolysis may advocate such an interpretation, which would drastically increase the amount of output that can be counted as recycled under a free allocation mass balance approach. Note that our approach, therefore, represents, as much as possible, a neutral scenario. The purpose of this report is not to discuss possible further possible cost increases due to operational decisions in the petrochemical installation, nor to discuss the respective implications of different mass-balance allocation rules.

[64] See Commission Implementing Decision (EU) 2026/1425 of 30 June 2026 laying down rules for the application of Directive (EU) 2019/904 of the European Parliament and of the Council as regards the calculation, verification and reporting of data on recycled plastic content in single-use plastic beverage bottles and repealing Commission Implementing Decision (EU) 2023/2683

[65] Note that mass-balance considerations are only necessary in process steps where blending occurs.

3.5. Capital expenditure and operational expenditure

In chapter 5, we take a closer look at the cost structure and cost drivers of two main chemical recycling operations, namely pyrolysis and solvolysis. In doing so, we rely on the methodological approaches relevant to these process industries, in particular with respect to the categories of costs that are relevant in production. One common distinction in industry and in particular for process industries is to distinguish between capital and operational expenditures:

Capex and Opex

Capital expenditure (cap.ex., Capex) and **operational expenditure** (op.ex., Opex) are concepts in economic analysis, particularly critical in the process industries, which include sectors like chemicals, oil and gas, and pharmaceuticals. "Capex" refers to funds allocated for acquiring, upgrading, or maintaining long-term physical assets, such as land, machinery, plants, infrastructure, or technology. These investments are typically one-time or semi-permanent and are essential for establishing or expanding production capacity.

In contrast, "Opex" encompasses the recurring costs of running a business, such as labour, utilities, maintenance, raw materials, and administrative expenses. These are more short-term, day-to-day costs necessary to sustain operations. The distinction between capex and opex is pivotal for financial planning, as capex often requires significant upfront capital and is amortised over time, while opex directly impacts cash flow and profitability on an ongoing basis.

In the process industries, where large-scale, capital-intensive projects are the norm, capex and opex play distinct but interconnected roles. *Capex* is central to the initial design and construction of facilities, such as chemical reactors, pipelines, or refineries, which demand substantial investment to meet safety, efficiency, and regulatory standards. These expenditures are critical for long-term competitiveness, as they determine the scalability, energy efficiency, and environmental compliance of operations. For example, a chemical plant's Capex might include advanced separation equipment or emissions control systems, which influence both operational performance and regulatory costs. *Opex*, on the other hand, dominates the current cost of operations, especially in industries with continuous processes. Energy consumption, feedstock costs, labour for maintenance, and waste management are recurring opex items that directly affect margins.

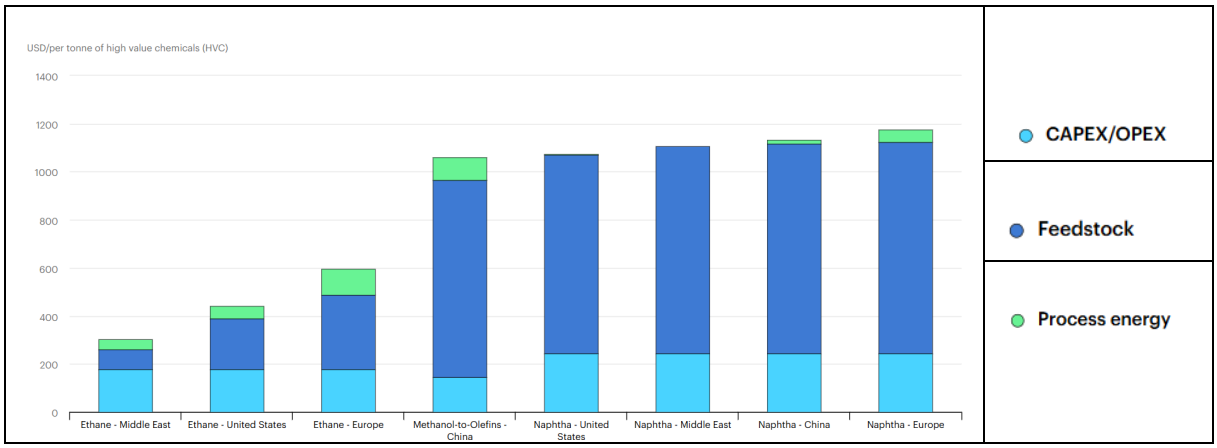
Minor discrepancies might arise in the grey area between capex and opex where they could be considered to overlap (typically some maintenance work and repair costs and equipment replacement), but those are usually small enough to be neglected in a first approximation and will not be investigated here.

In addition, capex is usually accounted for in unit production costs by "amortising" over a number of years, i.e. distributing the (initial) cost of capex over the period considered or planned to represent the "useful life" of the asset, e.g. 15 or 20 years for many industrial installations in the process industry. In our very simple model, we do not factor in the depreciation of capex over time (accounting for the cost of capital), but simply distribute (divide) the initial investment over the useful life. Many more sophisticated approaches for costing exist and have been investigated in the literature, for example in Voss et al. (2023)

In the mature chemical sector, and petrochemical activity in particular, the current structure of the industry is based on consolidated, very large-scale facilities with well-established and optimised processes, where profitability is driven by large-scale processing of standardised flows.

Although initial CAPEX may be very high (typically in the bn. € range) for processing units (e.g. refining plants, steam crackers, etc.), this capital equipment is fast amortised considering the sheer scale of the throughput that these facilities process (of the order of several 100k bbl/day), reflecting the throughput of the petroleum refining sector as a whole (100m bbl/day).

Figure 5. Simplified levelised cost of petrochemicals for selected feedstocks and regions, year 2017.



NB: 'Capex+Opex' category here interpreted to mean Opex *other than* feedstock and process energy + Capex.[66]

Source: IEA (IEA Licence: CC BY 4.0), using feedstock prices from ArgusMedia (2018), Key Prices, www2.argusmedia.com/en/methodology/key-prices .

As illustrated in the exemplary **Figure 5** from the International Energy Agency (IEA) (NB: from 2017 when crude prices were relatively high, but the capex/opex ratio is still relevant), the lead cost items in established petrochemical facilities are driven by OPEX, predominantly feedstock costs (i.e. crude oil, natural gas).

[66] Notes (IEA): "Fuel and feedstock costs are calculated based on average prices during both 2010 and 2017, whereas capital expenditure (CAPEX) and fixed operational expenditure (OPEX) are assumed to remain constant both over time and between regions, for a given technology. CAPEX assumptions: USD 1 500 /tHVC for ethane steam cracking; USD 1 000/t HVC for MTO; USD 2 050/tHVC for naphtha steam cracking. Fixed OPEX: 2.5-5.0% of CAPEX. Discount rate is 8%. A 25 year design life is assumed for all equipment. Energy performance ranges: 12-19 gigajoules (GJ)/tHVC for naphtha steam cracking; 14-17 GJ/tHVC for naphtha steam cracking; 11 GJ/tHVC for MTO. Feedstock requirements correspond to those shown in Figure 2.4. Process energy requirements include fuel, steam and electricity, are calculated on a net basis, assuming full utilisation of available fuel gas in the product stream. ME = Middle East, US = United States".

4. Data sources and evidence base

4.1. Published studies, reports, and other material

To inform our analysis, we have consulted over 100 documents consisting of academic research articles, expert reports, market studies, press articles, press releases, industry communications, etc. Almost all stem from the last five years, especially cost-relevant information, to ensure up-to-date data in this quickly evolving technology.

Data arising from the literature was reviewed and integrated into our analysis. Note that some of the data points (e.g., specific process yields, physical characteristics, market data, etc.) may not be directly reflected in the text of the relevant sections in the report. However, we present in more detail the background data and analysis underlying our assumptions and, where relevant, modelling, in **Annex A**.

4.2. Direct stakeholder inputs

Following an informal consultation launched in autumn 2024 with support from DG GROW, we received input from 24 stakeholders in total (whose contribution is acknowledged in the Acknowledgments section), of the following categories:

- 17 direct operators, 5 industry associations, 1 NGO, 1 government agency
- 13 with a specific focus on pyrolysis;
- 6 focussing on solvolysis (2 methanolysis, 2 glycolysis, 2 hydrolysis).

Note that among all inputs, 5 organisations were awarded support from the EU Innovation Fund in the area of chemical recycling.

Inputs received in confidence are not disclosed or revealed herein: where applicable, data provided has been aggregated and integrated with larger sets of publicly available or anonymised data and is no longer traceable to individual submissions. Where the granularity of individual cases is too specific (too few actors in the sector), data were mixed with broader datasets. For instance, to protect data confidentiality, we do not analyse/show stakeholder data separately for glycolysis, hydrolysis, and methanolysis.

4.3. Additional industry consultation

In addition to the direct input received above, the project team also consulted directly with both industry representatives and market analysis experts, in the context of focussed research to further investigate emerging processes or collect market data on niche or emerging product markets.

5. Cost analysis and economic viability of main chemical recycling processes

5.1. Economic viability of mechanical recycling: brief overview

Mechanical recycling is the incumbent technology for plastic recycling. We will not provide here an analysis of the economics driving the mechanical recycling of plastics, as many studies already cover the topic (Van Camp et al. 2024, García-Gutiérrez et al. 2023), but highlight a few salient points relevant for the context of plastics recycling in general:

- Mechanical recycling technologies are based on low-temperature processes (sorting, washing, shredding, extruding…) with established capital costs typical of light industrial installations. Around 2500 plastic mechanical recycling plants are in operation worldwide (ICIS 2024). In the EU27+3, a total of 850 companies have combined installed input capacities of 13.2 Mt (Plastics Recyclers Europe, 2023).
- Key cost drivers include feedstock prices (i.e. sorted plastic wastes, with very volatile prices), sourcing and logistical constraints, competition with virgin polymer, global competition (trade in recyclates) and to a lesser extent regulation and competition with fuel uses.
- Prices for mechanically recycled feedstock have been fluctuating around virgin plastic prices in recent years[67], which correlates to driving the sector in and out of profitability, since costs for recyclers are relatively constant and little dependent of the crude oil prices that drive virgin plastic prices.
- High-quality recycled polymers are typically traded at a premium (ICIS 2024), but there is strong competition from virgin feedstock and willingness-to-pay for recyclates is volatile.
- Mechanically recycled plastics hold a market share typically around 5-15% of the polymer markets, depending on resin type and location (higher demand in Europe and North America than Asia). In Europe, 17% of PET, 12% of PE and 6% of PP is of recycled origin (ICIS2024, 2023 figures).
- Emerging, so-called *advanced* mechanical recycling technologies[68] have the potential to extend the range of plastics recyclable through mechanical means while supplying higher quality (e.g. food contact) materials. Demonstration projects exist for PS (see e.g. Welle, 2023 and Ineos[69]) while challenges persist for polyolefins.

5.2. Economic viability of thermochemical liquefaction (pyrolysis and related processes)

As described in section 2.3.1, thermochemical liquefaction consists of high-temperature decomposition of plastic waste feedstock in the absence of air (pyrolysis), and occasionally in the presence of

[67] See for instance Uekert et al. (2023), supporting information S12.

[68] Advanced mechanical recycling usually refers to mechanical recycling with additional steps to improve output quality, such as increased sorting and washing. This has been demonstrated on a small scale in particular for rigid polyolefins, although flexibles currently remain a challenge.

[69] https://www.ineos.com/businesses/ineos-styrolution/news/ineos-styrolution-recycling-solution-becomes-finalist-for-2025-plastics-recycling-awards-europe/

other elements such as catalysts (catalytic pyrolysis) or additional reagents or heat carriers (e.g. hydrothermal liquefaction).

5.2.1. Process overview and scope

5.2.1.1. Background of pyrolysis processes for waste plastic treatment

Pyrolysis processes originate in the petrochemical industry where hydrocarbon processing is well-established and set up to operate in very large plants to benefit from economies of scale.

Unlike the kind of pyrolysis targeted specifically at plastic recycling from waste, such large-scale processes (oil refining, steam cracking) typically focus on narrowly-specified feedstocks and aim to extract the maximum value (from crude oil or intermediates) by producing a broad range of outputs, including fuels, lubricants, chemical precursors, which can be in solid, liquid or gaseous form, occasionally adding treatment phases to tweak the yield towards a particular product rather than another.

Optimising a process derived from oil refining towards (primarily) a narrower purpose is a relatively recent endeavour which has not yet been fully optimised: only a few specialised companies develop specific polymer-focussed technologies with the aim to increase polymer (monomer) yield. Researchers at the United States NREL (Uekert et al. 2023) actually consider pyrolysis and gasification as open-loop technologies with lower economic and environmental performances than virgin polymers overall, due to low yields and high energy requirements, with a role for fuels or other chemicals rather than plastic production (see also Fivga and Dimitriou 2018).

Note that we also include in our analysis of pyrolysis closely related processes which do integrate specific adaptations to increase the material recovery, such as hydrothermal liquefaction.

5.2.1.2. Boundaries and scope of analysed process

Virtually all consulted sources point to the fact that commercially envisaged thermochemical processes are not currently designed as standalone plastic-to-plastic operations from start to finish but should rather aim to integrate with the broader petrochemical industry, by providing mainly a process intermediate which can be integrated in the existing value chains. This allows piggybacking on existing infrastructure for which investments are usually very large and ensures an outlet for the outputs. Beyond this, as discussed below (future optimisation avenues), further process integration can also be envisaged to achieve greater process efficiencies (e.g. by heat-flow savings or co-product reuse).

- Output flow: we focus on processes which can produce as a main output an intermediate with suitable specifications to be **accepted as a drop-in naphtha substitute in steam cracking**, henceforth "naphtha equivalent" step. While several sources (Li et al. 2022, Li et al. 2023, Kusenberg et al. 2022b, UBA 2024) point to the compositional difference (sometimes significant) between pyrolysis output and virgin naphtha, the specifications allow for substitution up to an industrially viable share[70].

[70] e.g. market-research company ICIS reports data for a benchmark category of plastic-derived pyrolysis oil available in the market that can be incorporated at concentrations of up to 20%. For some processes, under certain conditions, much higher possible steam cracker concentrations have been reported, e.g. in Abdulrahman et al. (2025).

- Input flow: most processes described in literature (cf. **Table 4**) are tailored to accept as inputs mixed polyolefins (MPOs) i.e. a blend of different grades of polyethylene (PE), e.g. HDPE or LDPE, with polypropylene (PP), other plastics being considered as contaminants to the process. Different industry grades are being developed and proposed (such as the Process-ready Mixed Plastic Waste Bale specifications listed by market analysts Platts[71], typically containing around 84-90% of MPOs).

Waste plastics, however, are initially collected at best as Mixed Plastic Waste (MPW), so this is considered the initial input, as described in detail in the process analysis below. An example of MPW specifications is the set of standards for the German plastic recycling system (DKR-350).

Pyrolysis processes could also be adapted to accept a broader range of plastics (see Stallkamp 2023, Stallkamp et al. 2023, Stallkamp et al. 2024) and become more tolerant[72] to feedstock specifications but this is not investigated here as this would be reliant on even smaller volumes of homogeneous input for each process.

The model we develop below, for comparability purposes, therefore considers thermochemical processes that use MPW input as an entry point and naphtha-equivalent intermediate output as end point. Details and variations, as well as the ultimate fate of recyclates (steam cracking and beyond) are discussed under each step.

5.2.2. Thermochemical process: step-by-step process cost modelling and analysis

5.2.2.1. Cost modelling approach

The process we are analysing is well-suited for a cost analysis based on chemical engineering methods and analysis. However, for the sake of simplicity we focus only on the key elements which allow us to derive meaningful cost information for the overall process and its economic viability. Therefore, we do not use an existing commercial chemical-engineering package with a cost module but develop a highly **simplified model** capturing the essentials of the process.

The lack of detail (e.g. exact process step breakdown) is also commensurate with the uncertainty and wide variance in the data collected for these technologies, which have not yet reached large-scale commercial operation stage and therefore lack long-term, accurate and reliable data.

5.2.2.2. Description of the model and process overview

We break down the process along commonly accepted steps which recur across available literature (see among others Franke et al. 2024, CE Delft 2022, stakeholder input). Mentions of specific deviations or possible alternative routes are made in specific sections, e.g. when an innovation obviates the need for a preceding or ensuing step.

In our simplified model, we identify 9 Unit Operations (U.O.s) which we will group and model in 4 separate blocks. The 9 steps are described briefly in **Table 6** :

[71] https://www.spglobal.com/commodity-insights/en/pricing-benchmarks/our-methodology/subscriber-notes/012925-platts-proposes-european-advanced-recycling-mixed-plastic-waste-feedstock-assessment

[72] N.B. Increased tolerance to one contaminant may reduce tolerance to another (trade-off).

Table 6. Overview of thermochemical liquefaction process steps and unit operations.

Block		Unit Operation	Comment	Step input	Step output
PREPROCESSING	1	Collection and transport	Logistical sourcing	MPW	MPW
	2	Sorting	Isolation steps of desired waste plastic fractions	MPW	Mixed POs
	3	Pretreatment	Including sorting and preparation for pyrolysis, e.g. shredding or extrusion	Mixed POs	Pyro-ready plastics
PYROLYSIS	4	Pyrolysis (/ thermochemical process)	Core thermochemical decomposition process including pyrolysis or variants thereof yielding comparable outputs	Pyro-ready plastics	Raw (non-upgraded) pyro oil
POSTPROCESSING	5	Purification	To remove unwanted (non-hydrocarbon) elements (typically through hydrotreatment)	Raw pyro oil	Upgraded pyro oil
	6	Fractionation	To isolate the hydrocarbon components most suited for further processing	Upgraded pyro oil	**Naphtha equivalent** (light hydrocarbon fraction)
PETROCHEM	7	Transport	Towards established petrochem facility	Naphtha equivalent	Naphtha equivalent
	8	Steam cracking	Conventional petrochemical process step	Naphtha equivalent	Chemicals (+ fuels, etc.)
	9	Final post-processing incl. polymerisation	Conventional plastic processing	Chemicals (precursors)	Plastics

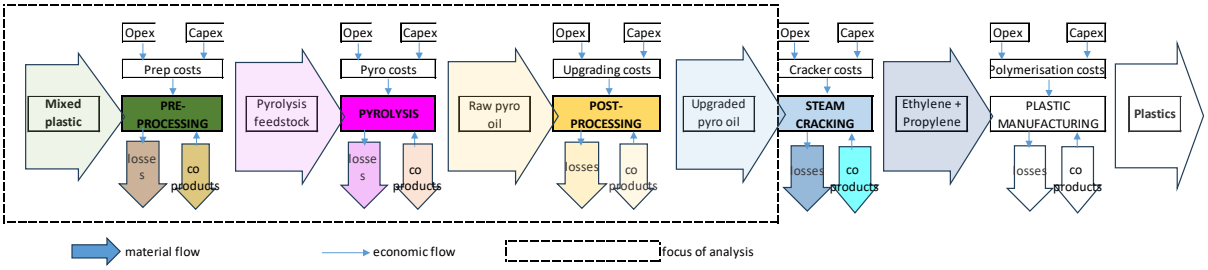
Note: MW=municipal waste, MPW=mixed plastic waste, MPO=mixed polyolefins.

Source: own elaboration

In **Annex A** we analyse each step in more detail to derive meaningful data e.g. yields and output costs from a plastic recycling perspective. Please refer to the Annex for further details and data.

The simplified flow diagram below (**Figure 6**) provides a general overview of the process with consolidated process steps (not showing individual Unit Operations). Figure 8 revisits this diagram with key cost and physical figures.

Figure 6. Overview of pyrolysis-based chemical recycling process.



N.B. the term "co-product" as used above is without prejudice to the "waste" status of the material but refers to streams that have potential market value, and are accounted for with a positive economic contribution in the model

Source: own elaboration..

Below is a summary of the main features and challenges of each process step, as further elaborated in Annex A:

- Collection:
  - Accessing dispersed plastic waste is challenging due to its diffuse origins, requiring cleaning and standardisation before pyrolysis.
  - Waste feedstock can be obtained through various procurement routes, and in the best case be obtained at zero or negative cost due to disposal regulations and energy prices.
- Transport:
  - Transport costs for waste are estimated at about 50€/t, with handling and administrative costs being significant, especially for short distances.
- Sorting:
  - Mixed plastic waste needs sorting to remove contaminants and isolate polyolefins (PE, PP) suitable for pyrolysis, with a yield of 55-75%.
  - Sorting costs range from 20-50€/t, and rejects can have positive or negative value depending on their potential for further recycling.
- Preprocessing (other pre-treatment):
  - Mixed polyolefins may require washing and physical processing to improve their form factor for the reactor, with costs comparable to mechanical recycling.
  - Preprocessing costs are around 80-150€/t, with a best-case scenario of negative cost due to gate fees, while the resulting output is valued in the range of 350-650€/t.
- Thermochemical Process (typically Pyrolysis):
  - Pyrolysis involves heating feedstock in the absence of oxygen, with variations like catalytic pyrolysis and hydrothermal liquefaction to enhance yields or energy efficiency.

- Capital expenditure (Capex) for pyrolysis facilities ranges from 1000 to >10,000€/ktpa installed capacity[73], with presently no clear economies of scale verifiable, and operating expenditure (Opex), excluding feedstock, centred around 300€/t.
- The operational yield of input feedstock to raw pyrolysis oil is around 69%, with costs for raw pyrolysis oil production ranging from 600 to over 2,000€/t.

• Postprocessing (Purification and Fractionation):

- Purification removes non-hydrocarbons and converts olefins to paraffins, while fractionation selects hydrocarbons suitable for steam cracking.
- Capex and Opex for these steps are relatively low and high, respectively, leading to an output value of upgraded pyrolysis oil ranging from 800 to 2,900€/t.

• Petrochemical Processing:

- These steps involve downstream processing of naphtha equivalent into high-value chemicals (HVCs) and fuels, with no specific analysis of cost impact due to lack of data on adaptations for pyrolysis-derived naphtha.
- The cost mark-up for pyrolysis-derived naphtha compared to virgin naphtha ranges from 500 to 1,500€/t, or a relative difference of 1.5-3 times.

5.2.2.3. Scenario modelling and assumptions

Our modelling, presented in detail in the Annex, combines input received directly from stakeholders with values obtained from literature, (academic sources, industry operators, and other/grey literature sources), to provide an evidence-backed picture of the costs that eventually determine the minimum sales price for pyrolysis-derived products.

In order to reflect the uncertainties linked to the processes analysed, the variability in the technologies used and the evolving market conditions, we consider 3 scenarios applicable to the different steps of the modelling: **current, baseline**, and **best-case**.

- **Current** assumptions capture values which appear to be already realistic today and could be achieved by operational facilities (mostly at pilot scale or early full-scale). Yields reflect performance already achievable with today's state-of-the art.
- **Baseline** assumptions capture likely values for near-term scaling-up of existing processes and technologies, not assuming any breakthrough but rather a predictable evolution and improvement of current performance towards industrial scale operation.
- **Best-case** stretches the potential performance to the limit of what could be achieved at every step given today's knowledge, assuming favourable market conditions, highly optimised processes and evolutionary technological progress. Note that "**best-case**" is a highly unlikely scenario, but is still included as a theoretical lower bound of achievable costs.

[73] The broad range indicated reflects data provided and literature data, with aberrations omitted but corresponding to various sizes of operation.

Each step is modelled along each of the 3 scenarios by adopting values that reflect the range of data collected for all relevant variables.

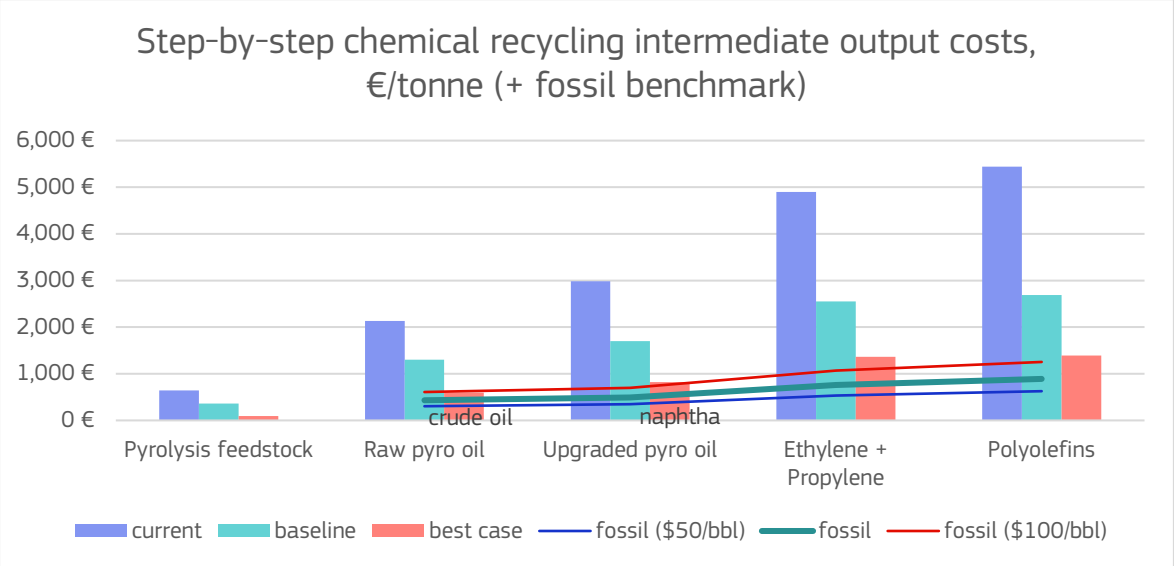
There are a number of **trade-offs** that can be arbitraged between different process steps, especially with regards to purity and specifications (see feedstock quality discussion in chapter 2). For instance, higher levels of contamination can be accepted by some pyrolysis processes. However, downstream processes would thereafter have to adapt consequently (ulterior decontamination). This also has a consequence in terms of costs: operators can elect to decontaminate at various points in the process chain, and these costs will be incurred differently (typically seeking an optimum). However, these costs will have to be allocated at some point, or the process will not be viable.

5.2.3. Cost model: results and conclusions

5.2.3.1. Summary of process efficiencies (yields) and intermediate costs

Building on the step-by-step review above, plus additional data sources and literature data, we compile the following process chain of intermediate-product costs (with a comparison to virgin-derived equivalents), shown in **Figure 7**. It should be noted that for the sake of simplicity, we do not enter into the discussion of mass-balance rules and their impacts: our simplified model is based on an assumption of standalone operation (waste plastic feedstock, not blended with fossil[74]) to reflect as much as possible the physical flows and process yields (see further discussion of this approach in section 3.4.3).

Figure 7. Unit costs per tonne of output throughout the pyrolysis process, €/t output (functional units vary).



Source: own elaboration based on own modelling.

[74] No blending assumed until the naphtha equivalent stage. Steam cracking and downwards are assumed as proportional (as if operated on 100% recycled feedstock). Note that favourable mass-balance rules in a blending scenario may somewhat improve yields by virtually reallocating some outputs, while unfavourable rules would significantly reduce the recycled amounts that can be claimed.

As can be seen, even with extremely optimistic ("best-case") assumptions and in a relatively high oil-price scenario[75], pyrolysis-derived outputs are barely competitive with virgin-derived products.

Influence of oil prices

Our modelling does not capture the likely repercussions of different external market conditions, primarily driven by variations in crude oil prices (we do picture in **Figure 7** the sensitivity to higher or lower oil prices, although in reality, also our figures for each case would themselves have to be slightly adapted).

The influence of crude oil prices on the economic viability of chemical recycling has not been extensively commented on in literature, although some sources (Closed Loop Partners 2021) mention that *higher* oil prices would bring chemical recycling *closer* to economic viability. This seems to be largely based on an extrapolation from mechanical recycling, where indeed historical data shows that recycled feedstocks become competitive against virgin in high oil price scenarios.

However, there are (at least) two antagonistic factors at play influencing the competitive landscape for chemical recycling outputs: In a low oil- (and by proxy, energy-) price scenario, the costs for feedstock for chemical recycling might be low, but Capex and Opex might be less impacted and, most importantly, prices for competing virgin products would also be low, which undermines the economics of chemical recycling. On the other hand, in a high oil price scenario, virgin naphtha and related products are more expensive and thus support higher market prices for chemical recycling outputs. However, also the market prices of plastic waste feedstock would likely be higher. Only in the case (discussed above) where feedstocks can be sourced as an alternative to disposal i.e. ideally with negative (gate-fee) prices, can chemical recyclers reap an unambiguous advantage from a high oil price.

5.2.3.2. Overall process yields and evaluation of feedstock requirements

We show the chain of process yields in **Table 7**. It shows for each processing step the relative yield, e.g. the processing of the input 'process-ready mixed olefins' into 'raw pyrolysis oil' has a yield efficiency of 65%, 71% and 85% in the current, baseline and best-case scenario, respectively. The 'reverse' quantities are the **amounts of intermediates necessary to produce 1 tonne of final recycled plastics** in each scenario. For instance, in our baseline scenario the plastic-to-plastic[76] yield is only about 30% meaning that ~3.7 tonnes of mixed waste plastics are necessary to obtain 1 tonne of recycled plastic:

[75] N.B. this analysis was carried out before the start of the war in the Middle East initiated at the time of publication (March 2026). "Fossil" central scenario reflects crude spot prices at the time ($71 Brent).

[76] Target polymer to target polymer

Table 7. Yields and quantities needed by process step, pyrolysis; different scenarios.

	Process step	PREPROCESSING	PYROLYSIS	POSTPROCESSING	STEAM CRACKING	PLASTIC PROD	TOTAL
input name		Mixed plastic waste	Process-ready mixed polyolefins	Raw pyrolysis oil	Naphtha equivalent	Ethylene + Propylene	Plastic
	current	60%	65%	85%	66%	90%	19.7%
step yield	baseline	65%	71%	90%	69%	95%	29.3%
	best-case	100%*	85%	95%	71%	98%	56.2%
	current	5.08	3.05	1.98	1.68	1.11	1.00
reverse tonnes**	baseline	3.67	2.39	1.70	1.53	1.05	1.00
	best-case	1.78	1.78	1.51	1.44	1.02	1.00

*assuming MPO as input

**tonnes of material needed at each step in the process to obtain 1 tonne of final plastic at the end of the process chain

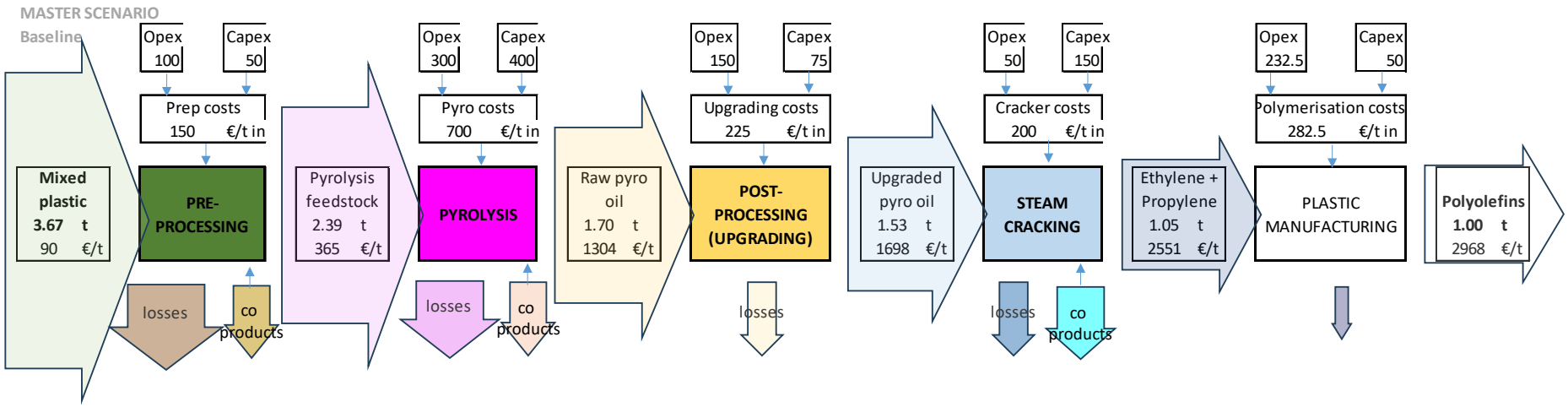
Source: multiple sources, see Annex A for details

This analysis illustrates that even in an (extremely optimistic) best-case scenario, only little more than half (56.2%) of the material is recovered as plastics, and only 29.3% in the baseline case.

As previously mentioned, the theoretical "best-case" scenario is a concatenation of best-case outcomes at each step of the process, and in practice has virtually no chance of happening in a real setting (i.e. the "stars cannot align" all at once; e.g. if a high yield is assumed at one stage, it would imply higher rejects at a further step). Also note, as a caveat, that in the general case some of the waste may also be recycled by other means, e.g. if non-polyolefin waste (PET) is sorted out as non-suitable (rejected at preprocessing stage) and is actually captured and fed into another recycling process. In that case the overall material recovery rate may increase, as a function of the material quality and actual availability of a recycling route applicable to that fraction. As a second caveat, we have chosen to start with mixed plastic waste and preprocessing as the first step. Arguably, preprocessing of mixed waste affects all plastic recycling operations, and is not inherent to pyrolysis and its technical yield characteristics. However, it is a real-world constraint and it is the relevant point of comparison vis-à-vis outside options such as incineration with energy recovery.

Finally, **Figure 8** below provides the general overview of the simplified process, with yields and costs of the key flows, illustrating in a snapshot the core principles and price evolution of materials throughout the full process; this figure is based on the central scenario (Baseline) and on physical mass flows (without mass balance adjustments)..

Figure 8. General overview of the pyrolysis process: flows, yields and costs (baseline scenario).



Source: own elaboration based on own modelling; multiple data sources, see Annex A for details.

5.2.3.3. Cost drivers, sensitivity analysis and avenues for cost reduction

A) Analysis of current cost sensitivities

The main sensitivities arising from the process analysis are:

- input costs: purity and price of the input material, preferably at zero or negative cost for the initial feedstock, but needing extensive processing.
- co-product valorisation: market fluctuation of revenues from non-target material outputs (co-products), which also compete with fossil-derived equivalents (typically fuels[77]).
- energy costs: savings can be achieved by arbitraging with external energy input to the process (influenced by crude oil prices), and by diversifying energy sources.
- plant size: like most chemical processes, chemical recycling should exhibit some economies of scale and offer the potential to reduce unit costs with larger plants. The extent of this potential is still unclear from the data collected in existing operations.

B) Future avenues for cost reduction

In the medium term the following avenues are being investigated to structurally reduce process costs:

- technological improvement: current processes are derived from mainstream petrochemical processes and can be optimised specifically to target higher plastic material yield (see e.g. Cao et al., 2024). Improvements of established pyrolysis technologies can be investigated, such as:
    - improved reaction kinetics with catalysts or plasma (see Li et al. (2022), §5.2.1 sqq., Mandviwala et al. 2024);
    - improved reaction kinetics with reagents (e.g. hydrothermal liquefaction with supercritical water, see Li et al. 2022, §6.1.2, Ozoemena and Coles 2023 and Peplow 2025);
    - optimisation of high-temperature processes by merging several process steps, e.g. also HTL, or feeding hydrogen at the pyrolysis stage as investigated in Strien et al. (2024).

At the time of writing this study, very few operators seem to be actively or openly involved in the development of novel processes or technological innovations specifically addressing the process limitations (efficiencies) of waste-plastics-to plastics pyrolysis, although there are published examples (see Peplow 2025, Mandviwala et al. 2024). However, several stakeholders contributing to the study mentioned ongoing proprietary work aimed at tackling efficiency issues and optimising material recovery in thermochemical processes.

- optimisation of process colocation (process integration): industry faces a trade-off for the deployment of pyrolysis installations to meet expected demand for chemically-recycled polyolefins:

[77] Depending on the process, some gaseous fuel outputs can be compressed and sold directly while liquid outputs can be marketed as Diesel or kerosene substitutes either directly or after further processing.

- on the one hand, standalone pyrolysis units dedicated to the production of raw or upgraded pyrolysis oil can be established relatively close to the source of waste plastics (e.g. populated areas or existing waste-sorting facilities ensuring a constant feedstock supply). This will limit the logistical costs of sourcing, however scale will be limited by the available supply. Deloitte (2022) or more recently Cao et al. (2024) reviewed existing operating facilities for plastic pyrolysis, none of which seem to exceed ~30ktpa of commercial production (it remains unclear whether larger facilities have been actually established and operated since then).
- on the other hand, larger units can be co-located with existing large petroleum-refining / petrochem plants (including cracking and hydrotreatment units), which will not only allow the installation of larger units (>100ktpa?) but also utilise already established and amortised infrastructure, and make the most of existing process flows in the facility, such as a possibility to recover waste heat to fuel the pyrolysis process and conversely feed co-products (light gaseous fractions) into further petrochemical processes where the best value can be derived (compression and storage for further sale, or integration in process e.g. cracker).

Current plans revealed by major pyrolysis companies seem to suggest a trend towards ~120ktpa scale for typical units planned in the near future, with the backing or direct ownership of large petrochemical companies, often associated with co-location at petrochemical plants (e.g. OMV announced up to 200ktpa capacity for an expansion of its ReOil process in Schwechat, Austria, coupled with a sourcing agreement based on a joint venture with a German sorting facility of up to 260 ktpa of MPW annually[78]).

Another avenue for cost reduction could be optimisation of the feedstock supply chain – this may even benefit from a public intervention for optimising collecting and sorting plants to better prepare specific feedstock as input for each recycling process.

- Scale-up and economies of scale: impact of plant size
    - Based on expert interviews, Arcà et al. (2025) suggest that the minimum plant capacity to be cost-efficient differs between the various chemical recycling technologies. For pyrolysis, the authors indicate a minimum plant size of 20 kt/y. (For gasification, minimum viable plant sizes are even higher, at 100 kt/y, but such plants can also take in other feedstock, like biomass). Larrain et al. (2020) noted that pyrolysis of mixed plastic waste with naphtha and wax production achieves break-even at 70 kt/y, whereas this threshold increases to 115 kt/y when focused on maximising naphtha production (NB a scale not reached operationally yet, to our knowledge). Roland Berger (2024a) put the scale required for the economic viability of *chemical recycling* at about 50 kt/y, without specifying a specific technology. Plans for very large plants for other technologies have been announced in the EU, e.g. a 220 kt/y solvolysis plant in France[79] and a 400 kt/y gasification plant in Spain[80].

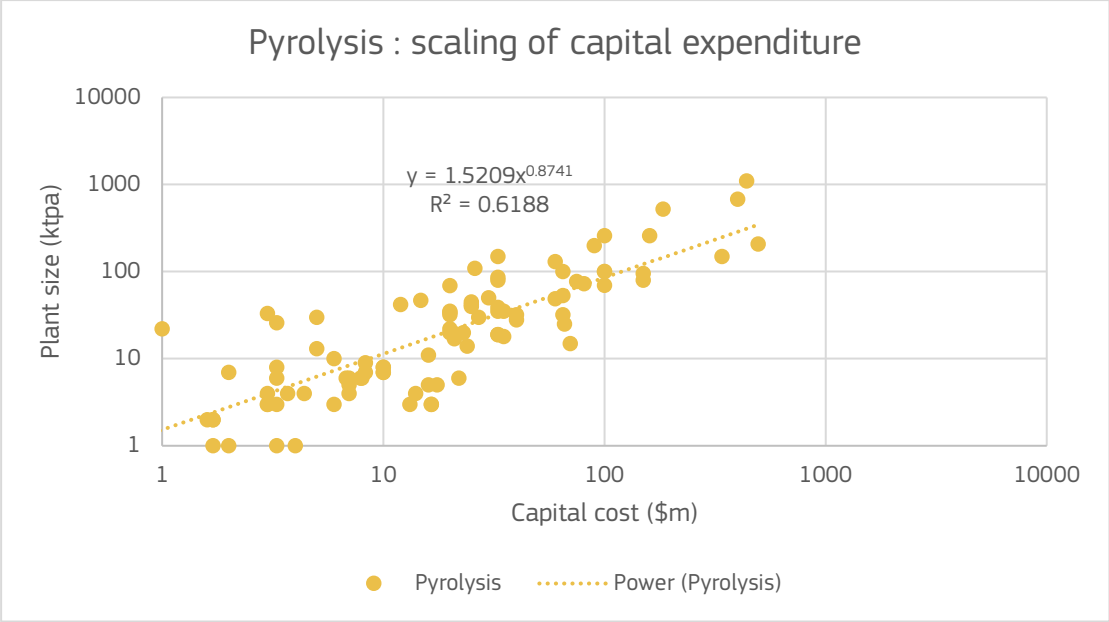
[78] https://interzero.at/en/blog/omv-and-interzero-joint-venture-for-largest-sorting-plant-for-chemical-recycling/ ; https://www.omv.com/en/media/press-releases/2023/omv-and-interzero-establish-joint-venture-to-build-and-operate-europe-s-largest-sorting-facility-for-chemical-recycling

[79] https://www.concertation-eastman-normandie.fr/project-brief.html

[80] https://enerkem.com/projects/ecoplanta

- De Tommaso et al. (2024) analysed the total capital investment declarations available on-line for various chemical recycling plants, including 105 pyrolysis (and 32 gasification) plants. As seen in **Figure 9**, the graph does not indicate any clear economy of scale, at least in terms of investment costs, with capital investment costs seemingly increasing on par with plant capacity (regression indicates a low power-law exponent of .87, meaning an 83% increase in costs for each doubling in size). However, it should be taken into account that many of the existing and announced chemical recycling projects today have been designed at a scale to assess or demonstrate technical and economic feasibility, rather than with the aim of maximising economic profitability.

Figure 9. Scaling of Pyrolysis plant capital costs



Source: Elaborated based on data from De Tommaso et al. (2024) using year 2023 USD to EUR conversion rates). Capital costs (m$) vs plant size (ktpa)

However, confidential data provided by stakeholders to the JRC suggest that unit costs, including CAPEX and OPEX, would decrease for increasing plant capacity in the future.

5.2.3.4. Fundamental cost limitations of the pyrolysis route for plastic recycling

Based on the analysis presented above in this section, it becomes clear that there are fundamental limitations to the efficiencies, and therefore unit production costs, in the pyrolysis route for plastic recycling, which may not be overcome by evolutionary improvements. We highlight the following:

- **feedstock costs** linked to the logistics of collection, sorting and preparation. The sources of waste plastics are inherently diffuse and variable, and on the other hand, the pyrolysis process is demanding in terms of feedstock specifications. Refinements of separate collection and automated sorting systems might lead to a certain improvement, but matching sourcing with input requirements will continue posing challenges in future.

- **physical limitations**: the efficiency of the pyrolysis process is constrained by physicochemical limits. Essentially, it relies on 3 (potentially 2 in the best case) high-temperature processes (pyrolysis, upgrading, steam cracking), in which material has to be heated to high temperatures (plus other lower heat processes such as melting and extrusion). A ballpark figure for the energy consumption of these processes is about 10% of the calorific value of the plastic at each step, so in theory the process cannot be more than about 70% efficient (~ 0.9^3). This value would in practice be closer to 50% with few valuable material co-products[81] and, currently, around 30% in terms of (waste)plastic-to-plastic, although complemented by the production of valuable fuels as a co-product. Even with process optimisation (see above, e.g. process integration), there is a physical upper bound to the savings that can be obtained. Additional energy-intensive steps are also involved such as hydrogenation, using hydrogen which is either energy-intensive or expensive or both.
- **energy input vs material losses**: as we discussed above, there is to some extent a trade-off between preserving the material along the process chain versus burning it to provide energy. However, in neither case does it come for free: using external energy to fuel the process does not address the fundamental energy requirements and will very likely increase costs. Instead of off-gas from the processes, it is feasible to use natural gas (probably the most common commodity option) or even coal (likely the cheapest, where viable) or electricity (potentially to reduce GHG emissions), but such external energy sources generally incur higher costs than those of self-recovered process heat or process co-product fuels (especially in an EU context). Potentially, some cheap process heat could be generated at very low cost (for instance from a thermal-solar installation on the facility), but no such project has been envisaged so far. The trade-off is therefore a loss of efficiency or an exposure to purchased energy costs.

As a consequence of the above, whether self-fuelled or fuelled externally, plastics obtained from pyrolysis will always incur a cost disadvantage vs. for instance mechanical recycling which is based on low-temperature and low-energy processes (sorting, melting). This is translated also in terms of environmental benefits, e.g. greenhouse-gas emissions from pyrolysis as reflected in various LCA studies (see García-Gutiérrez et al. 2023, CE Delft 2020, Arena et al. 2023). Öko-Institut (2022) finds that the GHG emissions from mechanical recycling are lower than those from chemical recycling by a factor of 9.[82] This is generally acknowledged by the sector (e.g. Roland Berger 2024a, Öko-Institut[83], Neste 2024), which considers that pyrolysis has to focus on a complementary role vis-a-vis mechanical recycling, with a focus on hard-to-recycle plastics (films, rejects of mechanical recycling) and the production of the highest plastic qualities, in particular food contact materials.

5.2.3.5. Overall process and output costs: comparison with literature data

In this section we provide a brief review of the published sources which provide overall estimates of the costs of outputs arising from pyrolysis, and discuss in the light of our own findings.

For the conversion of plastic waste to pyrolysis oil, the study of Lux Research (2020), which looks more particularly at North American market conditions (i.e. generally cheaper energy and feedstock

[81] e.g. Lange et al. (2024), Öko-Institut (2022), Kusenberg et al (2025)

[82] Mechanical recycling causes a total of only 0.311 kg CO2eq per kg of recyclate, while chemical recycling causes 2.91 kg CO2eq per kg (Öko-Institut 2022).

[83] https://www.oeko.de/en/news/latest-news/mechanical-recycling-is-more-climate-compatible-than-chemical-recycling/

prices[84], but also fewer regulatory mandates for recycling), estimates the production cost at 375 Euro per tonne of treated plastic waste, or 640 Euro/tonne produced pyrolysis oil, with energy representing nearly 80% of the cost. A later study (Lux Research, 2022) confirms these numbers. These figures are on the optimistic side of the spectrum in our analysis. Wood Mackenzie (2022) equally indicate that utilities, including electricity and natural gas, represent the largest part of the operating cost of pyrolysis, at around 47%. Nonetheless, these cost breakdowns only relate to the production of pyrolysis oil and not to any downstream operations.

However, our calculations presented above (based among others on confidential information provided to the JRC by industry stakeholders) put the cost of pyrolysis oil, including CAPEX, OPEX and feedstock cost, at e.g. more than twice the Lux Research value, or up to four times with conservative assumptions. The total cost figures are more in line with those from SIA Partners (2024) and Plastics Europe (2023), who concluded that chemical recycling production costs for plastics are currently about 2 to 3 times those of virgin materials (fossil-derived plastics, which in the Plastics Europe study were assumed to currently cost around 1395 €/tonne, vs. 2460€/t).

ICIS, a market intelligence company specialised, among others, in analysing the waste plastic and chemical recycling emerging market, is one of the few sources reporting regular market data on pyrolysis-derived oils. ICIS reports on raw and upgraded pyrolysis oil, as well as tyre-derived oil, with data since 2023. While there was initially wide volatility in feedstock price (ICIS 2024[85]), feedstock prices have stabilised in the past couple of years[86]. Regarding pyrolysis products, the premium for pyrolysis oil versus virgin naphtha has changed over time and pyrolysis oil prices have increasingly become decoupled from virgin values: contracts have largely shifted from a "naphtha plus" basis to "feedstock cost plus". ICIS indicates that the yearly average spread between virgin naphtha and naphtha-substitute (upgraded) pyrolysis oil remained close to its 2024 level across 2025 (~1400€/t above naphtha, or close to 2000€/t) and sharply above 2023 levels (+1200€/t spread or ~1800€/t); these higher values were a reflection of the tight supply for naphtha substitute pyrolysis oil and continued strong underlying demand from brands. The spread has fallen back again in early 2026 largely driven by falls in naphtha substitute pyrolysis oil prices, reflecting weakness in the overall chemicals sector, negative macroeconomics (creating higher cost-sensitivity among brands) and regulatory uncertainty around pyrolysis oil counting towards regulatory mandates (now partially clarified, as highlighted in section 2.3.3.1).

Regarding a potential future break-even or pathway to economic viability for plastic pyrolysis, two studies which look towards the medium term (Plastics Europe 2023[87], Bain & Company 2025[88]) concur. Results on the current and near future view converge with our data[89], but future projections are relatively more optimistic: both expect that **cost competitiveness of pyrolysis vis-a-vis virgin, under favourable market conditions, could occur within a couple of decades**.

[84] One industry stakeholder suggested typical feedstock costs for pyrolysis of 100 Eur/t in the US vs 300 to 400 Eur/t in the EU. As a reason he pointed to the greater availability of homogenous pre-consumer plastic waste in the US.

[85] see slide 36 in particular

[86] ICIS, personal communication

[87] see in particular Figure 22, based on Deloitte analysis.

[88] See in particular, Fig.1 of Bain & Company (2025) entitled "Chemical recycling in Europe could reach cost parity with virgin plastic production in 20 to 30 years, depending on price dynamics and other factors".

[89] OpEx reductions leading to EUR 1,800/t by 2030, down to 1,400 by 2040 and <1,200 by 2050.

5.2.3.6. Additional considerations and conclusions regarding yields and costs

In the sections above, we have identified and quoted several numbers and ranges for pyrolysis process yields, with the ensuing consequences on cost structures. Across all sources, we find a broad range of values for the plastic-to-plastic yields from thermochemical processes, from as low as 20% to almost 80%. Additional clarification is warranted regarding these yield values and their impact on economic viability:

- Current processes using established technologies would typically achieve yields in the low end of the range (25-40%). However, these processes generally use the calorific value of some of the feedstock to provide process heat, therefore limiting costs for energy that would otherwise need to be supplied in addition to the feedstock, as well as allowing integration in established processes.
- In the near-term, it is likely that process optimisation, integration and upscaling may bring these established processes closer to theoretical limits, e.g. in the 40-50% range.
- **Further improvements in material yield** can be achieved by extracting more target material from the fractions which are not directly suitable for e.g. steam cracking, as described e.g. in Kusenberg et al. 2025 where heavier fractions can be postprocessed (in fluidised catalytic cracking or delayed coker, in that example). This could theoretically increase yields to the 50-60% range and beyond (77%, ibid.), which we also retain in our best-case scenario. **However**, this postprocessing also **comes at a cost** and implies additional (external) inputs in terms of energy (and therefore costs and, potentially, carbon emissions too) as well as extra process units, catalysts, etc., driving up both Capex and Opex. This is described in Lange et al. (2024 – see supp. info) where such a yield improvement (from ~50% to 78%) would require **50% more energy**. Since this energy is likely to come from carbon-based sources as a benchmark (e.g. natural gas) there will be diminishing returns in terms of the carbon spent as fuel to recover carbon contained in polymers to be recycled. As an extra refinement, *decarbonised* (e.g. renewable) energy could then be used for this external energy input to mitigate the increased carbon footprint, but this is likely to **drive costs up** even further.
- Theoretically, it could be conceivable that this logic would be pursued and that close to 100% of the carbon content of hydrocarbon feedstock *could* be recovered as material[90] (through pyrolysis or gasification, followed by a range of known organic-chemistry processes such as purification, upgrading and reforming). However, the required energy use (as well as associated costs and overall carbon emissions) would, arguably, become extremely high. As is the case for fossil fuel extraction, the "carbon recovered on carbon invested" is set to reach a limit which makes it uneconomic. It is therefore important to focus not on the range of yields that is *physically achievable*, but that is economically realistic in current value chains, with sensible environmental impacts. This has led to the determination of the scenarios we analysed.

In addition, note that the yields considered in the report are premised on a (waste) plastic composition which is polymer-rich (only a few % of non-polymer content in plastic). While this applies to most packaging materials, extending the outlook to a broader range of plastics (e.g. automotive plastics, in the perspective of compliance with the new Regulation on circularity requirements for

[90] Some state-of-the-art recovery and upgrading solutions, such as Rewind MAX™/Rewind MIX™ from Axens, claim overall yields close to 100%.

vehicle design) would require a reconsideration of the distinction between plastic and polymer yields, where **non-polymer** components (fillers, plasticisers, dyes etc.) can make a significant (up to 30%) portion of the plastic feedstock.

5.2.4. Conclusions regarding the economic viability of pyrolysis for plastic recycling

Based on our analysis presented above, we highlight the following main takeaways regarding the economics of waste plastic pyrolysis:

- In the best case, yields could theoretically achieve over 50% plastic recycling; although in current practice, the process typically converts only about 1/3 of plastics back to plastics or other high-value chemicals; 1/3 is lost as heat or material losses and another 1/3 is used for fuels production (see among others Li et al. (2023); Kusenberg et al. (2022a); Ma et al. (2023))[91]. Further optimisation of the process from this baseline could be implemented to increase material yield, decrease losses and reprocess outputs that would normally end up as fuels; however these yield improvements come at an energy and operational cost.
- Its relatively low material recycling yields, in combination with significant feedstock and energy costs, imply that chemical recycling via **pyrolysis does not achieve cost parity** with mechanical recycling or virgin plastic production. The excess costs must be recovered by price mark-ups justified by added value in terms of quality, e.g. food grade outputs, or legal compliance.
- Our analysis indicates that with the current state of technology and industrial processes, using chemically-recycled waste-plastics as a feedstock for polymer production (taking naphtha-equivalent as a benchmark) results in a naphtha-equivalent intermediate that is in the range of **1.5 to 3.5 times more costly to produce than virgin**-derived feedstock, and is expected to remain substantially more costly for the foreseeable future. Note that this implies differences in recycled plastic market prices in a similar range.
- Absent any substantial technological breakthrough, the cost fundamentals outlined above are set to remain valid and cost improvements based e.g. on incremental process improvements, economies of scale or efficiency savings are not expected to fundamentally alter the economic viability of thermochemical liquefaction processes, at least not in the short- to medium-term.
- However, it cannot be excluded that in the longer term, dedicated R&I investments in technological improvements (catalysis, process conditions, and other process efficiency breakthroughs) that are specific to material recovery from the thermochemical decomposition of waste plastics with a target on high-value hydrocarbons, will enable cost reductions that would make pyrolysis-derived materials cost-competitive. Hydrothermal liquefaction, catalyst development and other process improvements are some of the avenues currently explored that may deliver these required step changes in efficiency.

[91] Therefore, if these output shares continue to hold, one might argue that pyrolysis does not constitute *primarily* a recycling process, although it does yield some recycled materials.

5.3. Economic viability of solvolysis

The technologies considered here are chemical processes where polymers are broken down into oligomer or monomer building blocks, by means of a solvent. Most prominently, these are technologies such as glycolysis, methanolysis, hydrolysis, including sub-variants like partial solvolysis or enzymatic solvolysis or others. The feedstock of these technologies are condensation polymers, like waste PET bottles, polyester rich textile waste (clothes, home textiles, etc.), and Polyurethane (PU) waste plastics (foams, car-seats, etc.). With chemical recycling by solvolysis, these waste plastics can be recycled back into new raw plastics of virgin–equivalent quality, e.g. rPET for new food-grade bottle packaging, recycled polyester etc.

The production process can roughly be subdivided into 5 stages:

1 - feedstock collection or acquisition

2 - feedstock pre-treatment

3 - depolymerisation

4 - purification (filtration, distillation, cristallisation)

5 - repolymerisation

In some studies and industry publications, steps 1 and 2 might be merged into one; similarly, step 4 might sometimes be classified as part of a more general step 3 'depolymerisation'.

Although different sub-variants of solvolysis exist, they will not be discussed systematically one-by-one in terms of their economic viability. This is the case, on the one hand, for the sake of keeping the length of the analysis manageable, but also, on the other hand, because data limitations (gaps, confidentiality issues) would arise. However, we will comment occasionally on characteristic differences between the most prominent sub-variants, e.g. glycolysis and methanolysis.

Finally, chemical recycling technologies are still young and constantly evolving, with new sub-variants or hybrid approaches still appearing (e.g. with use of microwaves, of enzymes, with partial depolymerisation etc.). Even within the specific technology of, e.g., glycolysis, individual facilities can have special features that make them one-of-a-kind, which means that they are not necessarily more comparable between each other than with those of, e.g., hydrolysis. This might change in the future, when certain technologies, after reaching a state of consolidation, could become licensed, standardised, and more widely employed.

As mentioned before, for solvolysis technologies the material recycling yield can be relatively high, with some processes reporting numbers as high as 90% and above on pre-treated feedstock[92]. Therefore, the input capacity of such facilities is, as rough approximation, similar to the output capacity. The business model of solvolysis facilities is generally to focus on recycled PET or polyester production - or their direct chemical precursors like PTA, BHET or DMT - as core business, different from conversion technologies (pyrolysis, gasification) which often follow a co-production business model, i.e. producing various marketable outputs, geared towards maximization of the joint value. Compared to the latter, solvolysis is still less commercially established, with only a handful of facili-

[92] (N.B. the inclusion of pre-treatment yield should be taken into account when comparing yields between different processes.)

ties being operated at the time of writing, and none at a fully industrial scale (e.g. Moreno-Marrodán et al. 2024, Parida et al. 2024). Among them, the majority focusses on recycling packaging and fewer – only 30 kt total capacity in the EU (Systemiq 2025) - on textiles recycling.

In terms of per unit production cost, operational (OpEx) and capital (CapEx) expenditures are typically considered separately. The most relevant OpEx items in solvolysis, based on inputs received from stakeholders and reviewed studies, are the following:

- Feedstock (plastic waste, e.g. rejects from MRF or mechanical recycling; waste textiles…)
- Chemical agents (solvents, catalysts, enzymes…)
- Labour
- Utilities
    - energy: electricity and/or natural gas
    - water, steam
- Maintenance
- Waste management (e.g. disposal of unmarketable or hazardous co-products)
- Transport
- Overhead / other

Detailed numbers are presented further below, but in general terms it can be said that the absolute amounts and relative shares of each OpEx item vary considerably between specific solvolysis technologies and facilities. E.g. some technologies might use relatively costly enzymes or other chemical agents, which on the other side might reduce energy costs by allowing to operate at lower temperatures and shorter timescales.

Overall, feedstock costs are one of the most or *the* most important cost item. E.g., Uekert et al. (2023) indicate that between 28% and 53% of the computed Minimum Sales Price (MSP) of the recyclate is represented by the costs for PET flake input. This also reflects the fact that suitable feedstock for solvolysis must be polyester-rich (typically 90% or higher), with higher feedstock prices commanded by feedstock with higher purity. On the other side, the business model of a given facility might include on-site sorting and pre-processing to produce its own feedstock flakes, in which case the nominal costs for buying low quality PET waste feedstock (e.g. mechanical recycling rejects) might be zero or even negative.

Next, the costs for the solvent can be very high for specific solvolysis technologies: according to Lux Research (2020) they represent over 60% of total costs (>800 USD per tonne of treated plastic), while Wood Mackenzie (2022) reports that catalysts and chemicals make up 73% of the total operating cost (note that both sources refer to a north American market context). Equally variable between different technologies and potentially very significant are energy costs, especially in the EU context where unit energy prices (natural gas, electricity) tend to be relatively higher than in most other world regions.

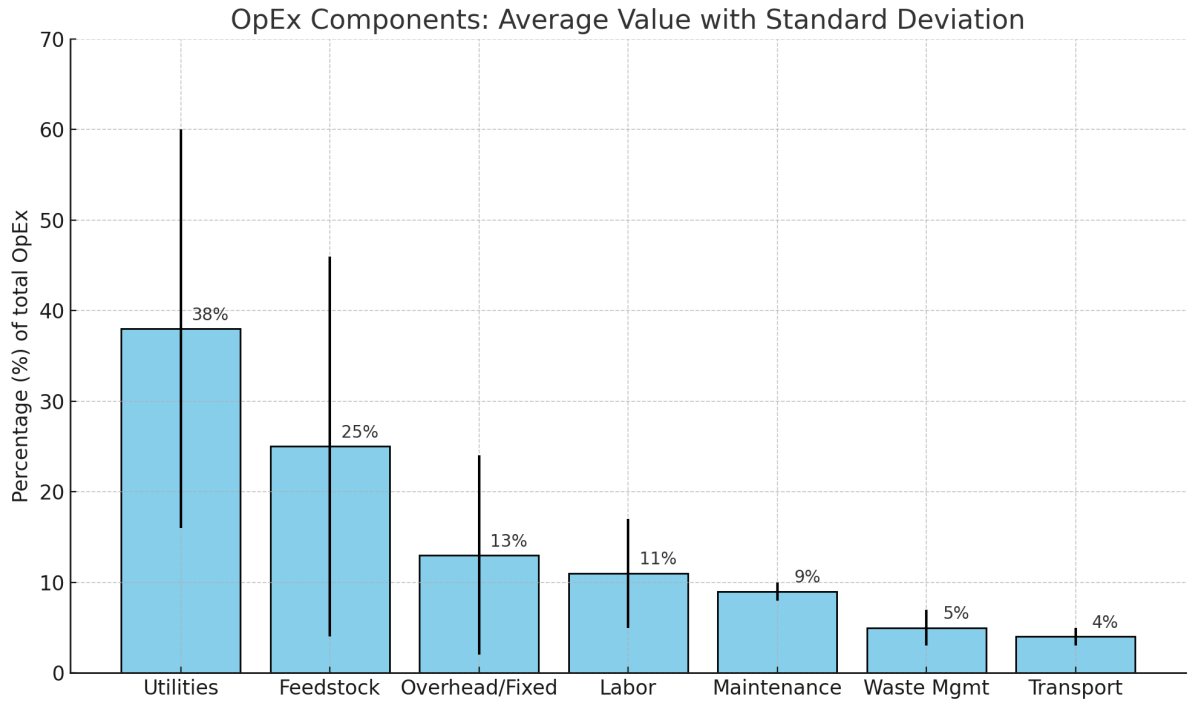
On the other side, the most relevant capital cost (CapEx) items in solvolysis are construction costs and costs for machinery. In general, capital costs have an overall lower weight in total (lifecycle) unit costs than OpEx, in the data reviewed for this study typically between 10% and 20%. That said,

plant size is still considered a key optimization parameter for economic viability, reflecting the fact that other cost items might be heavier, but also less controllable.

5.3.1. Detailed analysis of OpEx

Figure 10 shows the relative contribution of different OpEx categories to total OpEx, with average value and standard deviations. The variance is notably high, but utilities and to lesser extent feedstock costs clearly constitute the most important categories.

Figure 10. OpEx cost components for solvolysis. The thin bars denote the standard deviation.



Note: numbers do not sum up to 100% because not all facilities provided data for all cost types.

Source: own elaboration based on confidential data received by JRC from 4 EU facilities under construction. Feedstock is waste of PET packaging and, to lesser extent, polyester rich textiles. Utilities include process reagents e.g. solvents.

In this, it should be noted that the shown analysis relies on different sources, including data from stakeholders and literature, where it is not always guaranteed that cost categories are defined in the exact same way. Even when the same categories are used, there can be ambiguity as to how certain costs items should be classified. Therefore, the shown breakdowns of different categories need to be taken with a pinch of salt, recalling that the main purpose here is to highlight the most important categories.

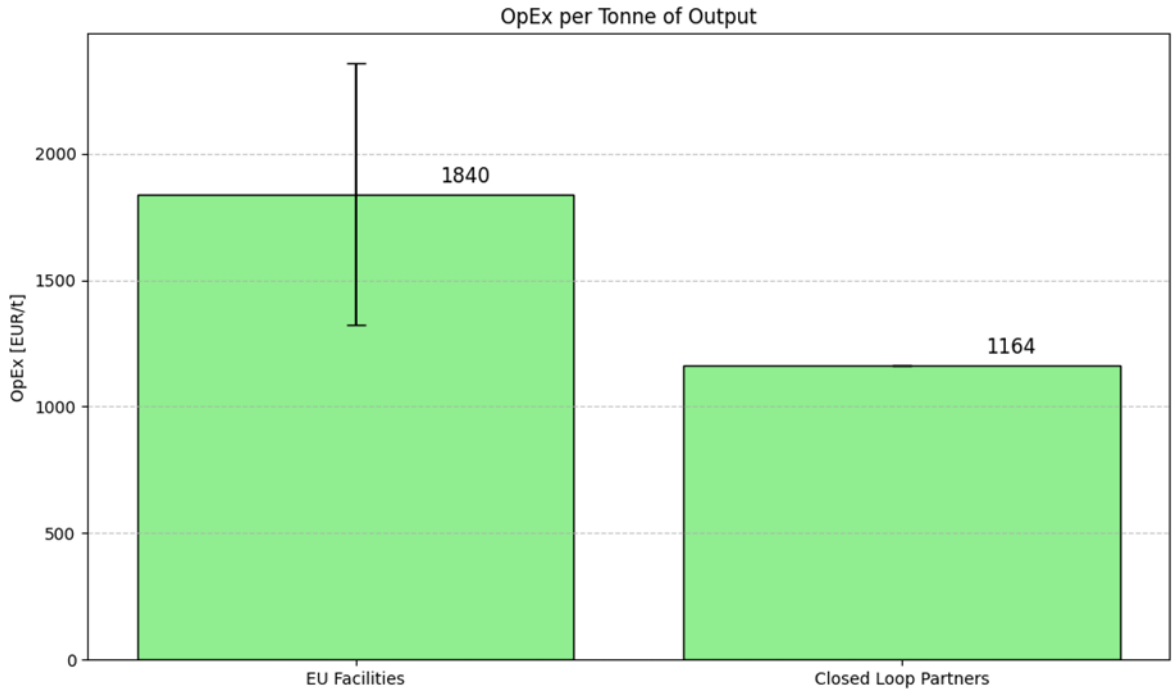
Data received from stakeholders is aggregated and only mean values and standard deviations are reported, to protect confidentiality. However, one pattern that was observed in this data is a complementarity of feedstock and utility costs, i.e. if feedstock costs make up for a lower share of total OpEx, utility costs are likely higher, and vice versa. The weight of specific items within utility costs, e.g. electricity, natural gas, or chemical agents, appears to be technology specific and may vary substantially. In fact, for technologies that use high value chemicals like enzymes, this can represent the highest single OpEx category. Such variability was also highlighted in the study by Uekert et al. (2023), who indicated that ethylene glycol represents about 21% of the total cost of glycolysis as

opposed to methanol representing only 6.5% of the total cost of methanolysis, and sodium hydroxide representing about 17% of the overall cost of enzymatic hydrolysis.

Overall, the numbers shown in **Figure 11** are also consistent with those published by Closed Loop Partners (2021) for the US/Canada regional context, namely 58% of total OpEx for utilities, 23% for feedstock, 8% labor, 8% maintenance, and 3% waste management. However, the absolute cost level, notably in the category of utilities, is reported lower in that region.

This is also reflected in the subsequent **Figure 11**, which compares estimates for total OpEx per tonne of output from different sources. The data received from EU facilities shows an average value of 1840 EUR, but with significant deviations between facilities. The corresponding value for the US/CAN context reported by Closed Loop Partners (2021) is considerably lower (e.g. due to lower feedstock and energy costs). Variations in total OpEx cost are driven by sensitivities to the costs of specific inputs, especially regarding items with a high weight in total OpEx. Notably, OpEx of solvolysis are highly sensitive to feedstock costs and quality (Uekert et al.2023, DesVeaux et al. 2024). Unit energy costs might also vary across EU regions and impact total OpEx. For example, if one assumes that around 50% of the costs for utilities represent energy, hence on average 19% of total OpEx (see previous figure), then this 19% would be the OpEx increase from a doubling of unit energy costs.

Figure 11. OpEx per tonne of output for solvolysis. The thin bars denote the standard deviation or range.



Sources: own elaboration; EU Facilities' is based on confidential data received by JRC from 4 EU facilities under construction, while the right bar is data from Closed Loop Partners (2021) and refers to a US / Canada market context (numbers are converted from USD figures with 1.18 USD/EUR, the exchange rate at that time).

In terms of differences between solvolysis technologies, academic studies and other literature suggest that methanolysis is typically more energy intensive than glycolysis, but can offer higher tolerance to feedstock impurities, e.g. in the presence of (non-target) bio-based plastic such as polylactic

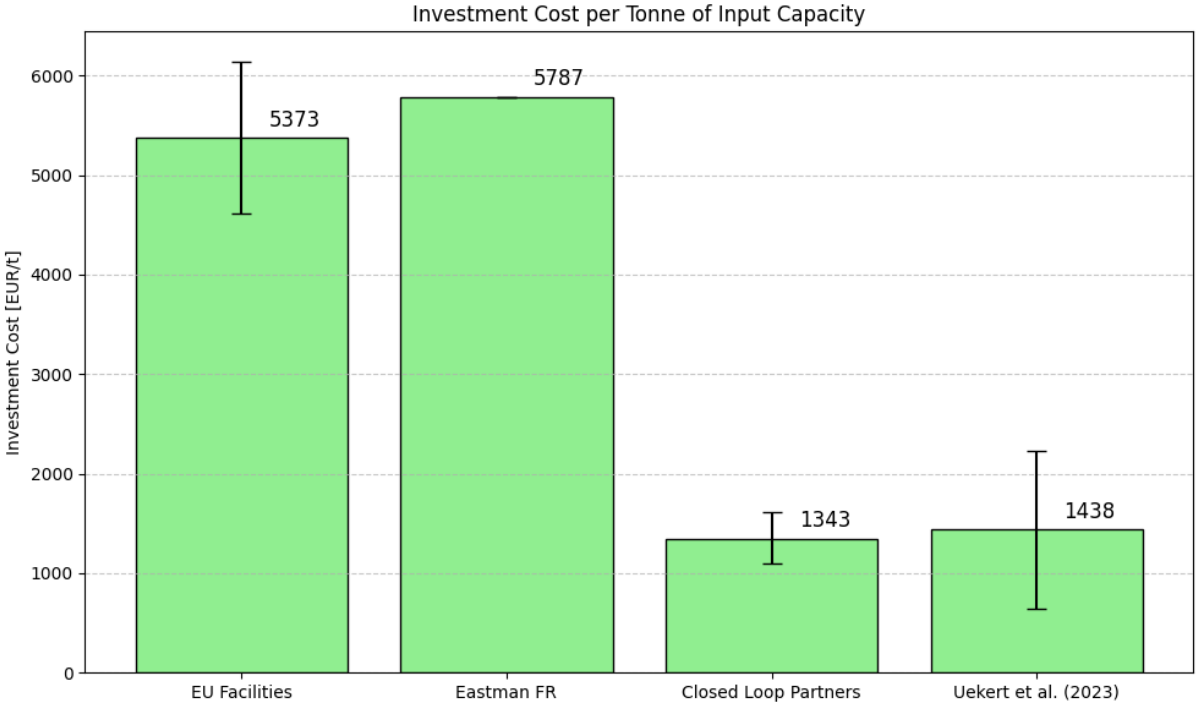
acid (PLA) and polybutylene adipate terephthalate (PBAT) (Tullo 2023, Uekert et al. 2023, DesVeaux et al. 2024, Babaei et al. 2024).

5.3.2. Detailed analysis of Capex

Generally, CapEx can constitute an important item in solvolysis economics. E.g., DesVeaux et al. (2024) indicate that for an advanced mixed polyester methanolysis process, capital costs are the second most important contributor (28%) to total costs, after feedstock costs. Still, in general total CapEx tend to be significantly lower than total OpEx.

Available reported numbers may refer to capital costs associated with solvolysis in different ways. E.g., one way is to quantify the initial investment costs, normalised per tonne of input processing or output production capacity (the latter two are not too different for solvolysis). Another is to consider life-time capital expenditure normalised to life-time output.

Figure 12. Investment costs for solvolysis. The thin bars denote the standard deviation or indicated range.



Note that the report of Closed Loop Partners (2021) and article of Uekert et al. (2023) refer to a US / Canada market context (shown numbers are converted from USD figures). The former also reports an outlier value that would have increased the average to almost 2000 EUR/t if it had been included.

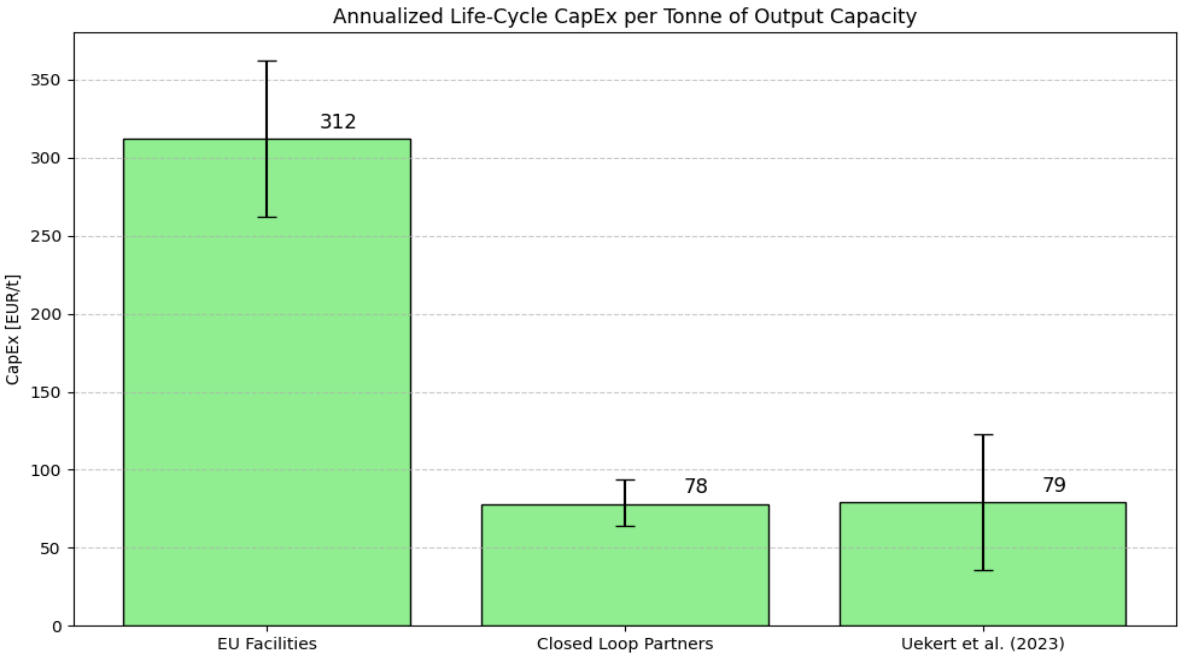
Sources: own elaboration ; 'EU Facilities' is based on confidential data received by JRC from 4 EU facilities under construction. 'Eastman FR' refers to public reporting for the envisaged plant in Port-Jérôme-sur-Seine, France (Tullo 2023).

In **Figure 12** we report numbers found in published studies and from stakeholder inputs received for the purpose of this study. They refer to investment costs per input capacity, which is a common way of representing capital costs. Values reported for Europe are typically above 5000 EUR per tonne of capacity, and possibly exceeding 6000 EUR, as also suggested by e-cube Strategy Consultants (2025). On the other side, the two studies that refer to the US / Canada context indicate con-

siderably lower figures in the range of 1500 to 2000 EUR (but note that some uncertainty is associated with the necessary conversion of USD into EUR). Overall, these figures are in line with a *global* average of around 3000 EUR implied by the data collected in De Tommaso et al. (2024).

For an assessment of economic viability, it is also informative to analyse the capital costs per tonne of lifetime output, i.e. the total capital expenditure distributed over some 20 years of expected plant lifetime, divided by the annual output of the main product, here recycled PET or polyester (or a direct precursor). This number, albeit still approximate, can then be used to derive an estimate of total unit costs, and eventually for a comparison with market prices.

Figure 13. Capital expenditure per tonne of output capacity for solvolysis. The thin bars denote the standard deviation or indicated range.



Note that the report of Closed Loop Partners (2021) and article of Uekert et al. (2023) refer to a US / Canada market context (numbers are converted from USD figures). The former also mentions an outlier value that would have increased the average to 114 EUR/t if it had been included.

Source: own elaboration ; 'EU Facilities' is based on confidential data received by JRC from 4 EU facilities under construction.

Following **Figure 13**, per unit CapEx in the EU are found to be slightly above 300 EUR per tonne output, with typical deviations of ±50 EUR. In line with previous figures, these costs appear to be significantly lower in the US and Canada market context, with two studies suggesting typical values of below 100 EUR.

5.3.3. Total unit costs

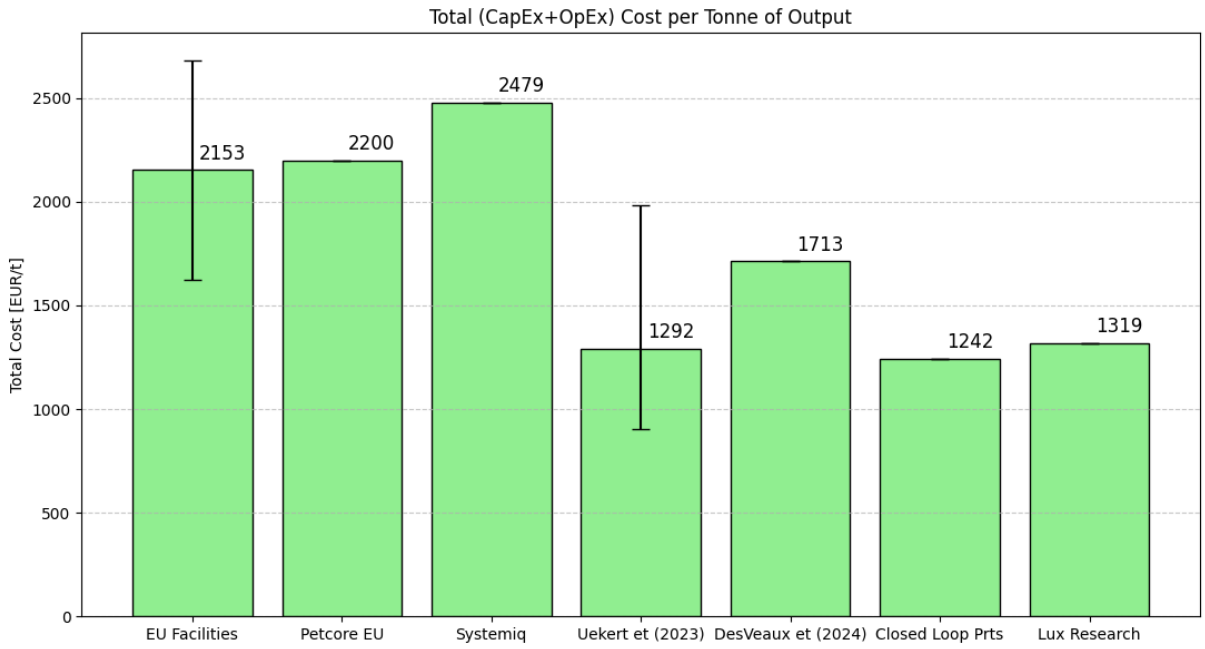
Adding up OpEx and CapEx allows to report total unit costs in **Figure 14**, here including also additional data points from studies that only indicate total unit costs without further breakdown. Only the three leftmost columns refer to the EU context. They suggest average values well above 2000 EUR per tonne (we take 2150 EUR/t, from the EU facilities, as indicative average value), with typical deviations of around ±500 EUR. This contrasts with those values referring to the US / CAN market context, which are all below 2000 EUR and not far from 1000 EUR. Another difference between

these two regions is that Capex represent on average about 15% of total costs in the EU, and markedly less than 10% in north America.

Note that the highest of the US / CAN numbers, from the study of DesVeaux et al. (2024), refers to a special scenario of recycled polyester output and in which the feedstock contains a significant share of bioplastics, which both increase costs. Likewise, the estimate of Petcore (2024) refers to a fibre-to-fibre polyester recycling scenario, in which the stage of repolymerisation and spinning accounts for 300 EUR (the others: 500 EUR collection/sorting, 600 EUR preprocessing, 800 EUR depolymerisation). In general, fibre-to-fibre recycling incurs higher costs and is therefore found at the higher end of the solvolsis unit cost estimates (Systemiq 2025).

This contrasts with numbers referring to the case of rPET production from plastics that are rejects of mechanical recycling or similar, not containing bio plastics, and which may define the end point of the process already at precursor products like PTA, DMT, BHET, or styrene monomer.

Figure 14. Total costs per tonne of output for solvolysis. The thin bars denote the standard deviation or indicated range.



Note that the reports of Closed Loop Partners (2021) and Lux Research (2020), as well as the articles of Uekert et al. (2023) and DesVeaux et al.(2024) refer to a US / Canada market context (shown numbers are converted from USD figures).

Source: own elaboration ; 'EU Facilities' is based on confidential data received by JRC from 4 EU facilities under construction, Petcore EU from Petcore (2024) and next Systemiq (2025).

5.3.4. Comparison with market prices

How do total unit costs of solvolysis compare to market prices of virgin equivalent products? In the absence of regulatory support and green premiums, a necessary condition for economic viability would be that they are lower, in order to generate sufficient margins for an entrepreneur to engage in this activity.

Relatively recently, meeting this condition was seen as possible in the **US / CAN market context**, where according to the modelling study of Uekert et al. (2023), both PET glycolysis and vapor methanolysis undercut the costs of virgin plastics production. The same study team also modelled the costs of recycled polyester production, finding that methanolysis and glycolysis exhibit lower costs than virgin polyester manufacturing (DesVeaux et al. 2024). Note that these results should be taken with a grain of salt, as they are based on theoretical modelling of technical costs, abstracting from on-the-ground business needs, e.g. long-term feedstock availability.

Reflecting this, a study performed by research and advisory firm Lux Research (2022) also suggests that production costs of PET solvolysis are below virgin market prices. However, the expected gross margins of around 100 USD per tonne are deemed critically low. An improved business outlook is expected only in the mid-term future, when further consolidation would increase margins to around 270 USD per tonne of treated plastic.

Closed Loop Partners (2021) is a US investment firm, which analysed a sample of four chemical recyclers representing different solvolysis technologies[93], again assuming US and Canada market settings with their specific prices and green premiums (e.g. rPET prices of 1900 to 2260 USD/t). Out of the four analysed cases, two technologies were found to be economically viable with internal rates of return above 20%, while the other two showed insufficiently low or even negative internal rates of return. The study emphasizes the indispensable role of sufficiently high green premiums – 10 to 15% is suggested – to achieve economic viability of solvolysis.

Hence, recent academic and corporate studies referring to north American market conditions suggest that at least some types of solvolysis technologies could be economically viable, even in the absence of legislative obligations to use recycled plastics.[94] However, **two important caveats** must be considered, which may explain why, despite these apparently favourable conditions, a greater number of chemical recycling facilities has not been established in North America, and why the direct applicability of these findings to the current EU context may be limited. First, these studies are mostly based on market conditions as observed during the years 2021 to 2022 (or before). For historical standards, these years were characterized by a very high level of virgin plastics prices, followed by a marked downturn of the market in more recent years. In fact, the company Eastman built the world's largest methanolysis plastic recycling plant during these high price years in the US, while plans for an additional US plant were put on hold.[95] Second, the positive view on low costs and economic viability needs to be weighed against the fact that all of the cited studies are based on model projections (Uekert et al. 2023, DesVeaux et al. 2024) or pilot / early commercial stage installations (Closed Loop Partners 2021).

More recent analysis and data obtained for the **EU context** generally suggest that the unit costs of chemical recycling (but not of mechanical recycling) are higher than the prices of virgin equivalent products, as shown in **Figure 15** e.g. Sia Partners (2024) assert that the "purchase price of chemically recycled resins remains too high to address the mass market (2 to 3 three times virgin materials' prices)." Similarly, Systemiq (2025) asserts that chemically recycled polyester fibre is 2.6 times more expensive than virgin products. EU business models, hence, rest on the assumption that some

[93] Including glycolysis, enzymatic solvolysis, microwave assisted hydrolysis.

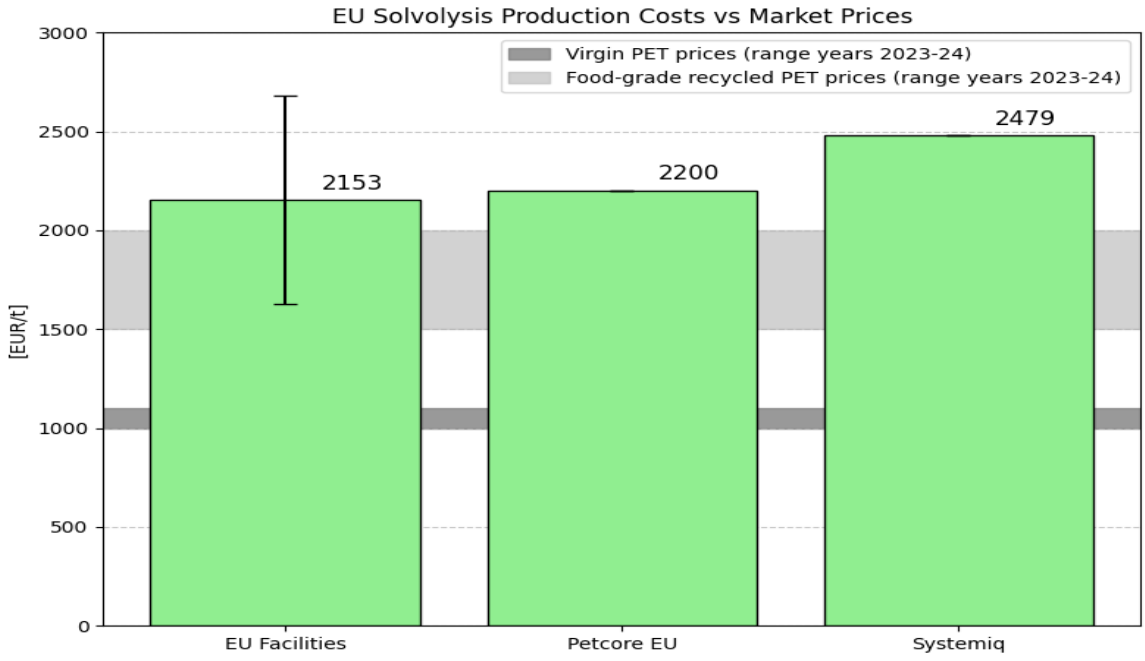
[94] At the same time, there seems to be agreement that the unit costs of solvolysis are around 1.5 to 3 times higher than those of mechanical PET recycling (Uekert et al. 2023, Lux Research 2020).

[95] https://resource-recycling.com/plastics/2025/08/01/eastman-to-delay-texas-plant-appeal-loss-of-doe-grant/

market players are willing to pay a significant green premium on top of what would be the price for the virgin product.

Reflecting this, EU solvolysis companies consulted as part of this study view prices for their recycled (food grade) PET of above 2000 EUR per tonne, even up to 3000 EUR, as necessary for economic viability and further capacity investments. This implies a green premium of between roughly 500 EUR and up to 1500 EUR per tonne. In general, this same order of magnitude is observed in market price analysis available from ICIS, who reports price spreads between recycled and virgin plastics mostly in the range of 400 EUR to 1200 EUR per tonne (ICIS 2024). However, as **Figure 15** shows, recent EU prices of food-grade recycled PET, the main product category targeted by solvolysis, were between 1500 and 2000 EUR, and thus mostly lower than typical solvolysis unit costs, and not in the '2000-plus' EUR range considered necessary for economic viability. These prices are currently determined by imports (mostly from Asia) and mechanically recycled rPET from the EU. It remains to be seen whether the increased demand for recycled plastics triggered by SUPD and PPWR will lead to a shift of market prices that is more favourable to solvolysis operators.

Figure 15. Total costs per tonne of output for solvolysis (as reported in the previous figure) and typical price ranges for virgin PET and food-grade recycled PET over last two years 2023-24



Source: Businessanalytiq.

Another measure to assess economic viability is the internal rate of return IRR achieved by a solvolysis recycling activity. According to one of the consulted EU solvolysis companies, an internal rate of return IRR of close to 9% would be seen as borderline low, but 10% as sufficient (note that also Closed Loop Partners (2021) use 10% IRR as minimum threshold of viability). However, the latter rate can currently only be achieved with the help of public financing support, according to one stakeholder, because the process is uneconomical on its own.

5.3.5. Future cost reductions, incl. from economies of scale

Stakeholders and studies agree that further consolidation and maturity of the solvolysis sector will lower unit production costs. As of today, the sector is mostly in a transition phase from demonstration, pilot and early commercial plants towards industrial scale facilities, mostly in the 30 to 50 kt capacity range. Currently an exception, Eastman plans to build a 110 kt capacity solvolysis plant in France and even announced plans for a subsequent additional expansion.[96] Overall, cost reductions are expected from technology improvements, economies of scale, and increased operational efficiency from learning by doing.

The industry organisation Plastics Europe (2023) makes a general projection that OpEx is likely to decrease by about -33% over the next two decades, as an average across all thermal and depolymerisation technologies. Similarly, Lux Research (2022) projects a unit cost reduction for solvolysis specifically in the US / CAN context, though only of around 50 USD/t. Finally, Systemiq (2025) assumes a 15% cost reduction from economies of scale and learning effects as reasonable.

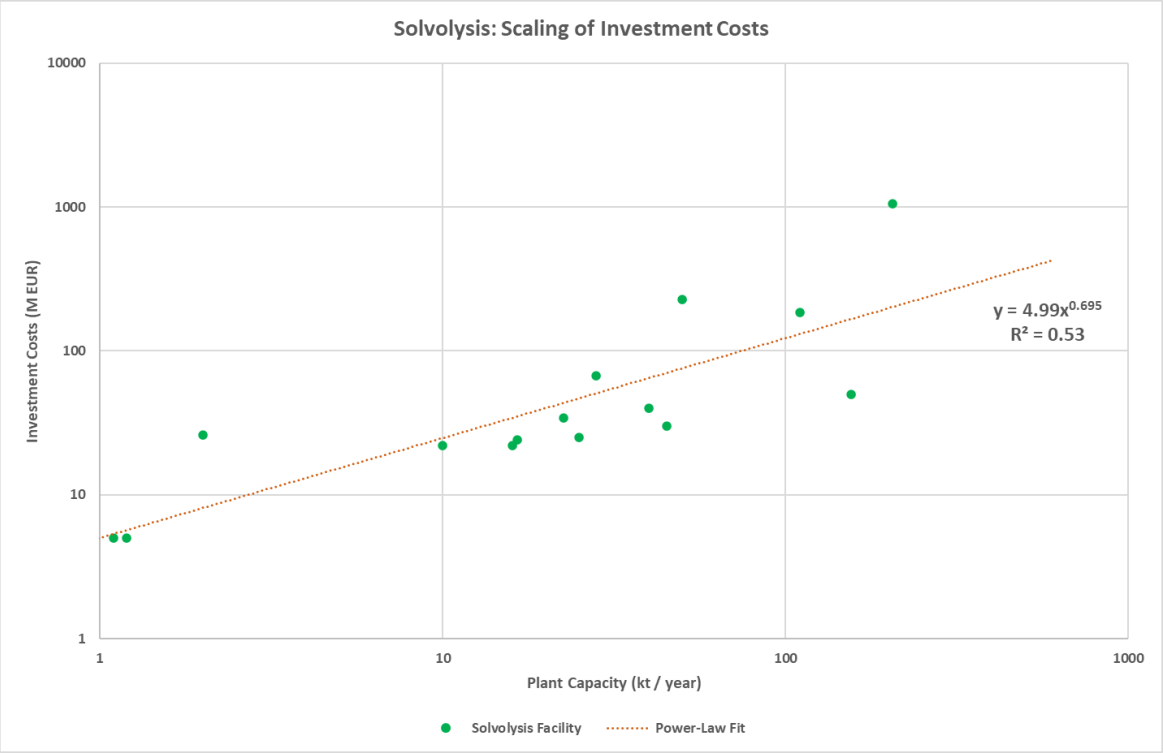
Processing capacity, i.e. size, is one of the most mentioned factors that can contribute to cost reductions. The academic study of Uekert et al. (2023) simulates the cost impact from using a smaller (18 kt) or larger (110 kt) capacity than the one assumed in the central scenario (55 kt), and find that "[p]lant size has a large impact on MSP [minimum sales price] (+23%/−5% for enzymatic hydrolysis, +21%/−4% for glycolysis, and +16/−5% for methanolysis)." From these numbers, a capacity of 55 kt seems to be quite efficient, given that doubling this size only leads to limited additional improvements of around –5% for the minimum sales price. Similarly, Sia Partners (2024) views minimum capacities of 40 kt as a necessary condition for profitability.[97]

Finally, De Tommaso et al. (2024) collected and analysed all capital investment declarations available on-line for various existing and planned chemical recycling plants, including solvolysis. Keeping only data for solvolysis plants, they show a 50 kt average and 24 kt median capacity. As reported in **Figure 16**, a simple data regression gives a scaling exponent of 0.695, hence indicating non-negligible positive economies of scale. A doubling of capacity would on average lead to a CapEx cost increase of 62% ($2^{0.695}$) instead of 100%. However, it should be noted that this data is still scarce (15 data points, only 3 with >100kt capacity) and partially based on announcements and expectations. Moreover, many of the existing and announced chemical recycling projects today have been designed at a reduced scale to assess or demonstrate technical and economic feasibility, rather than with the aim of maximising economic profitability.

[96] https://www.eastman.com/fr/sustainability/environmental/circularity/site-locations/france-site

[97] These findings, which are also in line with the size of currently planned facilities, somewhat contrast with Arcà et al. (2025) who, based on expert interviews, suggest for solvolysis a minimum input capacity of 4 kt/y, or up to 20 kt/y for price-sensitive sectors such as packaging.

Figure 16. Total capital investment costs announced by companies worldwide for solvolysis recycling plants of varying capacity



Source: own elaboration based on data from De Tommaso et al. (2024) using 2023 USD to EUR conversion rates). Best-fit Regression line based on power-law function, yielding exponent 0.695.

Among the EU facilities consulted for this study, it is considered that even the simple strategy of replicating existing projects could achieve a 10% cost reduction, stemming equally from lower CapEx (e.g. due to learning by doing in the engineering works) and lower OpEx (e.g. from thermal integration and process optimisation).

5.3.6. Business model considerations

Economic viability is determined not only by mere process costs, but also by factors such as the possibility to forge long-term offtake agreements or feedstock supply contracts, as well as by broader market trends in demand and pricing. One consulted chemical recycler emphasised that "long-term purchase agreements for recycled PET at viable economic conditions are essential." Projected revenue streams are typically based on product sales but may also include tipping fees and/or technology licensing. Business models also vary in their reliance on short-term and long-term green premiums or subsidies.

Closed Loop Partners (2021) suggest that the highest margins can be achieved with processes that produce finished polymers (such as plastic resins) or specialty chemicals. These outputs enable access to consumer-facing end markets like packaging, automotive components, and other plastic-based products. Products from these models can command an average premium of approximately 30% over virgin polymers and are generally less sensitive to fluctuations in oil prices.

According to Sia Partners (2024), strategies to de-risk investments in chemical recycling projects often involve forming partnerships across the value chain. These include collaborations with raw material suppliers, plastic waste processors, technology providers, petrochemical producers, and end

users of recycled plastics. Such partnerships are typically formalised through memoranda of understanding, joint investments, or letters of intent, helping to secure feedstock supply and offtake agreements for the produced materials. Less common in the solvolysis field are upstream agreements with waste management companies or with refinery companies, which is more characteristic for larger-scale conversion technologies (pyrolysis, gasification). Obtaining public financial support is another option for de-risking the private investment part and seen as important prerequisite.

5.3.7. Conclusions regarding the economic viability of solvolysis

- In the European Union, the **unit costs of recycling by solvolysis are significantly higher than the prices of virgin PET and polyester.** Cost estimates received by JRC indicate a range of 2150±500 EUR per tonne, which is 1.5 to 2.7 times higher than typical year 2023/24 virgin PET prices of around 1000 to 1100 EUR/t. Current demand is primarily driven by voluntary green premiums and anticipated future market growth from regulations such as the Packaging and Packaging Waste Regulation (PPWR) and the Single-Use Plastics (SUP) directive.
- There is **considerable variation and uncertainty in the available cost figures**, as no industrial-scale solvolysis facilities existed in the EU when this study was written, but also because of real cost variations between business models (recycling MRF rejects to packaging is cheaper than textile-to-textile) and technologies. As a result, data shown here is largely based on business plans, extrapolations from pilot plants, and theoretical modelling, and is thus not fully representative of a mature business reality.
- **Utilities and feedstock costs are the most significant cost components**, though they vary greatly. Feedstock costs can even be negative in some cases. There is potential for these costs to decrease further through improved collection and sorting systems, as well as more seamless cross-border sourcing.
- **Economies of scale appear non-negligible but limited**, with most planned or under-construction industrial-scale solvolysis plants in the EU designed for capacities of between 30 to 50 kilo tonnes per annum (ktpa), with just one exception targeting 100 ktpa.
- Securing access to feedstock and **establishing off-take agreements is critical for the economic viability** of solvolysis projects. In some cases, off-takers may be directly integrated into the project structure through joint ventures.
- Availability of **public financial support can make a crucial difference** for tipping the economic viability of a new solvolysis investment above acceptable thresholds, e.g. from below to above a 10% internal rate of return.

5.4. Conclusions regarding the economic viability of the main chemical recycling processes

This chapter has analysed the fundamental cost structure and cost drivers of both pyrolysis for polyolefins and styrenics, and solvolysis for condensation polymers, in particular PET / polyester. Overall, the following key conclusions emerge regarding these two pathways:

- Technology maturity: neither pyrolysis nor solvolysis has achieved the same industrial maturity as mechanical recycling, nor has demonstrated sustainably profitable economic operation.

- Costs: both process families produce outputs that do not achieve price parity with virgin materials or mechanically recycled materials, with a production cost ratio of at least 1.5 times and typically 2 - 3.5 times that of virgin equivalents.
- Solvolysis for PET competes directly with mechanical recycling of the same polymer, but may be able to process lower-grade feedstock, like mixed materials (e.g. polycotton textiles) or rejects from mechanical recycling, thereby tapping into new markets.
- Pyrolysis for polyolefins and styrenics has the potential to produce polymers for contact-sensitive applications, currently very difficult to achieve by conventional mechanical recycling for these polymer groups.

The key takeaway is therefore that, at least based on the two families of technologies analysed here, **chemically recycled materials will remain 1.5 to 3.5 times more expensive than virgin polymers**, at least in the short to medium term. This implies that they are uncompetitive vis-a-vis virgin production or mechanical recycling from the 'hard market' perspective discussed in section 3.1. Current production levels are very limited and rely on a willingness to pay substantial green premiums within a 'soft market' setting (green premium of 100 to 200%). Without the additional regulatory demand triggered by PPWR and SUPD, a larger-scale expansion of chemical recycling would therefore be unlikely.

We explore in the next chapter the extent to which there could be a market for chemical recycling technologies in a specific regulatory context.

6. Market and regulatory aspects

In this chapter, we discuss the conditions under which chemical recycling technologies could play a role in a market conditioned by regulatory and other constraints.

6.1. Preliminary remarks concerning the regulatory setup

As discussed in section 2.3.3, regulatory requirements in the EU create a demand for recycled plastic material, in particular food-grade/contact-sensitive plastic, which can only partially be met with existing mechanical recycling technologies. Recycled polymers for some particularly delicate applications, such as recycled polyolefins for contact-sensitive packaging, are virtually non-existent today and chemical recycling could offer a pathway to bridge this gap. However, this doesn't automatically create a quasi-captive market for chemical recycling with customers willing to pay any price for its output.

In fact, chemical recycling is only one of the potential solutions vying to supply this market.

In addition, based on the results of Chapter 5, since prices are expected to remain over 1.5-3.5 times those of virgin polymers, at least in the medium term, this creates an opportunity for other materials to enter in the market (see below 6.3).

In the following sections, we therefore review the uncertainties that will affect the market setup in the coming years, and then analyse what could be a possible market evolution that could set the competitive stage for chemical recycling.

6.2. Concerns of the EU chemical recycling sector

The industry stakeholders consulted as part of this study identified several market and regulatory issues that can impact the economic viability of chemical recycling. In the following, we report on these issues, broadly in the order of how frequently they were raised. Several of these issues are also raised in the recent study on barriers to the scale-up of polyester recycling by Systemiq (2025). Further analysis would be needed to better understand their relevance and economic impact on EU chemical recycling market conditions. However, a full assessment of these issues is beyond the scope of the present study.

1) **Mass balance** determination as recently adopted in the Commission Implementing Decision on the calculation rules of recycled content, in the context of the Single Use Plastics Directive[98]. These mass balance rules are a critical economic factor for chemical recycling technologies that co-produce material and fuel outputs, with a mixing of secondary (e.g. plastic waste) and primary (e.g. crude oil or naphtha) feedstock. This is the case, in particular, for pyrolysis and the refinery-integrated channel of chemical recycling.

2) **End-of-waste** regulation. Chemical recycling stakeholders seek clarity and EU-wide harmonization for the end-of-waste status of their intermediate outputs, with a view to reducing legal risks. For instance, end-of-waste status for monomers resulting from depolymerisation or for pyrolysis oil

[98] See Commission Implementing Decision (EU) 2026/1425 of 30 June 2026 laying down rules for the application of Directive (EU) 2019/904 of the European Parliament and of the Council as regards the calculation, verification and reporting of data on recycled plastic content in single-use plastic beverage bottles and repealing Commission Implementing Decision (EU) 2023/2683

would ensure that downstream users are no longer legally considered as waste management operators needing a specific permit. Stakeholders also suggest that an end-of-waste status for certain feedstocks, e.g., pretreated and compacted plastic and textile waste, would lower feedstock costs – currently one of the largest cost items – due to unrestricted cross-border sourcing. EU-wide harmonization is also seen as necessary for fair competition on the Single Market.[99]

3) **Regulatory certainty** on how exactly non-compliance with recycled content obligations will be monitored and penalised. E.g., the PPWR stipulates that Member States establish penalties that are "effective, proportionate and dissuasive", but the exact rules are still pending. If the potential penalties are too low, some producers might choose non-compliance as the most economic strategy. This, on the other side, would put current investments into recycling capacity at economic risk.

4) **Slow development of EU secondary legislation**, e.g. on mass balance calculation rules under the Packaging and Packaging Waste Regulation, on monitoring & verification, and the scope for imports. Independent of the evident importance of the content of secondary legislation, the mere fact that ongoing delays shorten the remaining time until the recycled content targets have to be achieved, creates a tension vis-a-vis the fact that industry capacity developments need several years of lead time, up to five years according to one stakeholder.

5) **Availability of public funding** support. With the current still limited maturity of the technology and persistent market uncertainties, it is seen as necessary to obtain public financial support for de-risking private investments into new chemical recycling infrastructure. The risk-return ratios are not (yet) capital market compatible. According to Systemiq (2025, p.30), de-risking could help to reduce average capital costs of solvolysis projects from currently 17.5% to 12%.

6) The inclusion of **waste incinerators in the EU ETS** is seen as a logical step to level the playing field between competitors for EU plastic waste feedstock.[100] In other words, burning plastics for energy recovery in incinerators becomes economically less attractive if operators must pay for the greenhouse gas emissions they generate, which also reduces their buying power on plastic waste markets. This, in turn, leads to a downward price pressure on these markets and thereby could facilitate feedstock access for chemical recyclers, if they are able to process it.

7) There is uncertainty and concern about the possibility of **new and additional sustainability requirements** on recycled plastics, e.g. under the Packaging and Packaging Waste Regulation, other than just being recycled, for the creditability of recycled content.

8) There is concern of **inter-sectoral competition** for the same polymers, as different regulations simultaneously affect different sectors (e.g. automotive and packaging), but with limited compliance options (and a recycled plastic supply) which could lead to supply bottlenecks and price impacts.

9) There is uncertainty regarding the unconditional **acceptance of imported recycled plastics**. In particular, there are concerns about unfair competition (dumping) with imported low-price recycled plastics of low quality and/or doubtful or unverified post-consumer waste provenance.

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[99] Note that the JRC is currently working on end-of-waste criteria for textiles. See: End-of-waste - European Commission

[100] insofar as the feedstocks would be fungible i.e. that chemical recyclers may be able to process some incinerator feedstock, previously considered 'unrecyclable' – such as rejects from mechanical recycling – which is likely to be possible only partially.

10) Simplification of **permitting for chemical recycling facilities**. It is seen as a facilitator for a faster and more economic development (less time before assets become productive) of chemical recycling infrastructure[101].

11) Uncertainty on the use and regulation of **bio-based plastics**. Different types of bio-based plastics are seen as relevant both as a potential substitute for and competitor with chemically recycled plastics. Moreover, novel bio-based polymers such as polylactic acid (PLA) become a complicating and cost-increasing factor for chemical recycling processes when contained in plastic waste feedstock.

12) More generally, the plastics sector in the EU, including plastic recyclers as well as plastic producers (petrochemical industries) **currently face serious near-term cash-flow challenges** that preclude most medium- and long-term considerations. Businesses who face increasing difficulties to continue operating in the EU over the next months (as a combination of higher EU energy prices and competition from Asian imports, among others), with several large-scale operations such as steam crackers driven out of business, have little leeway to consider investments for compliance with targets that will come into force in 2030.

6.3. Potential compliance strategies on the targeted markets

As discussed above, chemical recycling is positioned to bridge an important gap between the demand and supply of recyclates, in particular food-grade polyolefins / styrenics and to a lesser extent condensation polymers like polyester (as mechanical recycling of PET is technically capable of meeting a large share of this demand). From the perspective of packaging producers subject to the obligations of the Packaging and Packaging Waste Regulation and Single Use Plastics Directive, we project what could be possible avenues to respond to these obligations, ideally following a lowest-cost trajectory.

Note, as a caveat, that at the time of writing, some parameters determining the implementation of recycled content obligations have not been set yet, and will influence the analysis below. These include the exact calculation rules for the amounts of chemically-recycled output that can be credited as recycled under the PPWR (notably the "mass balance allocation" discussed in 3.4.2) and what alternatives can also count (bio-based products, eligibility of imported recyclates) for some part of the legislation (Packaging and Packaging Waste Regulation, new Regulation on circularity requirements for vehicle design). More broadly, the competitive and technological landscape might evolve and put forward novel approaches.

Potential compliance strategies to meet recycled-content obligations for plastics in contact-sensitive applications (and polyolefins in particular) could therefore include (not ranked in order of cost or complexity, but loosely from the least to the most disruptive business models):

- Incorporating 'drop-in' plastic materials counting as recycled. This could include:

[101] N.B. a project by the European Commission is underway to define permitting for FOAK plants, including chemical recycling (first-of-a-kind).

    - Mechanically-recycled plastics (assuming they could meet e.g. food-grade requirements). For instance, advanced mechanical recycling[102], traceable recyclates from controlled or small loop value chains, or other innovative processes.
    - Bio-based plastics, if they are a legal alternative to mandatory recycled content levels (to be determined[103]);
    - Chemically recycled plastics;
    - All of the above could be sourced locally or imported, depending on additional requirements for local content and/or proof of origin of imports.
- Switching packaging design from one plastic type to an alternative plastic type, also subject to recycled-content obligations but easier or cheaper to source. For instance, this could be replacing HDPE by mechanically or chemically recycled PET;
- Switching packaging design from one plastic type to an alternative plastic type, not subject to recycled-content obligations (for instance compostable plastics)
- Switching packaging design from plastic to an alternative packaging material, containing less or no plastic, such as liquid packaging board, glass, paper, metal, (non-plastic) textile, etc.
- Redesign to reduce or eliminate packaging or plastic components. This could include altering product design or product functionality, e.g. de-contenting or reducing product performance (e.g. having a less strong but lighter bottle). It may also include the introduction of re-usable plastic packaging that, despite a higher unit weight to ensure durability, would result in overall reduced virgin and recycled plastic material needs thanks to multiple use cycles (e.g. re-usable plastic bottles with deposit refund system);
- Redesign to increase the incorporation of non-functional recyclates to achieve recycled content targets. This could include increasing deadweight or adding non-essential parts such as external decorations made of recycled content;
- Noncompliance. If the cost of compliance is greater than the cost of non-compliance (e.g. in the form of a fine), it might make more sense to some producers to simply pay for noncompliance[104].

In view of the present uncertainties, it is not possible to anticipate which market developments will influence the adoption of the possible avenues mentioned above, or others that may emerge, let alone model or predict market growth for specific technologies such as chemical recycling. However, it is likely that the main drivers for adoption (and parameters for uncertainty) will remain:

- Crude oil prices and other material and energy prices;
- Trade arrangements and in particular impediments to recyclate trade;
- Regulatory parameters, their scope, and the date at which they are set

[102] See for instance https://www.ineos.com/businesses/ineos-styrolution/news/ineos-styrolution-recycling-solution-becomes-finalist-for-2025-plastics-recycling-awards-europe/

[103] As per Article 8.2.c of the PPWR.

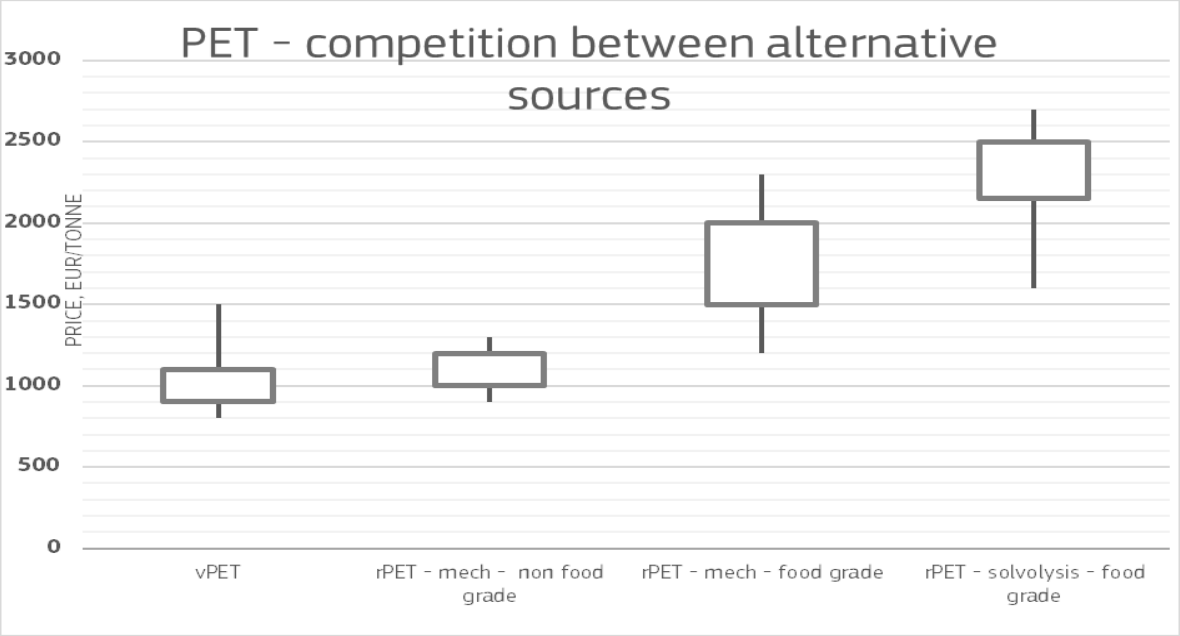
[104] Art. 68 of the PPWR calls for "effective, proportionate and dissuasive" penalties (e.g. fines) to be imposed.

– Emerging technologies and pace of innovation.

6.4. Competitive landscape for key recycled polymers

In view of the above (see e.g. **Figure 15**), below we report estimates of price ranges for chemical recyclates and potential competing technologies for the two main material types analysed in chapter 5, i.e. PET and polyolefins. Note that figures reported below combine current data and future estimates of potential costing and display a wide interval of uncertainty. They should be **interpreted as indicative** only and should not be taken as a fixed estimate of the future viability of the different technologies:

Figure 17. PET competitive landscape. vPET: virgin PET. rPET: recycled PET.

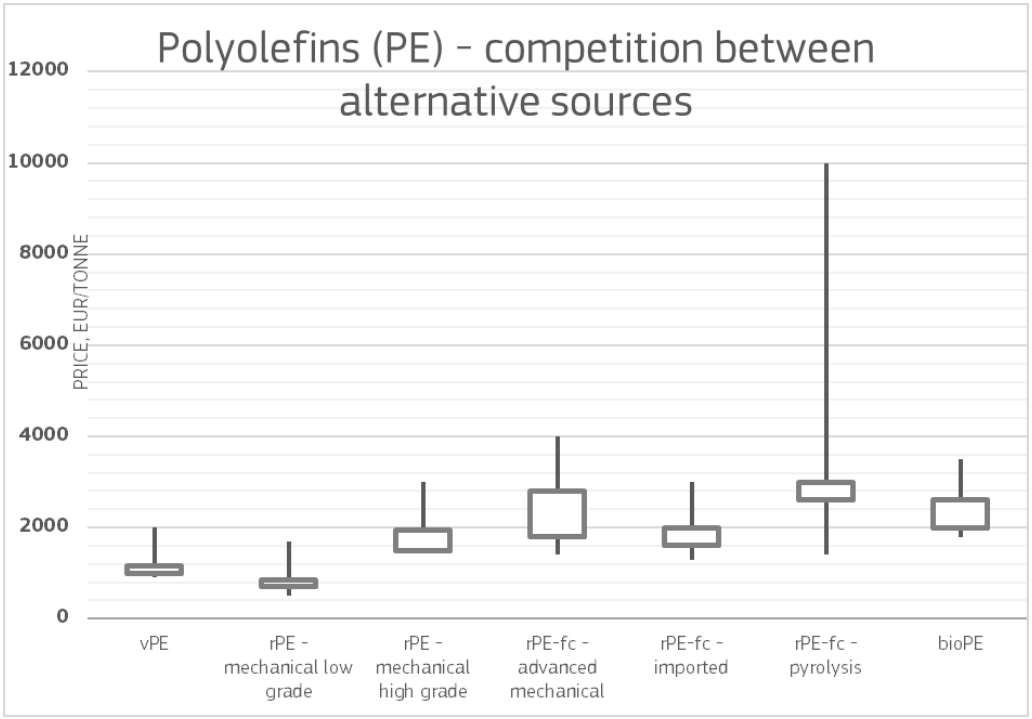


N.B.: estimated price ranges. Central box: current (2020-2025) price range. Max value: maximum observed or theoretical value. Min value: potential future (2030) price point in optimistic scenario

Sources: own compilation of data from industry sources, historical market prices (Businessanalytiq), own modelling[105]

[105] Sources include personal communication with industry stakeholders as well as unpublished reports and proprietary datasets.

Figure 18. HDPE: competitive landscape. vPE: virgin HDPE. rPE: recycled HDPE. fc: food contact.



NB: top of range for pyrolysis is premised on hypothetical, unfavourable mass-balance allocation rules (cf. §5.2.4)

Sources: own compilation of data from industry sources, historical market prices, own modelling presented in this report[106].

As the figures above illustrate, the perspective for chemically-recycled polymer prices to remain consistently high opens a wide competitive space for other technologies to enter the market and offer alternative solutions to the demand opportunity created by e.g. food-contact recyclate requirements. This means that it would be inaccurate to envisage chemical recyclates as the only category of polymers, or solutions in general, able to meet or by-pass that demand. It is likely that specific technologies will compete and contribute to meeting different market niches, e.g. advanced mechanical recycling may be able to provide some rigid polyolefin recyclates but not flexibles, while bio-based polymers will be used for other applications, etc. (see § 6.3).

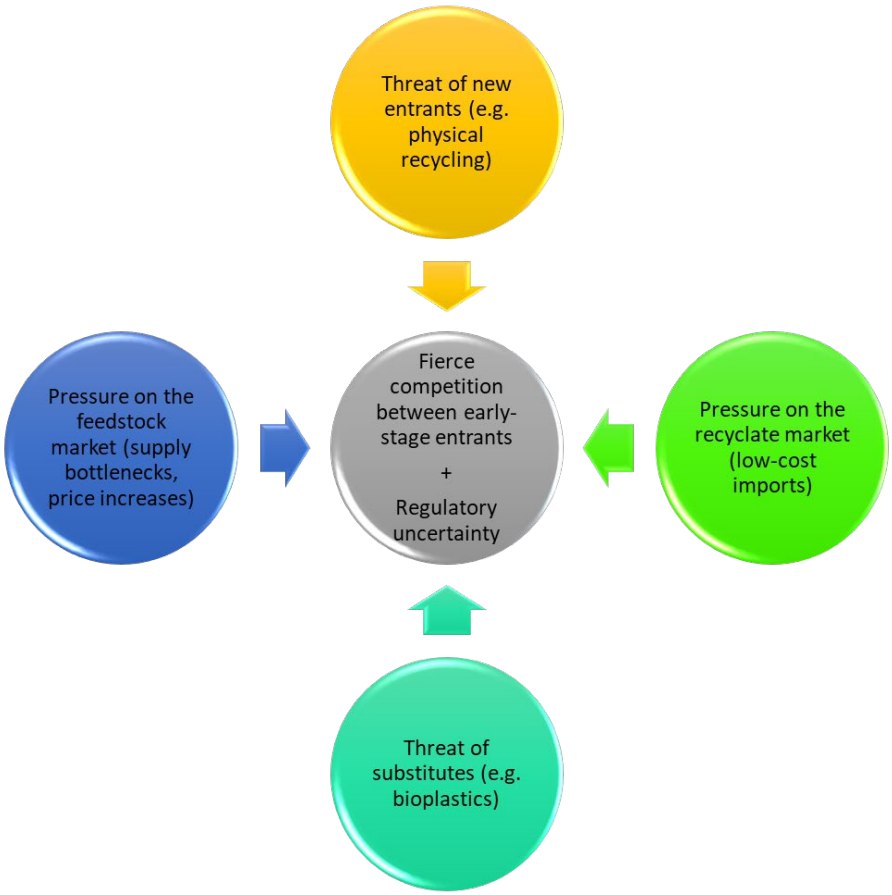
Demand for chemically recycled plastic materials should therefore not be considered as 'secured' whatever its production costs may be.

6.5. Competitive positioning for chemical recycling

In view of the above, we summarise the positioning of chemical recycling according to the "five forces" model proposed by M. Porter (Porter, 1979):

[106] Sources include personal communication with industry stakeholders as well as unpublished reports and proprietary datasets.

Figure 19. Competitive environment of chemical recycling



Source: own elaboration – adapted from Porter's five forces model

Revisiting the observations made earlier on the relative roles of mechanical and chemical recycling (see above in sections 1, 2.1, 2.3.4.1, 1), it appears indeed that the technologies could be both complementing and competing with each other, depending on the market evolution. While efforts to integrate mechanical with chemical recycling in an complementary fashion have already been announced107 (for PET or polyolefins), some degree of overlap or competition for feedstock may occur. Chemical recycling may be able to accept some rejects from mechanical recycling sorting operations. Nonetheless, the possible cost advantage for these reject fractions, which chemical recyclers can acquire at low or negative prices, is partly lost through additional energy costs and for further sorting and preprocessing. Mechanical recycling will retain a cost advantage for the feedstocks it currently processes, in particular to produce recycle for non contact-sensitive applications, but it is still unclear to what extent advanced mechanical recycling would be able to also capture a portion of the market for e.g. recycled polyolefin food-contact materials.

[107] https://packagingeurope.com/news/axens-and-sorema-partner-on-integrated-plastic-recycling-solutions/12545.article

7. Conclusions and discussion

7.1. Main findings

Chemical recycling covers a range of processes and technologies. These in turn vary on fundamental parameters, in particular the polymers they can process as inputs and outputs, the yields they can achieve and their economic performance. The two main families of processes analysed here are pyrolysis (thermal liquefaction) for addition polymers (polyolefins/ polystyrene) and solvolysis for condensation polymers, in particular polyethylene terephthalate (PET).

The potential advantage of chemical recycling technologies versus incumbent (mechanical) recycling processes is based on their ability to accept certain types and mixtures of polymers that are hard or impossible to recycle mechanically and to produce high-quality (virgin-equivalent) output materials., including for contact-sensitive applications such as food packaging. However, thermal chemical recycling technologies (pyrolysis, gasification) are co-production processes that typically achieve relatively low material recycling yields, suggesting that they could be viewed as mixed recycling/energy recovery processes rather than primarily recycling processes.

Specifically, the main characteristics identified for pyrolysis processes (polyolefins / styrenics) are:

- These high-temperature co-production processes are mostly not optimised for material recycling output: due to physico-chemical constraints, their plastic-to-plastic material recycling rates tend to be at or below 50%. For the most basic refinery-integrated pyrolysis processes, yields are approximately 1/3 material recycling, 1/3 conversion to fuels or energy recovery, and 1/3 heat and material losses.
- Material yields could theoretically be improved (to over 50% and theoretically over 70%), but at the expense of ever-higher resource (energy) use and process complexity, with unclear impacts on unit costs.
- With relatively low material yields, high energy demand and additional costs e.g. for upgrading, pyrolysis outputs for recycled plastics production are set to remain significantly more costly (over 1.4 to 3.7 times as much) than virgin equivalents.

For solvolysis processes (PET/polyester production), the main takeaways are:

- At the time of writing, several sub-variants of solvolysis are being established at pilot or commercial scale and compete with different business models (e.g. packaging vs. textile recycling). Some show higher promise for cost efficiency than others, although cost estimates differ between sources and are overall still uncertain.
- Solvolysis processes achieve high yields, with plastic-to-plastic recycling rates hovering around and above 90%.
- However, EU market conditions remain challenging for economic viability, due in particular to high energy prices and feedstock sourcing (competition with mechanical recycling), leading to cost mark-ups of 1.5 to 2.7 times compared to virgin PET.

In addition, some general comments are independent of the specific technology. They can be categorised into supply and demand side factors. Regarding the former, we observe:

- Technology maturity: neither pyrolysis nor solvolysis has yet achieved the same industrial maturity as mechanical recycling; scaled-up operations running profitably at name-plate capacity are still missing in the EU.
- Costs: both process families produce outputs that do not achieve cost parity with virgin materials or mechanically recycled materials.
- Economic viability hinges on the ability of markets to absorb this cost difference based on a voluntary or mandatory willingness to pay a cost premium for recycled plastics of virgin-equivalent quality (in particular, suitable as contact-sensitive material).
- The potential for break-through improvements in cost-competitiveness in the near to medium term appears to be limited, especially for thermochemical processes.

Regarding the demand side, we observe:

- EU regulatory obligations create market demand for recycled polymers, including contact-sensitive material, in the order of 1m tonnes per year.
- Chemical recycling is one of the technologies offering a pathway to compliance with the legal obligations. However, its significant cost mark-up opens opportunities also for other solutions to tap into this regulatory market:
    - These could include a shift from one polymer family to another; moving towards low-plastic or non-plastic materials e.g. paper composites, glass or metal; altering product design or product functionality (e.g. dead-weighting to comply with recyclate incorporation); or assuming the possible penalties for non-compliance.
    - Even within the strict substitution model, other technologies may be able to competitively provide equivalent polymers, at least for a portion of the market, such as advanced mechanical recycling, bio-based polymer production or emerging solvent-based physical recycling technologies.
- Demand for chemically recycled plastic materials should therefore not be considered as 'secured' whatever its production costs may be.

Finally, in terms of a mid-term outlook, we observe that:

- Current EU market conditions (high energy and feedstock prices, regulatory uncertainty, competition from imported polymers) create near-term challenges that hinder longer-term planning towards forthcoming regulatory obligations.
- It is yet unclear which role chemical recycling will eventually play in the market by the time regulatory constraints come into force.

7.2. Potential policy implications

In terms of policy implications and the current market situation for virgin and recycled polymers, several recyclers as well as petrochemical processors have flagged that they are currently too focused on near-term business survival to be able to engage meaningfully with longer-term planning questions related to recycled content obligations, including potential investments in chemical recycling capacity.

Based on stakeholder feedback, the root causes of the current business failures observed in the sector include

- high energy and feedstock costs;
- increasing competition from non-EU imports—sometimes associated with traceability concerns or cost advantages linked to state aid; and
- regulatory uncertainty surrounding the implementation of EU rules.

As a result, speculation regarding the ability of local (EU) capacity to meet the demand for recyclates generated by PPWR and SUPD obligations may become largely irrelevant if plastic production within the EU becomes uneconomical in the meantime and is not otherwise protected.

Regarding ongoing policy developments, mass balance allocation rules have been established for the SUPD and are currently being discussed for the PPWR, to provide clarity on the calculation of recycled plastic content derived from chemical recycling. However, stakeholders have highlighted that stringency in the calculation of the share of material creditable as recycled, adds to the high cost of recyclates and contributes to the cost gap between virgin/mechanically recycled materials and chemically recycled materials.[108] Furthermore, the rules concerning use of bio-based plastics as legal alternative to recycled plastic content remain also unclear for the time being.

Finally, in terms of broader policy and market perspectives, assuming a situation where regulatory restrictions force the market adoption of materials which are significantly more expensive than conventional (non-chemically recycled) alternatives, broader impacts on the affected value chains would have to be considered, i.e. how cost increases will be distributed along market actors, as well as the overall societal benefits of the measures.

7.3. Avenues for future research

Based on our findings, as well as the potential implications outlined in the previous section, future research could:

- Investigate the **societal costs and distributional impacts** of forcing a market to adopt more costly materials: who will foot the bill? How will costs be distributed along the value chains, between e.g. recyclers, petrochemical industries, fast moving consumer goods manufacturers, retailers, and final consumers? How will stakeholders decide on and develop short-, medium- and long-term compliance / avoidance strategies?
- Investigate (in the long-term / at system level) how the use of fossil resources can be optimised between primary fuel production, primary material production and secondary material and fuel production, based on global carbon accounting. For instance, what could be the role of recycling versus energy recovery in long-term scenarios of drastically lower fossil resource use in the EU?

[108] The implications of different scenarios for mass-balance allocation rules are outside the scope of the present report and are additional to the conclusions we present herein: however, it has to be noted that the cost gap between virgin plastic and plastic chemically recycled via the pyrolysis-refinery pathway may differ under various mass balance approaches suggested by stakeholders. In any case, no single mass balance approach is able to close the cost gap as long as pyrolysis oil has higher costs than crude petroleum.

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List of abbreviations and definitions

Abbreviations	Definitions
EPS	Expanded Polystyrene
FMCG	Fast-moving consumer goods
HDPE	High-Density Polyethylene
LDPE	Low-Density Polyethylene
kta	kilo tonnes per year (of capacity)
kt / yr	kilo tonnes per year
MPW	Mixed Plastic Waste
MPO	Mixed Polyolefins
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene (a.k.a. polythene)
PET	Polyethylene Terephthalate (often referred to as polyester)
PMMA	Poly (methyl methacrylate)
PP	Polypropylene
PS	Polystyrene
PU, PUR	Polyurethane
PVC	Poly (vinyl chloride)
RDF	Refuse-Derived Fuel
XPS	Extruded Polystyrene

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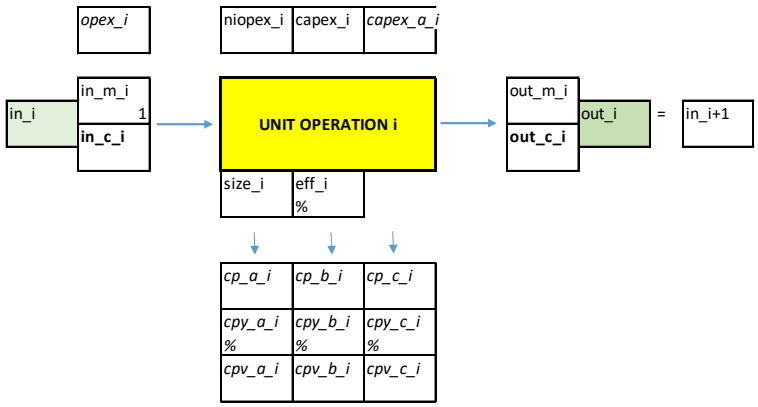
Annexes

Annex A – Pyrolysis process cost model

A.1 Unit Operation model

Each UO is modelled according to a simple input-output model pictured below in **Figure A. 1** based on collected data for each step and reflected mainly under fixed costs or Capex and variable costs or operational expenditure (op.ex., Opex (see section 3.5):

Figure A. 1. Basic cost model for one Unit Operation



NB pictured here with 3 coproduct flows

Source: own elaboration

Variable	Description	Unit
in_i	Input name	-
in_m_i	Input mass	tonne (t)
in_c_i	Input value (cost/price)	€/t
size_i	Unit Operation size	t/yr
eff_i	Process yield (efficiency)	%
capex_i	Step CAPEX	€
capex_a_i	Step CAPEX amortisation	€/t
niopex_i	Step non-input OPEX	€/t
opex_i	Step OPEX (total)	€/t
out_i	Output name	-
out_m_i	Output mass	tonne
out_c_i	Output value	€/t
cp_a_i	Coproduct A	-
cpy_a_i	Coproduct A yield	%
cpv_a_i	Coproduct A value	€/t
cp_b_i	Coproduct B	-
cpy_b_i	Coproduct B yield	%
cpv_b_i	Coproduct B value	€/t
cp_c_i	Coproduct C	-
cpy_c_i	Coproduct C yield	%
cpv_c_i	Coproduct C value	€/t

The cost calculation for each step (output cost) is based on the input cost and UO characteristics.

The calculation is performed as follows: the output cost is the input cost multiplied by the (main) process efficiency (yield), to which are added the Opex (on top of the input itself) per unit, and the Capex (amortisation) per unit[109] - see section 3.5; then potential additional gains from the sale of co-products are subtracted.

The formula is therefore as follows:

$out\_c_i = (in\_c_i + niopex_i + capex\_a_i)/eff_i - (cpv^a_i \times cpy^a_i + cpv^b_i \times cpy^b_i + \ldots)$

The link with the next UO is direct ($out\_c_i = in\_c_{i+1}$ – and $out\_m_i = in\_m_{i+1}$, where applicable)

[109] NB in this simple model, capital costs are not amortised by accounting for depreciation (with a depreciation rate through time) but only divided by the estimated useful life of the asset, typically 15 or 20 years.

Consideration of co-product income:

The calculation here is performed under the assumption that the output (out_i in each step) is the *main* output, and that other outputs are indeed "co-products". Considering the relatively low yields of thermochemical recycling in terms of process efficiency, the other products (e.g. fuels) and the question of their value become non-negligible. However, we assume that these have an outlet and are **sold at market value** for their specific characteristics: **we do not consider here any internal balancing of costs between process outputs** such as the ones proposed under potential mass-balance allocation and calculation rules.

Scenario modelling:

In order to reflect the uncertainties linked to the processes analysed, the variability in the technologies used and the evolving market conditions, we consider 3 scenarios applicable to the different steps of the modelling: **current, baseline**, and **best-case**.

- **Current** assumptions capture values which are already realistic today and could be achieved by operational facilities (mostly at pilot scale or early full-scale). Yields reflect performance already achievable with today's state-of-the art.
- **Baseline** assumptions capture likely values for near-term scaling-up of existing processes and technologies, not assuming any breakthrough but rather a predictable evolution of current performance towards industrial operation.
- **Best-case** stretches the potential performance to the limit of what could be achieved given today's knowledge, assuming favourable market conditions, highly optimised processes and evolutionary technological progress.

Each step is modelled along each of the 3 scenarios by adopting values that reflect the range of data collected for all relevant variables.

Step-by-step discussion of process details and yield/cost data:

In the following sections we discuss the process steps, their possible variations, sources of costs, and some examples from the relevant data collected.

NB unless otherwise specified, costs are expressed per tonne of INPUT for the specific step (e.g. capex, opex). *Output costs* are expressed per tonnes of output.

A.2 Step 1: Collection

One of the challenges of chemically recycling plastic waste is access to feedstock, which is by nature dispersed especially for post-consumer sources. It is the first fundamental difference with petrochemical processing which is built around a centralised model using a highly monitored, commoditised feedstock available in large quantities along established trade routes. In contrast, waste needs to be sourced from diffuse origins, cleaned and standardised before meeting the requirements of the pyrolysis process, posing a logistical (and economic) challenge.

Some recyclers have pointed to the fact that in some regulatory contexts, waste feedstock can be obtained at *zero cost*, or even *negative cost* through charging a **gate fee** (tipping fee) for the disposal of the waste (see section 3.2). This seems to be likely only in the combination of (a) stringent

disposal regulation for waste plastics and (b) either low energy prices, or legal impediments to incineration, which imply that the waste cannot be sold at least for its calorific value to the RDF value chain[110].

Several routes can be envisaged to procure waste feedstock:

- post-industrial / post-commercial plastics;

- plastic fraction from the separate collection of municipal waste;

- plastic fraction from advanced sorting of mixed municipal waste;

- rejects from (sorting in) mechanical recycling.

The most likely scenario is that waste pyrolysis facilities will be engineered to be flexible enough to accept a combination of all of the above in fluctuating quantities, in order to reach an operational scale. CEPS (2023) stress the importance that separation at source, and further sorting, will retain from the consumer perspective in a future where chemical recycling in general will play a larger role.

Transport

Waste can be transported at different stages of sorting/purification and through different means. The most common remains transport by road. Below a certain distance, the overwhelming part of the transport will be the resource cost of handling (loading/unloading) and administrative processing, which will not be much affected by distance itself, unless borders are crossed. As a simplifying assumption, we assume (for various stages of waste purity) a ballpark value of about 50€/t (*baseline*) for transport costs as indicated by one industry stakeholder and do not model different location models (centralised vs decentralised facilities).

A.3 Step 2: Sorting

As mentioned in 2.3.4.1 according to e.g. Eunomia (2022) pyrolysis is suited to accept mixed polyolefin (MPO) waste, such as PE and PP, as well as some styrenics such as PS. In this analysis, we are focusing on polyolefins as the pyrolysis pathway for PS is different, since there is no steam-cracking of the pyrolysis output involved, and there is only one full-scale PS pyrolysis plant operating in Europe, to our knowledge. However, other plastic types act as contaminants and need to be sorted out before processing. Therefore, mixed plastic waste (MPW[111]) needs to (at the very least) undergo additional sorting before providing pyrolysis-ready input. Costs for sorting are in the range of 20-50€/t input (Volk et al., 2021 estimate 31.84€/t).

Considering the typical composition of MPW (see e.g. Arena et al. 2023, Genuino et al. 2022, Strien et al. 2024, Roosen et al. 2020), mixed POs can make up 50-60% of all plastic waste (incl. HDPE, LDPE, PP); Hermanns et al. 2023 cites higher figures from the German dual system of 67% PE/PP.

We consider 65% as a baseline value (60% current) and 75% as best-case for the yield of the sorting operation from MPW to MPOs.

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[110] Otherwise, sourcing plastic feedstock for pyrolysis will have to compete with incineration: plastic bales have a calorific value of at least 20-25 GJ/t (indicated by one stakeholder) and more typically 28 GJ/t and above. As analysed in García-Gutiérrez et al 2023, this means a minimum value of ~80€/t or even 100€/t (comparable to coal which has a similar heating value).

[111] for instance meeting DKR350 requirements

Note that rejects from the sorting step include other plastics such as PVC and PET which may still be recovered (if they haven't been already in a previous step) and further processed towards eventual recycling. This could be achieved by conventional (mechanical) recycling, solvolysis, or even thermal processes as investigated by van Akker et al. (2025). The co-product of the operation may therefore have positive value which we evaluate at 50€/t in a best-case scenario based on (García-Gutiérrez et al. 2023, §3.3.1.1) if recycled and 20€/t as a central value if sold for calorific value at plant gate. Other rejects may incur negative value (disposal costs).

A.4 Step 3 preprocessing (other pre-treatment)

Mixed POs may require additional preparation before entering pyrolysis, such as washing to remove contaminants or physical processing to improve the form factor of the material in the reactor, such as shredding or extrusion. One stakeholder mentions losses from MPO323 to pyrolysis input of ca. 5%. While energy-consuming (heat process), the energy input required is low compared to high-temperature processes such as the ensuing thermochemical steps.

However, all sources (e.g. Eunomia (2022), Arcà et al. (2025), Systemiq (2022), CE Delft (2022)…) point to the selective nature of the pyrolysis process (not more tolerant than e.g. mechanical recycling[112]) which means that "Both mechanical and advanced recyclers require consistent streams of feedstock with minimal contamination and while advanced recycling should be viewed as a recycling outlet for a different range of materials, it should not be viewed as a recycling outlet for contaminated materials or unsorted materials." (Eunomia 2022), also pointing out that the key advantage of pyrolysis over mechanical recycling from a feedstock perspective is that it can readily accept films and that pyrolysis feedstock can contain both PE and PP at varying levels.

Therefore, pre-processing costs will be comparable (or higher) to mechanical recycling input preparation.

Steps 1-3 (feedstock sourcing and preparation): overall consideration

Overall, preprocessing costs are comparable to costs incurred by mechanical recyclers, and feedback from chemical recyclers confirm these data.

As discussed, input costs would typically be around 80 to 100€/t (90€ baseline) or more commonly 150€/t (current scenario). In optimistic cases where a gate fee can be charged for disposal, this cost (income, in that case) could be as low as –50€/t to –80€/t (Riedewald et al., 2021).

Looking at the output of the preprocessing step i.e. processed plastics ready for pyrolysis, based on (García-Gutiérrez et al. 2023, §3.3.1.1), feedstock costs for *separated* polymer fractions oscillate in the range of 220 to 360€/t. One input to our study mentions costs as high as 600€/t based on comparisons with mechanical recycling input, broken down into 240€/t for cap.ex. and 360€ for op.ex..

Other submissions mention costs ranging from less than 100€/t to, more commonly, around 300€/t suitable plastic waste feedstock.

Our analysis therefore yields central values around ~350 €/t (with 100€/t as a best-case scenario and 650€/t at the high end of the range) for a pyrolysis-ready waste plastic feedstock at plant gate.

[112] See discussion of contaminants in section 2.3.4.1

A.5 Step 4 – thermochemical process

This step is the core process of the thermochemical recycling route.

Variations

The main (pyrolysis) route consists of heating the feedstock in the absence of oxygen, however there are several variations to the process which have been developed to target e.g. higher yields of specific outputs, improved energy efficiency, etc.. The most significant alternatives include:

- catalytic pyrolysis: to selectively enhance specific reactions towards a desired output or lower the overall process costs (see for instance Li et al. 2022, §5.2; Peng et al. 2022; and Hasan et al. 2025 which reviews in particular the effects of catalysts on yields).

- hydrothermal liquefaction: in the presence of water, which at the considered conditions is in super-critical state. This solution to the low thermal conductivity of plastics may afford benefits in terms of reaction heat control / process homogeneity and efficiency as well as output contamination (see for instance Peplow 2025, Li et al. 2023, Ozoemena and Coles 2023).

- microwave-assisted and plasma pyrolysis: also aimed at improving energy efficiency by addressing heat diffusion (see for instance Hu et al. 2023, Harasymchuk et al. 2024).

These approaches can be combined together and also individual processes can be designed with usual reaction parameters (temperature, pressure, reactor design, residence time etc.) to provide the variety of technologies being explored today.

Capex

Most sources converge towards a roughly even split between Capex and Opex or a slight predominance of Capex (60/40% split) for this process step.

Regarding capital expenditure, it is unclear whether the kind of economies of scale which largely apply in petrochemical processes are also valid for waste-plastic pyrolysis facilities. For instance, a common rule of thumb for scaling of investment costs (the six-tenths rule[113]) is claimed by some industry practitioners to also apply here. However as discussed in section 5.2.3.3, for facilities installed so far it has not been possible to observe significant economies of scale. This may be because no real "large" scale (>50ktpa) facility so far[114] has been operational (see review of operational facilities and sizes in e.g. Li et al. (2022) p.8934, Deloitte 2022, De Tommaso et al. 2024). It is still unclear if such benefits should be expected in future scale-ups. De Tommaso et al. 2024 performs a transversal analysis of chemical recycling plants and finds that the first-order cost driver is energy losses, and therefore does not lend itself well to cost reduction by scaling up, since energy efficiency only improves modestly with reactor size. Their analysis reveals a modest factor for economies of scale of $n^{0.81}$ – $n^{0.86}$, which is difficult to observe at all at current plant sizes.

We therefore tentatively conclude no economies of scale for Capex and a linear scaleup with facility size; based on data sources (input from stakeholders and literature, e.g. Beckham et al. 2023, see supplementary information), values between 0.5[115] and >10 m€/ktpa installed capacity (million Euro per thousand tonne/year installed capacity) emerge.

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[113] i.e. Capex (n × capacity) = capex capacity × $n^{0.6}$ or a ~50% increase in costs per doubling of capacity

[114] See for instance https://corporate.exxonmobil.com/locations/united-states/baytown/newsroom/2025/doubling-down-on-double-capacity#We%E2%80%99reinvestedinadvancedrecycling

[115] Theoretical value from calculations (Riedewald et al. 2021)

A simple amortisation over expected useful life yields a baseline value of 400€/t (best-case 250, current over 500) for amortised capex cost per tonne input. (Deloitte (2022) cites a cost estimate of 700€/t *output* for one technology company).

Opex

In the data received by JRC from stakeholders, energy costs are reported to be the main (non-input) operating expenditure. One source quotes energy operating costs as lower than input and other costs (130€, vs 220€) adding up to 350€. However, there is no clear distinction between input and energy costs: interestingly, pyrolysis, like many typical petrochemical processes, offers some fungibility between the uses of the reagents and products; most of those can be used both as materials (targeted as output products) or as fuels, whether as part of the reaction or when burned externally to heat the reactor. This means that reactions can be designed towards a certain trade-off between material output and energy costs. Typically, in a market environment the balance would be tilted towards maximising the use of outputs and co-products as fuels, especially when these are inconvenient to ship and trade (gas) or low-value (char).

In any case, Netsch et al. (2024) report that the theoretical physicochemical heat demand for the pyrolysis reaction typically corresponds to 5% (4-6%) of the calorific value of the input plastics. In practice, with real-life reactors this value is more likely to be close to 10%.

The question therefore remains whether this energy requirement of the process will be provided by burning the feedstock (or co-products) or by an external energy source. In the absence of external incentives towards the maximisation of material recovery (e.g. recycled content incentives) or GHG abatement, external energy would have to be procured at non-zero cost for the process (e.g. natural gas or even electricity), as opposed to virtually free or even negative-cost outputs from the process itself.

Regarding geographical location, most operators stress that the EU is a high-cost location both for labour and now (since the war in Ukraine) also for energy. Prices (and Opex) are routinely 2.5-3 times higher than in most world regions both for labour and energy (set by the natural gas benchmark).

Opex values from literature and industry sources for the pyrolysis process range from 100 €/t (utilities only) to 500€/t and above. We centre on a value of 300€ for our baseline.

Outputs and yield

Most literature sources (Kusenberg et al. 2022, 2022a and 2025, Genuino et al. 2022, Hasan et al. 2025) as well as our stakeholder input converge towards an operational yield of input feedstock to raw pyrolysis oil in a narrow range of 67-71% (69%), also in line with the data presented in **Table 5**. The other outputs are solids (wax, char) and gasses which may or may not be burnt for fuel in the very process. (N.B. Note that as we discuss elsewhere, the process may be tailored and optimised to yield the highest-value target mix of hydrocarbons (see for instance Cao et al., 2024), taking into account ancillary revenue streams for the overall process; we assume here a target for naphtha-like output and components allowing high ultimate plastic output)

Output cost

With all the above considered, our modelling yields cost values for the production of **raw pyrolysis oil in a range of 1300 to over 2000€/**t (with a best-case scenario of under 1000€/t)**.** This is in line with most reported values from the literature and stakeholder submissions, with one reported value of 900€/t as a low outlier.

A.6 Step 5 & 6 Postprocessing (purification and fractionation)

These two steps have broadly different goals, but in practice are often carried out simultaneously ("Upgrading"), as described in Kusenberg et al. (2022, 2022b, 2025).

Purification consists of removing so-called "heteroatoms" which in this particular process are non-hydrocarbons, the most problematic at this (post-pyrolysis) stage being (Source: Franke et al. 2024) Br, Cl, O, N, and S. The process is energy-intensive but offers high yield *per se* as the contaminants removed constitute trace amounts (90-95% yield). Hydrotreatment also has the effect of breaking up double carbon bonds of the hydrocarbons themselves, thereby converting olefins to paraffins (therefore closer to crude-derived compounds, see Li et al. 2022 Fig.17).

Fractionation or distillation on the other hand is a much lower-yield process as it consists of selecting among the widely-distributed hydrocarbon chains those which are most suited for steam cracking – a process akin to crude oil distillation.

Typically, only 24-39% of the raw pyrolysis oil is made up of **naphtha**-like fraction, which is the objective of this process (Kusenberg et al. 2025).

At this stage, it is important to mention, as discussed in chapter 2, that yields may be greatly improved if the focus is on plastic production as opposed to general petrochemical operation. Indeed, the medium liquid fraction from pyrolysis (diesel-**gasoil** like) can be cracked to yield shorter-chain hydrocarbons also suitable for naphtha replacement. We mentioned above potential increases from the 31%-63% range to a higher 35%-77% potential.

As always this trade-off is arbitraged between the energy cost / yield and the projected material revenue from the process. In a market setting the most natural outlet for heavier products may be simply selling them as such (for fuel use), but this choice may be reoriented towards material upgrading with high enough material market value.

Note also that alternative approaches to the main thermochemical process step may reduce the subsequent need for purification and upgrading; e.g. hydrothermal liquefaction (see Abdulrahman et al., 2025).

Capex and Opex

In the wider scheme of large-scale petrochemical processes, this step has a comparatively low capex-intensity, but is quite energy intensive (most of the Opex). One of our confidential sources quotes capex/opex ratios of about 1 to 3, translating to amortised Capex costs of 100-140€/t vs. Opex of 300-420€/t. Hydrogen production is highly energy-intensive and thus expensive and ultimately accounts for a significant part of the opex, even in the case of process integration where H_2 can be sourced elsewhere in the facility.

In terms of Capex, the currently observed industry set-up and business models point to the alternative between setting up **dedicated upgrading facilities** for pyrolysis oil (see for instance the - now terminated - PULSE project[116] or the ReOil25000 project[117]) or piggybacking on **existing refining infrastructure** to perform this step. The trade-off is not only based simply on technoeconomic considerations arising from process integration (i.e., co-location with large existing facilities to take advantage of e.g. process heat flows or co-product fuel gas) but also on the regulatory impact of

[116] https://climate.ec.europa.eu/system/files/2022-12/if_pf_2022_pulse_en.pdf

[117] https://ec.europa.eu/assets/cinea/project_fiches/innovation_fund/101190955.pdf

the so-called “mass-balance” calculations, i.e. whether and how recycled content can be claimed if recycled input is mixed with fossil input in a larger process.

Output costs

Based on the above, our modelling yields a range of cost values for (naphtha equivalent) upgraded pyrolysis oil in the **800 – 2900 €/t** range (1700€/t baseline). This is to be compared with virgin naphtha prices of around 700-1000 €/t (fluctuations broadly tracking the fluctuations of crude oil prices).

Combining industry, literature and direct sources (stakeholder submissions to our study and e.g. Plastics Europe 2024, Netherlands 2023, ICIS 2024) and our own modelling therefore suggests cost estimates for the production of **naphtha-like pyrolysis output** (steam cracker drop-in input) **in a range of 1450 to 2100€/t** with outlier values between 800€/t and 2900€/t.

This represents a premium in absolute terms compared to virgin naphtha of ~500 to 1500 €/t, or a relative difference of 1.5-3 times.

A.7 Steps 7-9 Petrochemical processing

These steps cover the downstream processing of the naphtha equivalent, where it is transformed into HVCs and fuels alongside virgin (crude derivatives).

As these steps are not specific to chemical recycling, and we lack data on the specific adaptations (if any) and costs that would have to be incurred as a result of using pyrolysis-derived naphtha as opposed to virgin from this step downwards, we do not analyse the cost impact any further and focus on the price differential at the naphtha-equivalent stage.

However, it is important to stress that these (conventional) steps incur additional losses and energy use. In essence, the core of the steam cracking process is a **second pyrolysis** step (with key differences: from purer feedstock, at higher temperatures, in the presence of water), as described in Ren et al. (2006) and Ren et al. (2008), and therefore necessarily energy-intensive, yielding a variety of outputs although it is designed to be very selective towards ethylene and propylene.

A.8 Overview

Data from the steps above are compiled together for comparison and to illustrate overall process outcomes :

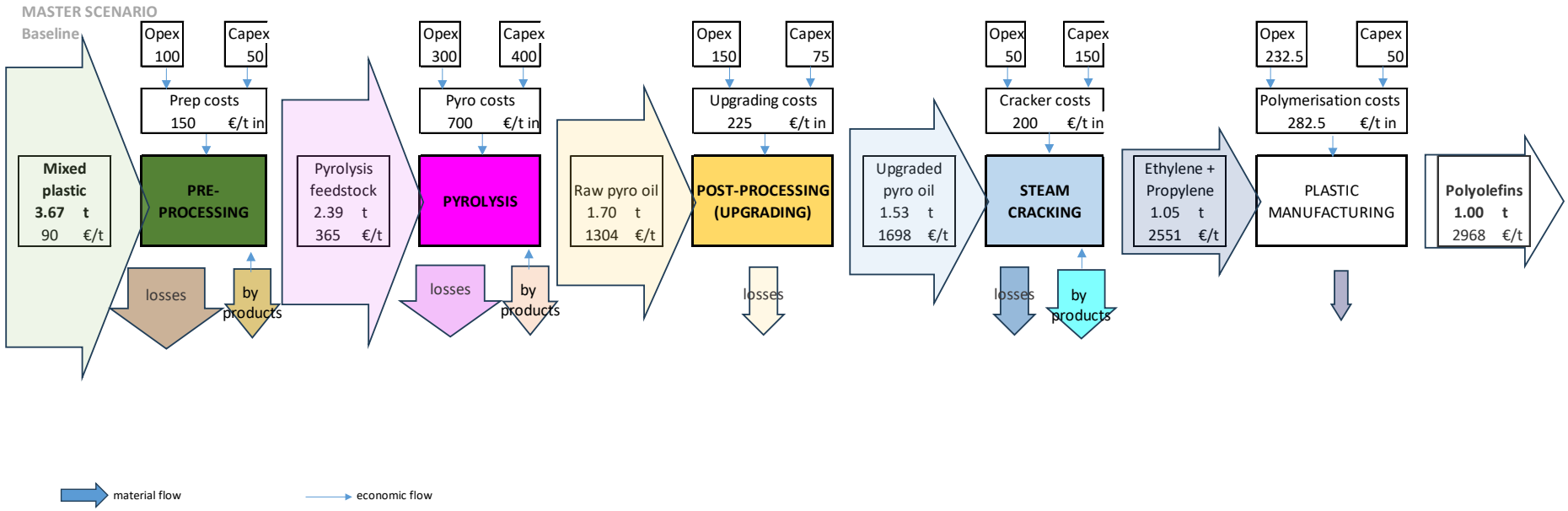
Table A. 1 Yields and quantities needed by process step, pyrolysis; different scenarios.

	Process step	PREPROCESSING*	PYROLYSIS	POSTPROCESSING	STEAM CRACKING	PLASTIC PROD	TOTAL
input name		Mixed plastic waste	Process-ready mixed polyolefins	Raw pyro oil	Naphtha equivalent	Ethylene + Propylene	Plastic
	current	60%	65%	85%	66%	90%	19.7%
step yield	baseline	65%	71%	90%	69%	95%	29.3%
	best-case	100%*	85%	95%	71%	98%	56.2%
	current	5.08	3.05	1.98	1.68	1.11	1.00
reverse tonnes* **	baseline	3.67	2.39	1.70	1.53	1.05	1.00
	best-case	1.78	1.78	1.51	1.44	1.02	1.00

*note that the yield of this process step should be taken into account similarly for the purpose of comparisons with other processes where it also occurs, e.g. mechanical recycling **assuming MPO as input ***tonnes of material needed at each step in the process to obtain 1 tonne of final plastic at the end of the process chain

Sources include: Arena et al. 2023, Beckham et al. 2023, Jeswani et al 2021., Genuino et al. 2022, Strien et al. 2024, Roosen et al. 2020, Kusenberg et al. 2022, 2022a and 2025, Hasan et al. 2025, García-Gutiérrez et al. 2023, Li et al. 2022, Ren et al. 2006 and 2008, as well as direct contributions from several stakeholders to the study including ExxonMobil, LyondellBasell, SABIC, Neste, MURA, Ineos and PlasticEnergy. Data has been assessed for plausibility and subject to compilation, comparison, and averaging; it aims to reflect the best composite rendition of the processes using information from the variety of sources used.

Figure A. 2. General overview of the pyrolysis process: flows, yields and costs (baseline scenario)



Sources include: Arena et al. 2023, Beckham et al. 2023, Jeswani et al 2021., Genuino et al. 2022, Strien et al. 2024, Roosen et al. 2020, Kusenberg et al. 2022, 2022a and 2025, Hasan et al. 2025, García-Gutiérrez et al. 2023, Li et al. 2022, Ren et al. 2006 and 2008, as well as direct contributions from several stakeholders to the study including ExxonMobil, LyondellBasell, SABIC, Neste, MURA, Ineos and PlasticEnergy. Data has been assessed for plausibility and subject to compilation, comparison, and averaging; it aims to reflect the best composite rendition of the processes using information from the variety of sources used.

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