Chemical and physico-chemical recycling of plastic waste

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CHEMICAL AND PHYSICO-CHEMICAL RECYCLING OF PLASTIC WASTE

FINAL REPORT

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SUMMARY

The project aims at understanding the different existing technologies for the chemical and physico-chemical recycling of plastic waste. These promising technologies could allow to process hard-to-recycle plastic waste and produce new food-grade plastics. However, little information is currently available to compare these processes with each other and to assess their performance in economic or environmental terms. The uncertainties associated with these new technologies are also high given their early stage of development (often at pilot/demonstration stage). The purpose of this study is therefore to draw up a state of play of the various chemical and physico-chemical recycling technologies via a literature review and to clarify the pending points, notably by means of expert consultations.

KEY WORDS

Chemical recycling, Physico-chemical recycling, Pyrolysis, Gasification, Dissolution, Solvolysis, Hydrocracking, Vapocraking, Plastic waste, Expert's consultation.

RESUME

Le projet a pour but d'appréhender les différentes technologies existantes de recyclage chimique et physico-chimique des déchets plastiques. Ces technologies prometteuses pourraient permettre de traiter des déchets difficilement recyclables et produire des plastiques aptes au contact alimentaire. Cependant, peu d'informations sont disponibles à l'heure actuelle pour comparer ces procédés ainsi que pour en évaluer les performances en termes économiques ou environnementaux. Les incertitudes liées à ces nouvelles technologies sont également fortes étant donné leur stade de développement actuel (souvent à l'échelle d'une unité pilote ou démonstration). Ainsi cette étude a vocation à dresser un état des lieux des différentes technologies de recyclage chimique et physico-chimique via une revue de littérature et à éclaircir les questions en suspens à l'aide, notamment, de consultations d'experts.

MOTS CLES

Recyclage chimique, Recyclage physico-chimique, Pyrolyse, Gazéification, Dissolution, Solvolyse, Hydrocraquage, Vapocraquage, Déchets plastiques, Avis d'experts.

I. Contents

I. Executive summary

Chemical and physico-chemical recycling technologies are promising for specific applications, where mechanical recycling is unable to meet the market's needs.

The interest in chemical and physico-chemical recycling technologies has risen this last decade, due to the encouraging results that they promised to deliver. Indeed, the recycling landscape is divided between mechanical recycling, which offers limited possibilities when it comes to the purity requirements of the output polymer, and chemical and physico-chemical recycling technologies, which can help achieve a better output quality.
Moreover, mechanical recycling technologies have very stringent feedstock specifications, which, in some cases, chemical and physico-chemical recycling technologies might overcome. The latter thus present with an undeniable interest regarding the treatment of hard-to-recycle plastics or highly contaminated waste streams.

Chemical and physico-chemical technologies are rapidly developing.

Numerous technology developers have been announcing investment in future chemical and physico-chemical recycling facilities and a large number of stakeholders of the value chain (including brands) have already partnered up with some of them. Most of these planned plants are expected to open in the next five years. The chemical and physico-chemical recycling market will thus be more and more active in the coming years.
The European, Japanese, and American landscape are seeing most of the development on their region as they seem to be favorable to these technologies. Indeed, the European market is demanding more recycled materials, to face consumer pressure and regulatory targets. The American market encompass less stringent regulations, especially for thermal treatment processes, than other regions, which makes it a territory of choice for chemical recyclers. The Japanese market seems also favorable to the implantation of chemical recyclers, as it provides an access to clean and well-sorted waste streams.

However, this development is hindered by economic, legislative, and environmental uncertainties.

Chemical and physico-chemical recycling technologies usually produce a recycled material, that is more expensive than its virgin alternative, with sometimes a lesser quality. It is thus to be expected that, without a price premium, chemical and physico-chemical recycling technologies will not be economically competitive with their virgin counterparts. The amount of the price premium to pay will be dependent on the quality required for the final product, which will decide the type of feedstock to be used and the different pre-treatment and post-treatment steps to implement.

In addition, environmental assessments conducted are often unclear on the benefits that chemical and physico-chemical recycling technologies could provide. They are usually more beneficial than incineration but more detrimental than mechanical recycling (although the quality of the output- *the functional unit* – is different). However, due to questionable methodologies and hypothesis, the environmental impact of such processes can hardly be clearly understood by consumers.

Finally, regulatory uncertainties about these technologies are threatening this development due to the risks of new unfavorable legislations. Among the three geographies studied (Japan, Europe, and USA), not one clearly states its position on chemical and physico-chemical recycling and if these technologies could qualify as "recycling". There is thus an urgent need of alignment from policy makers on this topic.

The value chain of chemical and physico-chemical recycling needs to be structured and strengthened to ensure these technologies' future.

Despite the fast development of chemical and physico-chemical recycling technologies, the collection system is staying as is and the feedstock availability of the upcoming plants is not ensured. Indeed, few feedstocks are actually complying with the developers' requirements, which can be highly problematic at a commercial scale. There is thus a need for all the value chain players to come together and structure the entire value chain, from feedstock supply (with sufficient volumes and quality) to the manufacturing of end-products.

II. Presentation of the study

1) Background context of the study

Over the past decades, worldwide markets experienced a steep increase in the use of plastic materials. In 1950, plastics' production amounted to about 1.5 million metric tons a year (Mt/y). Since then, these materials started being widely used in numerous applications and sectors (e.g., automotive, construction, consumer goods, etc.) on account of their convenience and unique properties (lightness, malleability, resistance, durability, etc.). By 2020, production had grown to 367 Mt/y[1], most of which PP, PE, PET, and PS used within the packaging, building & construction, and automotive sectors. Projections show that by 2025, plastics' production will amount to approximately 445 Mt/y[2].

Despite the multiple benefits associated with the use of plastics, stakeholders in the industry have increasingly become aware of the issues associated with the use of these materials, including their end-of-life. There is now staggering evidence of how the mismanagement of plastics' lifecycles and associated waste streams negatively impacts the environment, society, and the economy. As an example, the maturity and efficiency of collection, sorting and recycling schemes significantly differ from one country to another, which can lead to variable recycling rates. Another critical point to be considered is that most plastics are non-biodegradable. Whenever dumped into the environment, these materials take decades to degrade and never fully disappear (generating micro-plastics instead).

Over the past years, the increasing understanding of the downsides associated with the use of plastics has been driving key stakeholders to put pressure on this industry. Numerous medias and NGOs have been reporting on plastic pollution and its impacts on the environment (especially on the ocean), leading to a negative consumers' perception. By improving the circularity of the plastics' industry, recycling technologies can address part of the problems associated with this sector. On a global level and especially in EU countries, different regulations have been enacted to set mandatory targets for plastics' recycling rates and increase of recycled content in products. Cross-sector initiatives such as the Circular Plastics Alliance have been launched worldwide to align different market players and support plastic's recycling goals. At the same time, brand-owners across different industries (including H&M, Unilever, Adidas, Danone, etc.) and other stakeholders of the value chain (e.g., petrochemical industries, polymer manufacturers, etc.) have been committing to ambitious objectives such as improving the recyclability of their products or increasing recycled content within their products' portfolio.

Today, the great majority of recycling activities are carried out using mechanical recycling solutions. These technologies have successfully been deployed on a commercial scale within a multitude of countries and are well adapted to resins such as PET, PE, and PVC. Yet, for the time being, recycling rates remain low due to the existence of numerous barriers (e.g., technological brake, consumer behavior, illegal markets, etc.). Common issues notably include the fact that customers are often unaware of how to properly sort plastic waste, the fact that complex product design (e.g., multilateral packaging) can make sorting and recycling challenging, as well as the fact that some plastics can be dumped into the environment during their lifecycle (notably after the use phase of the product). According to the OECD, on a global level, only 9% of the waste plastics produced in 2019 was recycled[3]. Within the European Union[4], 29.5 Mt of plastics were collected in 2020 compared to a yearly demand of 49.1 Mt. Out of the collected plastics, approximately 23.4% were landfilled and 42% incinerated for energy recovery purposes. Only 34.6% of collected plastic waste was sent to recycling (34.4% being mechanically recycled)[5].

[1] https://www.statista.com/statistics/282732/global-production-of-plastics-since-1950/

[2] https://www.statista.com/statistics/664906/plastics-production-volume-forecast-worldwide/#:~:text=It%20is%20projected%20that%20the%20global%20production%20of,of%20more%20than%2030%20percent%20compared%20with%202025.

[3] https://www.oecd-ilibrary.org/sites/de747aef-en/index.html?itemId=/content/publication/de747aef-en

[4] 27 members + Norway, Switzerland, and the UK

[5] https://plasticseurope.org/wp-content/uploads/2021/12/AF-Plastics-the-facts-2021_250122.pdf

Low mechanical recycling rates and limited recyclates' quality have been driving interest in the development of innovative recycling technologies. It is in this context that chemical and physico-chemical solutions have been gaining increasing popularity as they could allow to process hard-to-recycle plastic waste and produce high quality recycled plastics. While these technologies have been researched and tested for a longtime, the market situation was never favorable enough for them to be widely deployed at an industrial scale. Today's plastics crisis is providing the objectives, means, and financial stability to leverage the development of these recycling solutions. Yet, despite the growth that has been experienced by the chemical and physico-chemical recycling sector over the past couple of years, there is still an ongoing questioning on the actual recycling capabilities of these technologies, their maturity level, environmental impact, economic viability, and regulatory constraints.

The purpose of the study is to provide an objective depiction of existing chemical and physico-chemical recycling solutions (plastic-to-plastic applications) based on available information as of the date of this executive summary. The report presents detailed information on the opportunities and limits of these technologies, their economic and environmental performances, their perspectives of development as well as the current regulatory context (in the USA, EU, and Japan). This work was built upon RECORD's previous publication on the subject "Chemical recycling of plastic waste: context and perspectives. State of the art and expert's opinion" (2015).

2) Objectives of the study

As previously mentioned, the projects aims at understanding the different existing technologies for the chemical and physico-chemical recycling of plastic waste. These promising technologies could notably allow to process hard-to-recycle plastic waste and produce new food-grade plastics.
However, little information is currently available to compare these processes with each other and to assess their performance in economic or environmental terms. The uncertainties associated with these new technologies are also high given their early stage of development (often at pilot/demonstration stage). The purpose of this study is therefore to draw up an objective state of play of the various chemical and physico-chemical recycling technologies via:

- a literature review: this step will allow to have a global overview of the development of such processes, their main advantages, and barriers to overcome to reach commercial scale.
- an expert consultation: this second step will allow to clarify some pending points, notably environmental and economic performance of these processes which is often not disclosed in detail by the technology providers. Technical, regulatory, environmental, and economic aspects of the processes will be discussed with an international panel of experts.

This work was built upon RECORD's previous publication on the subject "Chemical recycling of plastic waste: context and perspectives. State of the art and expert's opinion" (2015)[6].
Please note that the intent of the authors is to provide an overview of these technologies as objective as possible based on available information as of the date of this report. The authors have strived to develop a comprehensive understanding of these technologies and disclose in a transparent manner the limits of the different sources of information (in terms of quantity and quality) through the present document. However, the plastic recycling sector is a fast-moving field, which entails refining the messages presented based on current and future work progress around recycling technologies. In this context, this report, and associated documents (e.g., extended abstract) should be considered as indicative.
The authors are not responsible for recommending which solution is best to adopt or contributing to decision-making with regard to the definition of a specific strategy. The sector/industry players shall meet and make their own decision.

[6] Original title: Recyclage chimique des déchets plastiques : situation et perspectives. Etat de l'art et avis d'experts.

3) Scope of the study

Technological scope: The study focuses on chemical and physico-chemical recycling which refers to several processes. The studied technologies are the following:

- Dissolution
- Chemical treatment
- Thermal treatment

The steps related to the purification and extraction of the monomers (for depolymerization technologies) are also considered.
The scope of the present study is “plastic to plastic”. Thus, the processes focused on “waste to fuel” are not taken into account.

Geographical scope: The development of the recycling processes worldwide will be studied. However, the study will present the regulatory context in the US, Europe, and Japan due to strong activity of the chemical and physico-chemical recycling sector in these geographical areas.

4) Methodology

The study will be conducted via 3 tasks:

- Task 1: literature review on chemical and physico-chemical processes and development of a list of points to be further discussed with experts
- Task 2: selection of the panel of experts, organization, and facilitation of several working sessions (technology and scaling up, current and future regulatory context, environmental performance of recycling processes, economic performance of recycling processes and perspectives for the development of the studied recycling technologies by 2030).
- Task 3: consolidation of the key learnings from Tasks 1&2 in the present report.

5) Panel of experts

Name	Surname	Organization
ABRAHAM	Fabrice	**Renault**
CHANOINE	Augustin	**Deloitte**
COOKSON	Craig	**The American Chemistry Council (ACC)**
DEVER	Cédric	**L’Oréal**
DE KORT	Patrick	**Plastic Recyclers Europe (PRE)**
DI GREGORIO	Fabrizio	**Plastic Recyclers Europe (PRE)**
DRAPEAU	Pierrick	**Deloitte**
DUBOIS	Jean-Luc	**ARKEMA**
DURAND	Christophe	**Michelin**
IMHOF	Pieter	**TNO**
KJELL	Theresa	**ChemSec**
KLEIMARK	Jonatan	**ChemSec**
MUHURI	Prapti	**The American Chemistry Council (ACC)**
NOUGIER	Sandrine	**Ministère de la Transition écologique**
PARENTY	Arnaud	**Lille University**
POOL	Henk	**Cefic**
SEEBOTH	Nicolas	**Michelin**
TAVEAU	Mathilde	**Plastic Recyclers Europe (PRE)**
TERAS	Outi	**Neste**
VAHK	Janek	**Zero Waste Europe**
WAIBEL	Chaim	**Plastic Recyclers Europe (PRE)**

III. Introduction

1) Studied processes

Due to the variety of existing processes, it has been decided to classify and describe them by technology category. The considered technologies categories are the following:

- Chemical treatment (solvolysis):
  - Glycolysis
  - Methanolysis
  - Aminolysis
  - Hydrolysis
  - Enzymatic depolymerization: due to the growing interest of the market and development of these technologies (notably the Carbios process), it has been decided to make a focus on this process, which is classified within the "hydrolysis" category.
- Dissolution
- Thermal treatment
  - Non catalytic pyrolysis
  - Catalytic pyrolysis
  - Hydrocracking
  - Hydrothermal cracking
  - Gasification
- Downstream steps: example of vapocracking (steam cracking)

Notes

- A selection of the main technologies under development is presented in this report. Please note the list of studied technologies is not exhaustive. As an example, ammonolysis is not included.
- The processes will be presented by category in this report. However, it should be kept in mind that each technology developer has its own characteristic features (e.g., specific process, conditions, catalyst, etc.). This is why, a focus on some start-up companies will be presented when relevant.
- Due to the low development of aminolysis technologies on the market, this category is only briefly presented in this report.
- Please note the Technology Readiness Levels mentioned in this document are only indicative.
- In general, the technology developers' objective is the treatment of plastic waste that is currently not mechanically recycled and sent to landfill or incineration. In most cases, the considered chemical and physico-chemical recycling processes and mechanical recycling could be considered as complementary as they usually do not target the same feedstocks and do not allow to produce the same quality of output. However, as the processes are under development, technology developers test different feedstocks to assess the flexibility of their technology, including some waste streams that are usually treated via mechanical recycling (e.g., colored PET bottles). This point is specified in the report when necessary.

A classification of the chemical and physico-chemical recycling technologies of plastic waste is presented below. Please note there is currently no consensus regarding the classification of chemical and physico-chemical recycling technologies. As an example, the last report of Closed Loop Partners consider that molecular recycling excludes pyrolysis[7].

[7] Assessing Molecular Recycling Technologies in the United States and Canada - Closed Loop Partners

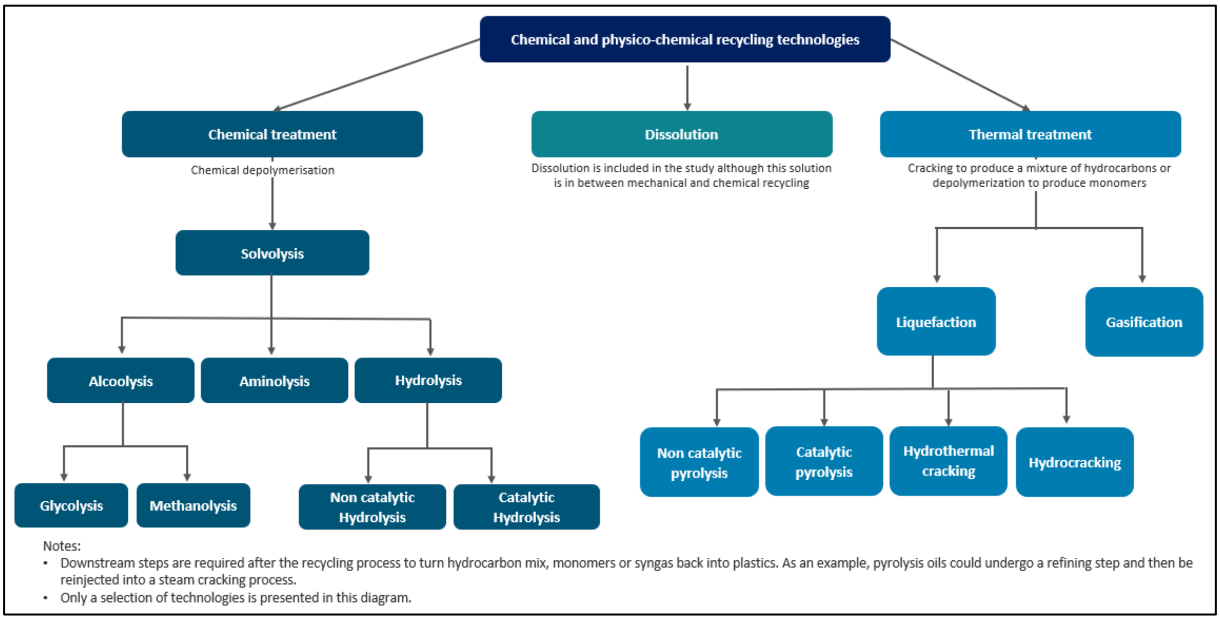


Figure 1: Studied recycling technologies (RECORD, 2022)

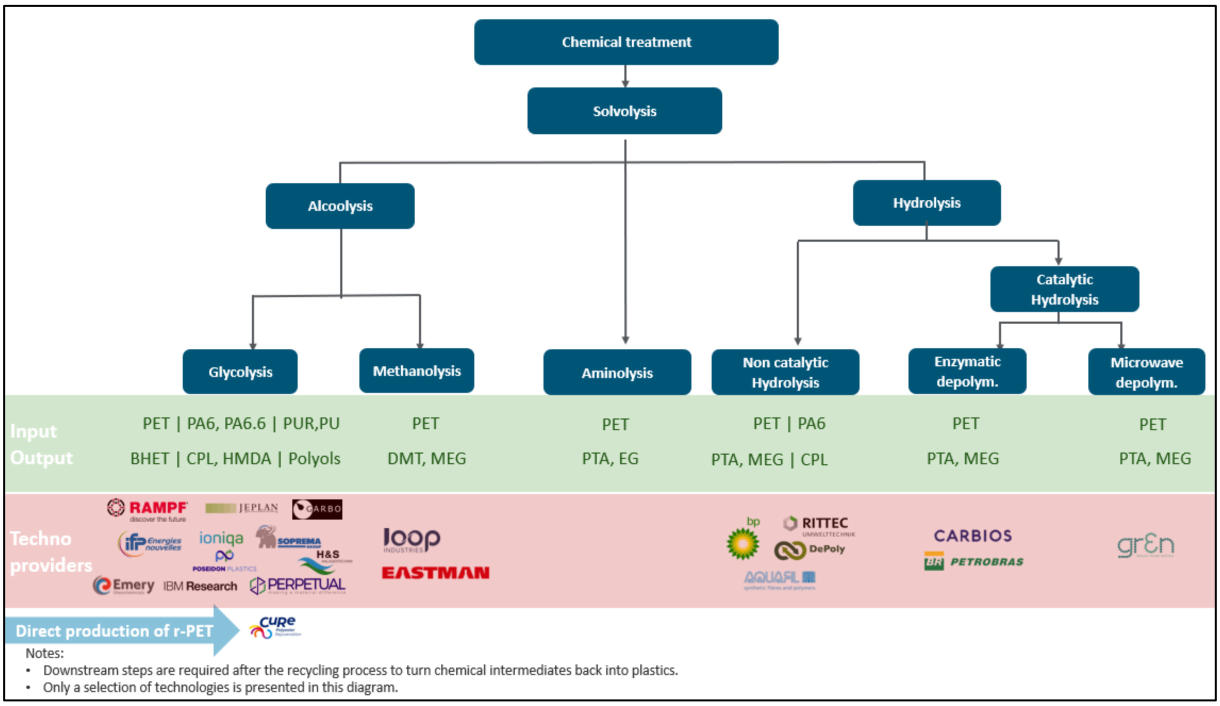


Figure 2: Chemical treatment technologies (RECORD, 2022)[8]

8 Contrary to other technology developers, CuRe technology is not depolymerizing completely the polymer but is using a partial depolymerization, going back to smaller polymer chains. The output is afterwards purified and directly repolymerized to obtain recycled PET.

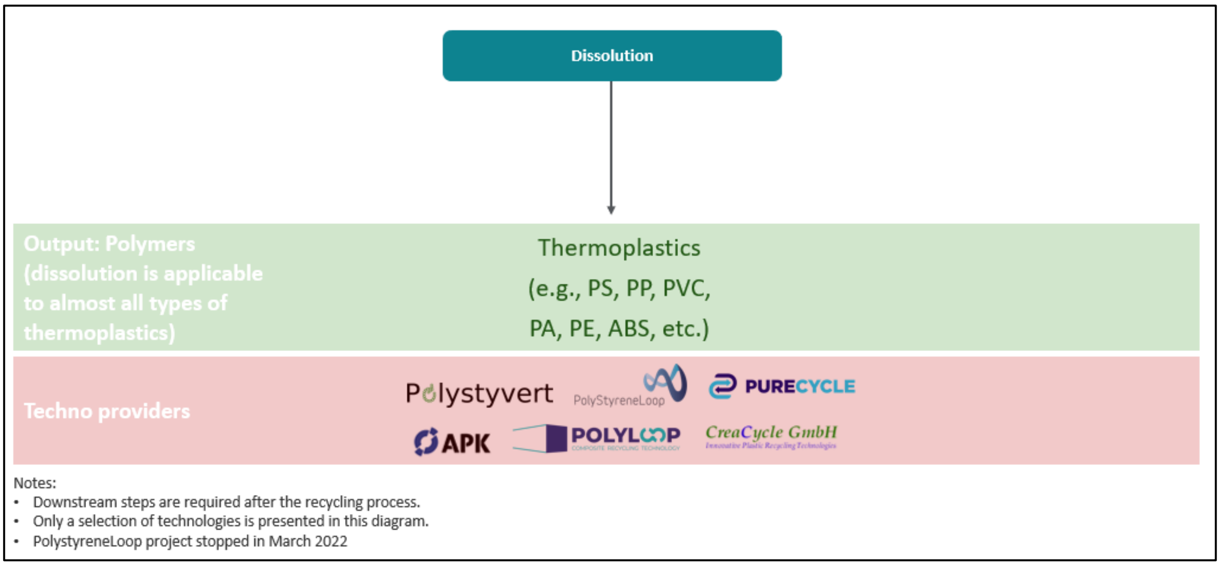
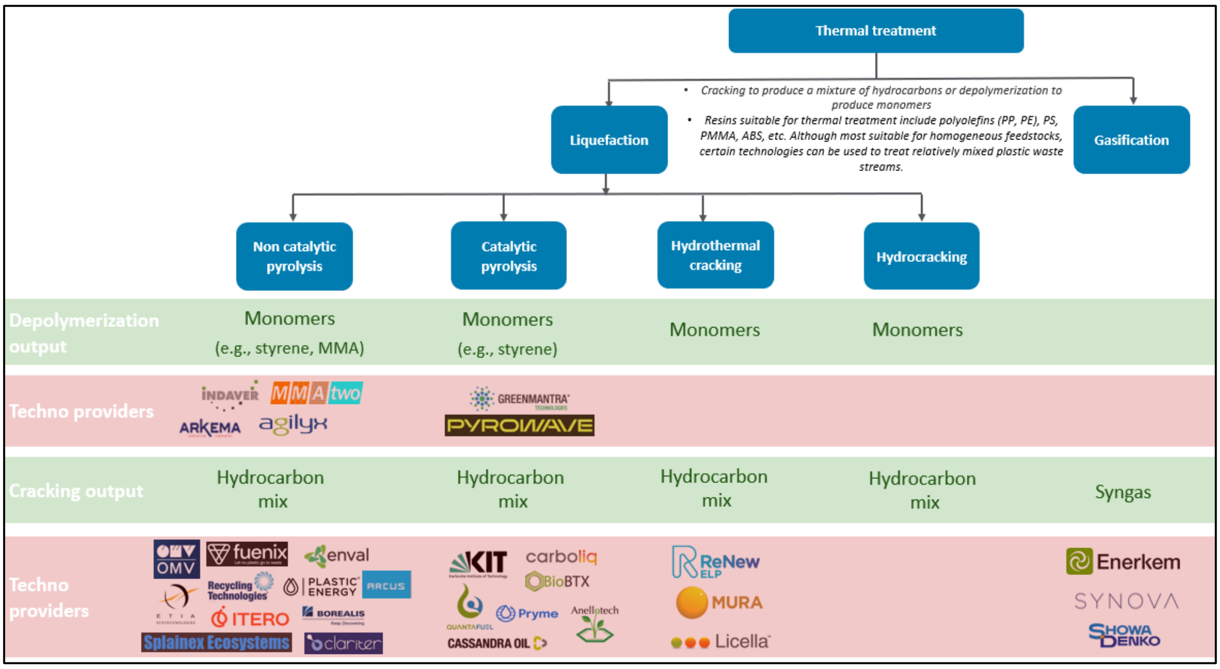


Figure 3: Dissolution technologies (RECORD, 2022)



Note:

- Downstream steps are required after the recycling process to turn hydrocarbon mix, monomers, or syngas back into plastics. As an example, pyrolysis oils could undergo a refining step and then be reinjected into a steam cracking process.
- Only a selection of technologies is presented in this diagram.

Figure 4: Thermal treatment technologies categories (RECORD, 2022)

2) Challenges by polymer type

The present report is structured around main chemical and physico-chemical recycling technologies. However, it has to be taken into account the challenges at collection, sorting and recycling steps can significantly vary from one polymer to another, especially between commodity polymers and specialty polymers (please see some examples in the Table 1 below). Commodity polymers are plastics produced in high volumes for applications where highly specific material properties are not needed (such as PET, PP, PE…). On the contrary, specialty polymers are advanced materials designed to answer a specific need in terms of mechanical, thermal, and chemical properties (such as PMMA, PPA, PPS, HPP…). In reading the report, it is thus key to keep this point in mind.

	Waste collection	Sorting/ pre-treatment	Recycling process
Specialty polymers	• Accessing a feedstock in sufficient quantity might be challenging due to the geographical dissemination of this resource. • In order to increase the feedstock volumes, there could be long-distance transport to reach the recycling plant.	• Pretreatments steps should be more thorough as the expected properties of such materials are higher than for other plastics. Indeed, these polymers are required to meet desirable mechanical, thermal, and chemical properties when subjected to harsh environments. • Chemical and physico-chemical recycling processes should be more efficient while treating lower volumes. It may therefore be necessary to put an intermediate plant which will additionally sort sorting refusals containing specialty plastics.	• Significant gains in terms of GHG emission reduction can be achieved compared to their virgin counterpart, as their virgin materials manufacturing processes are more energy intensive. • Buyers of specialty polymers use these materials because their properties are superior to those of other plastics. In some cases, such high purity is not achievable through recycling processes or requires high energy consumption.
Commodity polymers	• Accessing enough feedstock is challenging due to different factors such as purity levels (the resin can be assembled with other compounds) or concentration in the polymer of interest (that is to say the available quantity of polymer in the waste collected).	• Pretreatments steps will mainly consist in sorting and purification of the feedstock to obtain the required concentration in the polymers of interest.	• It can be challenging to show positive environmental results as energy consumption and CO_2 emissions remain lower than for specialty polymers during manufacturing of virgin fossil-based resins. The overall difference from the same recycling process between the recycled material and the virgin one can thus be lower for commodity polymers.

Table 1: Examples of challenges faced by specialty and commodity polymers (RECORD, 2022)

3) Bibliography

As previously mentioned, a literature review on chemical and physico-chemical processes has been conducted during Phase 1 of the project. Numerous public documents have been analyzed such as press releases on the website of the technology developers, scientific publications, reports (from CE Delft, BASF, Zero Waste for example), position papers, regulatory documents, etc. Some information shared by the RECORD members was also included in this report.
Please note that the latest news of the technology developers (e.g., announcement of future plants, new partnerships, etc.) have been included in the report early 2022.

Based on this literature review, the following points could be highlighted:

- The general principle of chemical and physico-chemical recycling is significantly described by the literature as well as the basics of the main technologies (e.g., solvolysis, dissolution, pyrolysis). However, most reports underline a lack of data on the environmental and economic performances of these technologies but also on the pretreatment of feedstock required before entering the processes.
- With regards to documents focused on the environmental impact of the chemical and physico-chemical recycling technologies, two approaches are in general considered. Either chemical and physico-chemical recycling processes are compared with other end-of-life processes (e.g., incineration, landfilling) or they are compared with traditional production processes. These

approaches “cradle-to-grave” and “cradle-to-gate” are both relevant and depend on the considered scope of the study. It can be noted that solvolysis is assessed against incineration in some cases, while the production of polymers from pyrolysis oil is assessed against the traditional production of fossil-based polymers.

- The technology developers’ websites are notably used for commercial communication purpose. It has to be reminded that many brands and petrochemical industries enter into a collaboration with technology developers to accelerate the scaling-up of their process. Thus, there is a strong competition between the start-ups. This is why, optimistic claims are made by the latter regarding the flexibility of the technology, the type of feedstock used, the deadline and capacities of future plants, the purity of the produced material, etc. However, they do not necessarily detail some specific points such as the calculation of yield, the methodology used behind the life-cycle analysis (LCA) figures presented on the website, the economic data, etc. Thus, this data should be considered carefully. In general, the information related to environmental and economic performances of the recycling processes are confidential and can only be discussed under non-disclosure agreement. This is also the case for the specific features of each process (e.g., type of catalyst used).
- No public and robust study on the economic performance of the main chemical and physico-chemical recycling processes (solvolysis, dissolution, pyrolysis) has been identified so far.
- The studied geographical areas do not address chemical and physico-chemical recycling in the same way when it comes to regulation. A lack of clarity can be highlighted on chemical and physico-chemical recycling and on the implementation of a mass balance approach in regulatory documents.

This is why, working sessions with experts will be conducted to better understand these topics and try to remove some of the limitations mentioned above.

4) Data availability and reliability

As previously mentioned, the information consolidated in this report is based on a public literature review (notably scientific articles, website of technology providers, reports of trade associations, etc.), information shared by the RECORD members and expert consultation.
The figure below presents the level of data currently available depending on the technology studied. It can be highlighted that plastic waste recycling through thermal treatment (notably pyrolysis) and alcoholysis is extensively studied in the literature.

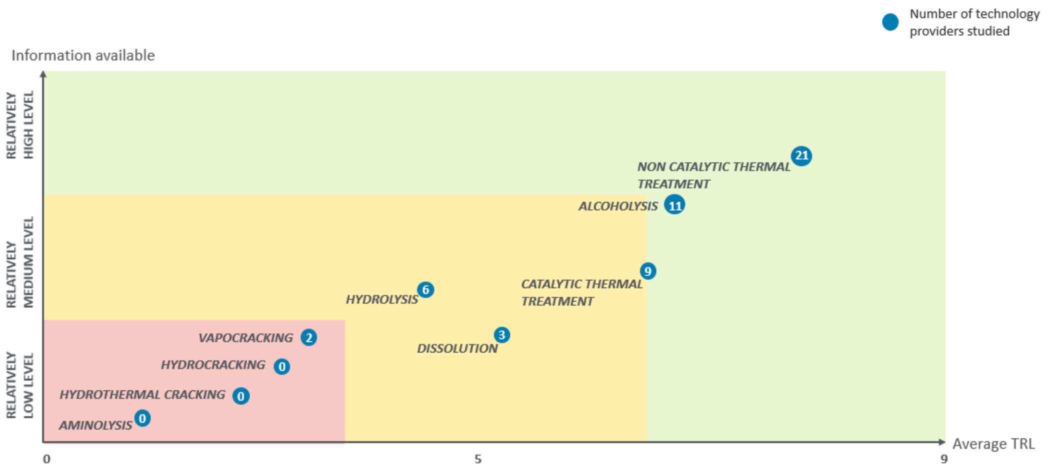


Figure 5: Public data available per technology (RECORD, 2022)

It has to be noted that there is a lack of public data available on:

- the economic performance of the studied processes. The presented information on this point is currently limited and cannot be verified.
- the environmental performance of the considered processes (notably LCA or LCA-like studies). The table below displays the information on the environmental performance of the processes currently available. As an example, glycolysis is extensively studied. Environmental

performance data is available on this technology. In addition, information is available on the comparison of the environmental performance of glycolysis with virgin resin production, incineration, and mechanical recycling.

Note: Numerous studies compare the environmental performances of chemical and physico-chemical recycling with mechanical recycling. It has to be highlighted that these processes could be considered as complementary. As they usually do not target the same feedstock and do not allow to produce the same quality of output, comparing chemical and physico-chemical recycling to mechanical recycling may not always be relevant.
However, comparison may still be considered as useful if, for example, it is meant to justify the interest in continuing to develop these two technologies in a complementary manner. Please note this point has been discussed with experts and is further detailed in the section dedicated to the synthesis of experts' opinion.

Considered recycling process	Availability of LCA data on the considered recycling process and sources	Availability of LCA data on the comparison of the considered recycling process and virgin resin production or other end-of-life processes and sources			
		Virgin resin production	Incineration	Landfill	Mechanical recycling
Glycolysis	Private institution, academics, technology developers	Private institution, academics	Private institution, Academics	Technology developer	Private institution, Academics
Methanolysis	Academics, technology developers	Academics			Academics
Aminolysis					
Hydrolysis	Technology developers	Technology developer, PlasticsEurope			
Enzymatic depolymerization					
Dissolution					
Non catalytic pyrolysis	Technology developer	Technology developer	Technology developer		Technology developer
Catalytic pyrolysis	Technology developer	Technology developer			
Vapocracking (steam cracking)					
Hydrocracking					
Hydrothermal cracking					
Gasification	Private institutions		Private institutions		Private institutions

Table 2 : Availability of LCA data and sources (RECORD, 2022)

Data available

Data not public – only the difference with an alternative (e.g., virgin polymer production, incineration) is disclosed

Data unavailable

In terms of data reliability, the following points can be highlighted:

- Process:
    - Yields are highly dependent on the feedstock and thus can actually be lower than theoretical or announced yield depending on the facility.
    - Numerous technology providers claim that no presorting/pretreatment of the feedstock is necessary before entering the process. Although this information cannot be confirmed, it is likely that such a step may be needed in practice.
- Environmental performance: the methodology and scope of the LCA results are often not communicated by the technology developers. Although this information is presented in the report on an indicative basis, the information cannot be verified and has to be considered carefully. Moreover, some LCA results were published before the publication of the delegated act on taxonomy which sets a methodological framework for chemical and physico-chemical recycling LCA. Some studies thus might not respect this framework.
- Economic performance: Qualitative information is often disclosed by the technology developers. The latter are confident their recycled material will be cost-competitive with the traditional petro-based material (with an “acceptable” premium in some cases). Again, this information cannot be verified.

In general, the technology developers are ambitious when communicating on process yield, future capacities, environmental and economic performance of the technology, etc. Please note that the information from the technology developers presented in this report are indicative and has to be considered carefully as it cannot be confirmed.

IV. Sorting and pretreatment steps

Note: for the purpose of this study, the term *pretreatment* refers to all intermediary processes (advanced sorting and separation, size reduction, stream preparation) that plastic waste may undergo before entering the recycling process. It has to be noted that limited information on the pretreatment of feedstock is publicly available.

Appropriate sorting of waste is necessary to supply both mechanical and chemical and physico-chemical recyclers with the input streams that are most suitable to their recycling operations. Collected plastic waste features contaminants, additives, multi-layered or mixed materials, which represent an obstacle to the recycling process. Continuous improvement of sorting technologies is necessary to tackle feedstock-related challenges that are encountered in recycling process[9]. Even after sorting, pretreatment of feedstock may still be needed before entering the recycling process to ensure the input requirements of the technology developers are met.

1) Separation of plastic waste in sorting centers

Waste sorting and separation is one of the most conventional steps of the recycling supply chain. After the collection phase, waste streams usually contain a variety of plastics products (rigid/flexible, different types of polymer, plastic mixed with another material, etc.), non-plastic materials (wood, paper, metals), as well as additives (e.g., brominated flame retardants, plasticizers, dyes) that could potentially contaminate recycling streams (1). Separating waste consists of removing non-plastic materials and dividing different types of plastics in diverse bales in a sorting center based on the rigidity/flexibility of the product, type of polymer, etc.

Sorting processes can be manual, automatic, or combined. A combination of automated separation is used in sorting centers to extract smaller unwanted components and divide plastics by polymer type (2). Numerous current separation processes also begin or end with a phase of manual separation (or control) carried out by operators removing unwanted materials[10]. Sorting centers are usually responsible for the primary sorting and separation of waste. Following this phase, sorted waste bales are handed over to mechanical recyclers.

As of today, the feedstock used by several chemical and physico-chemical recycling technologies generally consists of waste that is rejected by sorting centers (i.e., refuse stream) and that would alternatively be incinerated or landfilled. The composition of the sorted streams largely depends on the Extended Producer Responsibility (EPR) scheme within a country (if any) and the ongoing or future projects.

In 2019, the packaging PRO CITEO and the stakeholders of the packaging industry created a plastic packaging waste “development stream” in France. Under this new scheme, plastic packaging waste that used to be excluded from dedicated plastic collection is now disposed of within the separated plastics’ bin. This waste includes colored PET (notably bottles), opaque PET (e.g., milk bottles), PET trays (e.g., for pastry, fruits and vegetables, meats), PS pots and trays (e.g., yoghurt pots)[11]. Once plastic packaging waste has been collected, it is sent to sorting centers. During a first sorting phase, material sorting centers divide plastics and create bales composed of colored and opaque PET, PET trays, PS pots and trays. These bales are then sent to plastics sorting centers which further separate plastics and redirect

[9] https://www.plasticseurope.org/en/focus-areas/circular-economy/zero-plastics-landfill/waste-collection-pre-treatment-and-sorting

[10] Please note that organizational diagrams of sorting centers (number and nature of the sorted streams) can be different from one country to another (and even from one sorting center to another at the national level).

[11] It should be noted that colored PET bottles were already recycled before the new scheme, which creates a specific stream for this waste. Moreover, part of opaque PET bottles and mono-PET trays have been missed in PET bales during sorting and sent to mechanical recycling for several years.

them to the appropriate recycling channels. The channels include both recyclers using well-developed and under development technologies (such as chemical recyclers). The “development stream” was created to simplify waste sorting for end-consumers, to ensure high quality sorted plastic stream, and to support R&D for new solutions for hard to recycle waste[12].
This is an example of how the future evolution of waste composition and the nature of streams sorted by sorting centers should thus be taken into account to identify the feedstocks that could be used by chemical recyclers[13]. In addition, the design of products put on the market by brands is also changing with a shift towards monomaterial packaging. The evolution of the regulations will also have an impact on waste composition.

2) Pre-treatment of plastic waste before entering the recycling process

a. Feedstock pre-sorting before entering the chemical and physico-chemical recycling process

The sorting and separation phase in a sorting center is crucial to efficiently separate streams of valuable plastic waste, prevent the contamination of recycling streams, and subsequently to ensure high quality recyclates. The majority of technology developers do not officially disclose whether their recycling process requires prior sorting of the feedstock. Although able to process waste that is not suitable to be mechanically recycled, pretreatment of feedstock may be still required to remove unwanted components (e.g., plastics such as PVC) and other materials which can contaminate recycling streams, damage machinery, or deactivate catalysts (3). Hence, chemical and physico-chemical recyclers are likely to pre-treat plastic waste through a series of sorting, grinding, washing steps, etc...

A limited number of developers (Polyloop, PolyStyreneLoop, CreaCycle, etc.) explicitly mention that their process requires prior separation of feedstock, without however providing additional information concerning the type of sorting technologies they use, whether they sort waste within their facilities or if advanced sorting is carried out by an external business partner.

APK AG (dissolution of mixed plastics waste) is among the few developers that discloses information concerning its sorting process. This developer relies on the use of air-screening to sort its waste. Air-screening is a type of automatic dry sorting technology which is capable of dividing light material fractions (film particles, fibers, corks, etc.) from heavy ones (hard plastics and heavy impurities). Following this first separation phase, the collected heavy fraction is processed through densitometric separation (no further explanation available). That way, waste is further divided by plastic type.

In 2020, the technology developer Agilyx (non-catalytic thermal treatment of PS) created the joint venture Cyclyx International, which is focused on the development of a proprietary sorting process in partnership with ExxonMobil. Cyclyx (name of the venture and of the technology), aims at innovating the field of feedstock management to increase both mechanical and chemical and physico-chemical recycling rates. The technology can be used to process plastic waste into customized valuable feedstocks that meet recyclers’ specifications. According to Cyclyx’s claims, the technology will be able to increase recycling rates from 10% to 90% by sorting up to 300 kt/y by 2025, and 3000 kt/y by 2030[14].
In 2021, other companies joined Cyclyx as founding members, these include LyondellBasell, Chevron Phillips Chemical, INEOS Styrolution, AmSty, North American Plastics, Braskem, Sonoco Recycling, Casella Waste Systems, MilliporeSigma, Reynolds Consumer Products, and Corning. At the end of the same year, Exxon Mobil announced and began engineering works for the construction of the first large-scale Cyclyx plant on the Gulf Coast, in the USA. The facility, which will be completed by the end of

[12] https://www.citeo.com/interview-dun-expert/le-flux-developpement-accelerateur-de-rd-pour-le-recyclage-des-emballages
[13] Please note that all of these factors may evolve over time and that they significantly differ from one country to another. The composition of waste that is available to chemical and physico-chemical recyclers may therefore be subject to future evolutions as well.
[14] https://www.icis.com/explore/resources/news/2020/12/11/10585303/agilyx-exxonmobil-form-cyclyx-plastic-recycling-jv

2022, will support ongoing advanced chemical and physico-chemical recycling projects that Exxon Mobil is carrying out around the same geographic location.

Additional information was also found on ITERO, JEPLAN, Pyrowave, and Carboliq. It is known that a sorting step is required to ensure that polymer types in the feedstock are suitable for ITERO's technology (non-catalytic thermal treatment of mixed plastic waste). JEPLAN (glycolysis of PET) necessitates to sort waste by material and mixing ration, extract polyester from clothes, while also removing components such as buttons, blended materials, and zippers. Pyrowave uses a "mixture" (composition not specified) that is able to remove labels, films, as well as other contaminants and impurities. Carboliq (catalytic thermal treatment of mixed plastics waste) requires a step of feedstock separation and homogenization to ensure that the size of materials does not exceed a pre-determined size (40 mm for 2D waste, 5 mm for 3D), that humidity does not exceed 18%, and that waste streams are free of metals, stones, glass, ceramics, and porcelain. No details were found on the type of sorting technologies used by these developers, nor on whether they carry out these processes within their facilities, neither if a third-party is in charge of these steps. As for Plastics Energy, it is known that the developer receives waste from municipal recovery facilities and recycling factories. After receiving the waste, the developer uses pre-treatment technologies (names not indicated) to remove unwanted materials (metals, heavier plastics, etc.) and to separate only the plastics that they process (PE, PS, PP).

As a final remark, it is relevant to point out that several recyclers do not provide information on sorting steps that might be required prior to recycling (such as PureCycle Technologies – PP). Quantafuel (catalytic thermal treatment - PE, PP, PS) claims that its process does not require costly separation and cleaning due to the technology's ability to treat impurities, mixed, and colored plastics. It is however known that in July 2021 the company purchased a site in Esbjerg, Netherlands, where it plans to build one of the largest waste sorting centers in Europe (project's timeline unknown)[15]. It is also known that the Quantafuel invested in a plastic pre-treatment line in Aalborg to sort feedstock for one of its plants. No further details were found on these subjects. Other developers operating via dissolution (such as Polystyvert) claim that the phase of separation of feedstock and removal of contaminants (labels, films, impurities) is already included within their recycling process (additional information publicly unavailable).

b. Focus on other pre-treatment steps

The phase of size reduction consists in either cutting or shredding waste. This step can take place both before or after the sorting and separation phase. Of the reviewed technology developers, information was found on Polyloop, Pyrowave, APK AG and Enerkem reducing the size of their waste. It is known that Polyloop crushes its waste, while Pyrowave, APK AG, and Enerkem shred it. Pyrowave shreds waste so that its size does not exceed 5 cm. As for ITERO and Carboliq, it is known that these developers require their input to respect specific size measurements, it is however unknown whether this implies that the developers reduce the size of its feedstock within their own facilities.

In addition to sorting and shredding, other types of pre-treatment steps could include washing, drying, cleaning, and delamination.

Even after sorting and separation, plastic waste may contain a variety of substances (e.g., contaminants, odors, inks, additives, etc.) that could make recycling processes more challenging by affecting the yield and quality of the output. Literature available on this topic is extensive when it comes to mechanical recycling, yet very limited in reference to chemical and physico-chemical recycling. Hence, although chemical and physico-chemical recycling is thought-out to tolerate a higher degree of impurities compared to mechanical recycling, it remains uncertain whether pre-treatment operations targeted at the removal of such substances are required by technology developers. Of the reviewed technologies, only CuRe (solvolysis of PET), and APG AK respectively mentioned a phase of washing and cleaning of feedstock, without however providing any further details on these processes. Polyloop claims that pre-cleaning processes may be required based on the type of feedstock (no additional information available).

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[15] https://www.mynewsdesk.com/no/quantafuel-asa/pressreleases/quantafuel-purchases-a-site-for-its-esbjerg-plant-3115703

The subject of stream preparation for chemical and physico-chemical recycling is further complexified by the fact that this process is often presented as a solution for plastics that are too contaminated to undergo mechanical recycling. Developers such as CuRe, Polystyvert, Pryme and CreaCycle, state that the removal of contaminants as inks, odors, and other substances (such as flame retardants or chlorine) are included within the recycling process. This topic raises questions on the maximum levels and nature of contamination that can be handled by each technology developer and on the subsequent need for complementary stream preparation. In general, technology developers conduct some tests with different types of feedstocks to assess the flexibility of their process, determine feedstocks requirements (including the maximum level of contamination) and the necessary purification steps to be conducted to reach the required output quality.

Similarly, the ECHA believes there is a lack of evidence for what it concerns the fate of legacy substances contained in chemically recycled plastics. Missing proof on whether chemical and physico-chemical recycling technologies can target the presence of substances of concern increases the importance and the need for developing screening and sorting technologies[16].

Evidence on the subject is limited and too narrow to reach general conclusions on the topic of stream preparation techniques required by chemical and physico-chemical recyclers.

[16] https://echa.europa.eu/documents/10162/1459379/chem_recycling_final_report_en.pdf/887c4182-8327-e197-0bc4-17a5d608de6e?t=1636701265520

V. Chemical treatment – solvolysis

1) Glycolysis

a. Technology

Input

This recycling technology is generally used on polymers from polycondensation (such as polyesters or polyamides)[17] as their bonds can be degraded by alcohols reagents (4). Polyesters (such as PET, PBT, PTMP) are the most easily recyclable through glycolysis due to their ester group that can be easily cut by glycols (5).

- PET feedstock: The most advanced technologies currently are focusing on PET. The feedstocks targeted are usually PET streams that cannot be mechanically recycled, such as opaque PET[18] (Ioniqa Technologies, IBM), polyester fibers (JEPLAN, Poseidon, Ioniqa Technologies, Eastman, PerPETual), films (PerPETual), trays (SOPREMA), multilayered PET (Garbo), and other complex packaging (SOPREMA). For post-consumer streams, presorting is necessary to ensure the quality of the output product. This is confirmed by some developers, such as CuRe who assert that sorting, washing and preparation of the feedstock is needed before it can enter the process[19]. JEPLAN is adding the precision that, when the feedstock is composed of textile and clothes, polyester extraction is necessary (which consists in removing buttons, blended materials, zipper…)[20]. However, IBM Technology claims that no additional sorting is necessary[21]. This information cannot be confirmed. In practice, such a step may be needed as PET can contain impurities (such as colors, glues, and other contaminants).
- Polyamide feedstock: Some technologies are being developed to treat polyamides through glycolysis (4). These technologies are still at an early stage of development and very few companies are mature on an industrial level (4). Indeed, based on the list of technology developers studied, only JEPLAN is at a commercial scale. Polyamide waste streams are smaller and more dispersed than PET streams, which makes feedstock access more challenging. The main issue of mechanical recycling for polyamides is that waste feedstock comes in a blend of polyamide 6 (PA6) and polyamide 6 (PA6.6), which have different properties. It is however important that recycled materials have well-defined and repetitive properties, even after multiple processes. For now, there is no evidence that chemical recycling can treat a mixture of these two compounds. Presorting is thus necessary to ensure that glycolysis treats separately PA6 and PA6.6. Competition with mechanical recycling is consequently high (6).
- Polyurethane feedstock: Technologies such as RAMPF Eco, H&S anlagentechnik or Emery Oleochemicals target polyurethane foam scrap, post consumption waste from mattresses or industrial waste. The waste stream contains very diverse materials (flexible, rigid, semi-rigid, elastomers) and is thus challenging to treat without presorting. This implies supplementary costs.

These technologies require significant preprocessing to ensure the advanced sorting of the feedstock. This can be achieved either by locating next to a partner that supplies the feedstock or initiating strategic partnerships such as Biffa's agreement with Poseidon Plastics, Dupont Teijin Films, Alpek, GRN and

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[17] Polycondensation is a polymerization reaction during which two monomers are forming a bond and loosing smaller molecules in the process such as water or methanol.
[18] In France, clear colored PET can be mechanically recycled. Historically opaqueopaque PET bottles have been mixed with colored PET and mechanically recycled. There are now ongoing developments on the mechanical recycling of opaque PET as a specific stream. Outside of France, the mechanical recycling of opaque PET is developing but is still at a very early stage.
[19] https://curepolyester.com/
[20] https://www.jeplan.co.jp/en/products/

O'Neills, in which Biffa will separate out the difficult to recycle PET plastics, such as colored PET and trays, and supply this as feedstock for Poseidon Plastics' plant[22].

Process

These technologies use an alcohol as a solvent to degrade the bounds and thus go back to smaller molecules (monomers, dimers, or oligomers). This alcohol is usually ethylene glycol (or, in rare cases, a diol).

These processes require heat. The quantity of heat is highly dependent on the process and the feedstock chosen. Challenging feedstocks, such as multilayered PET, are usually more heat-intensive (4). Usually, glycolysis processes occur at more than 200°C (4).

In the case of PET, IBM technology (also known as Volcat) confirms this temperature as they have made publicly available the information that the process temperature is higher than 200°C[23].

The required heat is also very dependent on the process chosen and the presence of catalysts for instance. For instance, PerPETual states that, to minimize undesirable side effects of the traditional much higher temperature depolymerization process, they used a materially lower temperature process. They estimated 75% energy savings when comparing their technology to conventional virgin PET manufacturing[24]. However, this temperature range is not publicly known.

In general, complete conversion of the polymer is achieved for times often exceeding 5 hours. Metal-based catalysts are often required to significantly increase the reaction rate (4).

SOPREMA's recycling process (Sopraloop) consists of a unique combination of mechanical and chemical recycling. First, plastics are shred and cleaned. Then, the obtained flakes are processed through glycolysis[25]. Then, the product is repolymerized and converted into polyols.

The temperature range is quite similar for polyamides as a study found the temperature of 275°C to be efficient on PA6.6 (7). Another study refers to glycolysis of PA6.6 at 190°C and atmospheric pressure (8). As for PA6, a study found that the reaction lasted 3 hours at 250°C (9).

JEPLAN discloses a depolymerization yield of 98% for its process (10) and Ioniqa Technologies claims a depolymerization yield of 93% (14). Yields are not disclosed by the majority of the other technology developers, but IFPEN/Axens is stating that the yield obtained ensures the technical and economic viability of the process[26]. However, it is likely that these yields do not include the purification yield.

As Emery Oleochemicals underlines, the yield is also dependent on the application. The purest a material needs to be, the lowest the yield will be due to additional purification steps. Indeed, foam production can have high yield loss in case the grade needed for the material is high[27].

Output and downstream steps

When recycling PET, the output obtained by a total glycolysis gives out BHET (Bis(2-Hydroxyethyl) terephthalate) as chemical intermediate.

Contrary to other technology developers, CuRe technology is not depolymerizing completely the polymer but is using a partial depolymerization, going back to smaller polymer chains. The output is afterwards purified and directly repolymerized to obtain recycled PET. There is thus no need of a downstream partner to repolymerize the product[28].

[22] https://packagingeurope.com/biffa-backs-project-to-recycle-previously-non-recyclable-plastic/
[23] https://www.greenbiz.com/article/ibm-chemists-have-found-faster-way-recycle-plastics-even-stuff-coated-residue
[24] https://www.perpetual-global.com/about/#story
[25] https://www.citeo.com/le-mag/sopraloop-une-usine-la-pointe-du-recyclage-des-emballages-en-pet/
[26] https://www.ifpenergiesnouvelles.fr/innovation-et-industrie/nos-expertises/climat-et-environnement/recyclage-des-plastiques/nos-solutions
[27] https://www.emeryoleo.com/sites/default/files/2019-11/Emery-INFIGREEN-Recycled-Content-Polyols-Overview.pdf
[28] https://curepolyester.com/

As for the French company SOPREMA, the monomers obtained from complex PET waste are then repolymerized as polyols which are used in the production of polyurethane insulating foams for the construction sector[29].

Regarding polyurethane, its glycolysis produces mixes of polyols.

The products of the glycolysis of polyamides are oligomers or small-molecular-weight chemical compounds with different physico-chemical properties and functionality. The aim of polyamide depolymerization is to obtain caprolactam and hexamethylenediamine, which can be utilized in the synthesis of new polyamide 6 or PA6.6 respectively (8).
A study was conducted on PA6.6 recycling through glycolysis, which gave out hexamethylenediamine, esters and another primary amine (7). Hexamethylenediamine can afterwards be used to reproduce PA6.6 via step growth reactions[30]. However, adipic acid is lost during the reaction and must be added to complete the repolymerization.

In most cases (including clear PET flake streams), purification steps are needed to remove residual colorants and contaminants. These steps are often done by the technology developer (such as CuRe, Garbo or Poseidon Plastics, PerPETual). The purity of the product obtained can be very close to the virgin resin. For instance, Poseidon Plastics' technology has been verified by independent corporate partners that have successfully validated the quality of the recycled product through the manufacturing of polyester with recycled content between 25 – 100%[31]. However, there is no further information on the type of finished product this polyester is intended for. Indeed, the quality requirements are different if the end product is supposed to be food grade or not for example.

The DuPont Teijin Film process upcycles mechanically recycled material. This means that the depolymerization process occurs exclusively on mechanically clear and clean PET flakes. The recycled material thus does not seem to need further purification steps, due to the high quality of feedstock[32].

DuPont Teijin Films is repolymerizing BHET into a polyester polymer, which is itself converted into BOPET (biaxially-oriented polyethylene terephthalate) films. Their products MYLAR® and MELINEX®, produced from post-consumer recycled contents, are afterwards commercialized.
PerPETual is also using the output ester to produce polyester yarns for textiles.

b. Technology scaling-up

Average Technology Readiness Level
Most of the technology developer studied are between laboratory stage and demonstration stage. Their TRL thus ranges from 3 to 7.
However, technologies such as JEPLAN and PerPETual are currently very advanced (TRL= 8-9) as they are already owning their first industrial capacities[33].

Current and future capacities
The technology developers studied are operating plants from a few hundred tons per year to 20kt/year for the most advanced developers.

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[29] https://www.soprema.com/en/article/news/sopraloop-a-process-that-turns-plastic-waste-into-insulation
[30] Type of reaction mechanism in which monomers are reacting together to form dimers, trimers and gradually longer chain until the polymer attains its final length.
[31] http://poseidonplastics.com/
[32] https://www.plasticsnews.com/article/20190408/NEWS/190403357/dupont-teijin-films-launches-pet-chemical-recycling-process#:~:text=DuPont%20Teijin%20Films%20has%20launched,for%20use%20in%20various%20applications.
[33] https://www.jeplan.co.jp/en/products/

Today JEPLAN owns two operational factories: a PET Refine Technology plant with capacity of 22 kton/year (bottle to textile – not specified if input or output) and Kitakyushu Hibikinada Plant demonstration facility with a capacity of 2 ktons/year (input/output not specified) aiming at recycling textile to textile. Both plants use JEPLAN's proprietary technology. In 2018, JEPLAN announced the beginning of a research project for the construction of a textile recycling plant in the Lyon area, while news on the advancement of the plant's construction is unavailable, it is known that the French and Japanese governments agreed to support JEPLAN's business development plans in the area [34] [35]. In 2019 the developer also disclosed its intention to build recycling facilities across China, Indonesia, and USA. JEPLAN is partnered with the Japanese Ministry of the Environment, Nippon Steel Sumitomo Metals Co. Ltd. (technology partner), Sojitz (acquired a 25% stake in the PET Refine Technology), collection sport partners (e.g. Aeon, SelfService, Aeon Mall, Seven&Iholdings, ah, GrandTree Musashikosugi, Seibu Sogo, Food systems, Tower records, Loft, Starbucks, Ryohin Keikaku Co., Ltd.) and financing partners (Jafco Co. Ltd., Shijo Ltd., Taiyo Kogyo Co. Ltd, NTT DoCoMo Inc., Kamakura Investment Trust Management Co, Ltd).

Since 2014, IFPEN/Axens has been developing a proprietary glycolysis technology (called Rewind PET) for the recycling of PET colored and opaque bottles. In 2022, IFPEN/Axens signed a collaboration agreement with JEPLAN to develop and commercialize the Rewind PET technology. The two developers are using their respective technical expertise to conduct testing at JEPLAN's demonstration (2 kt/y) plant. The commercialization of the technology is expected by the end of 2022[36].

Among more advanced technologies, Ioniqa Technologies operates a 10kt/y plant in the Netherlands (the first batches of PET plastic waste were processed in Summer 2019 - no news on the topic have been released since then). Ioniqa Technologies is a spin-off of the Eindhoven University of Technology. Its partners include Unilever and Indorama Ventures with whom Ioniqa Technologies established the common goal to develop a technology recycling PET for food-grade applications[37]. The developer also received a loan extension from Coca-Cola to speed-up the development of the technology[38]. The developer's long-term plans include an expansion through the deployment of licenses for its PET recycling technology, as well as the development of new solutions for the recycling of PA and PEF. In May 2021, Ioniqa Technologies received a 10 million euros funding (source unknown) which will be used for scaling-up its facilities.

As regards to Poseidon Plastics, they are currently producing 1,000 tons per year of consumable product grade BHET per year. The developer is collaborating with Alpek Polyester UK, Biffa Waste Services, GRN Sportswear, O'Neills Irish International Sports Company and University of York to develop Poseidon's enhanced PET recycling technology. Poseidon Plastics is building its first 10,000 ton/year facility (no deadline for the completion of the construction of this plant is disclosed). They are currently in advanced discussions with a leading German engineering and construction contractor in the PET industry (name not disclosed)[39]. DuPont Teijin Films is a partner in the development of recycling solutions for flexible PET films. Specifically, Dupont Teijin is supporting the developer during the testing and processing phases as well as in relation to existing regulatory aspects and certifications. In February 2021, Poseidon Plastics entered a reverse takeover process with Curzon Energy (a global energy company). The transaction was supposed to be finalized by mid-2021, no additional information has been found on this topic.

CuRe Technology has built its first pilot plant in Emmen, the Netherlands. The pilot plant has a capacity of 20kg/hr. in a continuous process, which is intended to be scaled up to 25 ktons/year. They are as well

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[34] http://www.jeplan.co.jp/uploads/JEPLAN-INC.Research-Project-for-Commercialization-of-Clothing-Recycling-in-Lyon-France.pdf
[35] https://www.jeplan.co.jp/en/2019/07/22/8286/
[36] https://www.ifpenergiesnouvelles.fr/article/recyclage-du-pet-axens-ifpen-et-jeplan-vont-demontrer-et-commercialiser-procede-innovant
[37] https://ioniqa.com/unilever-ioniqa-and-indorama-launching-breakthrough-food-packaging-technology/
[38] https://ioniqa.com/the-coca-cola-company-announces-loan-agreement-with-ioniqa/
[39] http://poseidonplastics.com/about/

constructing a repolymerization line (of a 25 kt/year capacity, which is expected to start at Q1 2021 – no updates as of January 2022)[40]. In September 2020, the Dutch Government decided to grant CuRe Technology a subsidy under the DEI+ program[41] (amount unknown). In June 2020 the developer had also received a funding from Coca-Cola Europacific Partners (CCEP) Ventures for the scaling-up of their process from pilot to commercial scale[42]. In exchange for the investment, CCEP will receive the majority of the output from the CuRe Technology-licensed plant (no further news published).

Following the expansion of its plant in 2019, PerPETual now owns a commercial plant operational in Nashik, India that processes about 30 kt/year[43]. A further expansion of the plant is scheduled for 2022. PerPETual's goal for 2021 was to recycle over 500 kt/year[44]. According to available news, this goal has not yet been achieved. Brands such as Adidas, Zara, H&M, Decathlon are already integrating the PerPETual recycled yarns within their products.

Garbo has successfully completed its lab-scale stage (capacity 10kg/day, it is not specified whether it refers to input or output capacity). As of 2019, they began a pre-industrial phase through the deployment of a demonstration plant with a capacity of 3 t/day (equal to approximately 1000 tons a year, it is not specified whether it refers to input or output capacity). Garbo's partners include the University of Modena and University of Bologna (partners in the development of Garbo's ChemPET recycling technology), IKEA (partnership not specified), Indorama (partnership not specified), and the European Union (through the H2020 program).

CuRe Technology, PerPETual, Garbo, and Gr3n (please refer to the paragraph on hydrolysis) have been enlisted within the Full Circle Textiles Project – Polyester. The project, launched by Fashion for Good, aims at gathering partners and financial supporters for chemical recycling technologies which could support recycling within the fashion industry. The consortium running the project is composed of different actors along the supply chain including brands, innovators, supply chain partners and catalytic funders. This project (announced in December 2021) will last 18 months during which developers will produce r-PS. The partners of the project will then evaluate the output produced and assess the scaling-up potential of the technology[45].

H&S Anlagentechnik's technology recycles flexible and rigid PU foams. The feedstock however needs to be consequently purified in order to ensure that they are free of contaminants that could impede the recycling process[46]. The flexible PUR foam reactors can be supplied with batch capacity from 1t to 5t and the rigid foam reactors can be supplied with batch capacity from 1t to 5t or bigger if required. The developer signed a contract with RetourMatras (Dutch recycling company) to build an industrial scale plant in Flevoland, Netherlands, for the recycling of polyurethane mattresses[47]. Dow is additionally deploying their technology within the project Renuva, which aims at developing solutions for the recycling of PU foams contained in mattresses[48]. The project is at its pilot phase, the first reactor was inaugurated in September 2021 and has a capacity of approximately 200 000 mattresses per year[49].

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[40] https://curetechnology.com/news/our-pilot-plant-is-expanding/

[41] The DEI+ program is run by the Dutch Government. The goal of the scheme is to fund pilots and demonstration projects that aim at reducing CO_2 emissions to meet the Dutch government's 2030 climate targets.

[42] https://curetechnology.com/news/coca-cola-european-partners-ccep-ventures-funding-for-cure-technology/#:~:text=The%20funding%20from%20CCEP%2C%20through%20its%20innovation%20investment,the%20output%20from%20a%20CuRe%20Technology-licensed%2C%20new-build%20plant.

[43] Calculation from technology provider data of 3,000,000 clear bottles/day, with the assumption of a 30g bottle.

[44] Calculation from technology provider data of 50,000,000 bottles a day

[45] https://curetechnology.com/news/cure-technology-participates-in-the-fashion-for-good-project/

[46] https://www.hs-anlagentechnik.de/en/recycling-reactors-for-pu-residues.html

[47] https://www.gupta-verlag.com/news/technology/25066/hs-new-reactor-plant-for-the-recycling-of-end-of-life-pu-mattresses-in-the-netherlands

[48] https://fr.dow.com/fr-fr/renuva-programme.html

[49] https://fr.dow.com/fr-fr/renuva-programme.html

Other developers are choosing used mattresses as their feedstock of choice. Indeed, the chemical company Orrion Chemicals Orgaform of Semoy inaugurated in 2021 its new unit, intended to treat 200.000 old mattresses in France. This is the result of a two- and half-year process in collaboration with Dow Chemicals[50].

Dupont Teijin Films announced they developed the LuxCR™ depolymerization process in April 2019 which allows to recycle clear post-consumer PET waste into advanced BOPET (biaxially-oriented PET) films. Commercial launches of a range of packaging formats (including for high temperature food-contact applications) were expected in Q2 2019, but there has not been any news confirming it has effectively taken place[51]. The developer collaborates with Poseidon Plastics as a technology partner to adapt Poseidon's technology to the recycling of flexible PET films.

It is also known that Eastman owns an operational glycolysis plant in Kingsport, Tennessee (status and capacity unknown) and that they claimed their goal in 2020 was to process up to 50 million pounds of scrap plastic (equivalent to approx. 23kt, no further details provided).

With the support from ADEME and Citeo, SOPREMA has opened a recycling facility in Strasbourg, France in 2018. SOPREMA claimed that from 2019 they would have been able to recycle an input of 5kt/y of PET, no additional information has however been published since that year. The company additionally envisioned that their capacity would have reached a total 10kt/y by 2024[52] (no news since 2019). Complex PET waste is treated by SOPREMA to produce recycled polyols. The latter will be used to produce insulating panels made of polyurethane foam for building applications.
In 2019, SOPREMA indicated that up to 50% of virgin polyols could be substituted by recycled polyols. The developer aims to increase such rate in the long term[53].

A technology that seems so far to be less developed is that of IBM Research's (which is moving from lab phase to pilot phase).

Among the glycolysis technology developers studied, planned capacities ranges from 10 to 50 ktons per year and are mostly planned for the coming years.
Some developers don't intent to operate their plants and aim at selling licenses. For instance, Ioniqa Technologies aims at spreading their technology by licensing it out worldwide for the production of monomers on an estimated 50+kt scale (news date unavailable). In 2021, they declared that their first 10kt/y plant will be ready by early 2022 (no updates as of January 2022)[54].

c. Economic performance

This recycling process requires high costs, especially in waste pretreatment, that is to say presorting and purification steps. Moreover, compared to mechanical recycling, capital expenditure (CAPEX) and operating expenses are high as well due to the fact that solvents need to be reprocessed and the equipment needs to be made of noble materials that resist corrosion.
Moreover, monomers obtained from the process are currently not sold at a very high price which makes it difficult to ensure the economic viability of the process (5).

However, BHET (and higher oligomers) obtained from glycolysis process can be used as building block for the synthesis of other polymers, with higher economic value, such as unsaturated polyesters, polyurethane foams, polyisocyanurate foams, co-polyesters, polyurethane coatings, alkyd resins, low-temperature thermosetting resins or PET for food packaging (4).

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[50] https://www.larep.fr/semoy-45400/actualites/recyclage-chimique-de-matelas-usages-dans-le-loiret-une-premiere-mondiale_14015742/
[51] https://europe.dupontteijinfilms.com/news/2019/dupont-teijin-films-makes-a-significant-step-forward-in-chemical-recycling-with-the-luxcr-depolymerisation-process/
[52] https://www.soprema.fr/fr/article/news/soprema-lance-sa-premiere-unite-de-recyclage-d-emballages-pet
[53] https://www.citeo.com/le-mag/sopraloop-une-usine-la-pointe-du-recyclage-des-emballages-en-pet/
[54] https://siliconcanals.com/crowdfunding/ioniqa-raises-10m/

d. Environmental performance

LCA data (or similar studies), notably carbon footprint

Glycolysis avoids the use of methanol, sometimes under supercritical conditions, used in methanolysis, and limits the environmental impact of recycling, since strong acids or bases, necessary for PET hydrolysis, are not used (12).

Glycolysis process uses however non-biodegradable and toxic metal catalysts, such as Zn salts, which are considered to be the most efficient in PET Glycolysis (12).

Poseidon Plastics, a joint venture between Green Lizard Technologies Ltd, Panima Capital and Abundia Industries LLC., conducted an LCA of their technology and deduced that it saved 1705 $kgCO_2$ per ton of PET which was recycled instead of being sent to landfill[55].

Eastman asserts also that making their proprietary product Tritan Renew (recycled bisphenol A-free copolyester), which is composed of up to 50% recycled resin (using the ISCC mass balance), is 20-30% less greenhouse gas intensive than using fossil fuel-based feedstocks[56]. However, the results of both assessments have not been published nor detailed publicly and thus are unverifiable.

Comparative analysis between end-of-life processes

Ioniqa Technologies' process has been assessed by CE Delft (the study was funded by the Dutch government) (13). Summaries of the different calculations and methodologies applied are available but do not comprise the full detail of the calculations. Three methodologies were applied:

- A linear comparison from a waste perspective, which analyses the processing of one ton of PET waste by Ioniqa Technologies and compares it with mechanical recycling and processing by incineration in an average Dutch facility.
- A multicycle equation, which models the processing of one ton of PET waste by Ioniqa Technologies over two successive recycling loops and does the same for mechanical recycling.
- A product comparison, which analyses the production of one ton of PET from the Ioniqa Technologies process and compares it with the production of 1 ton of conventionally produced PET from fossil raw materials.

The results were as follows, given for 1 ton of PET waste for linear comparison and multi-cycle analysis and for the production of 1 ton of PET for product comparison (13):

	Combustion	Ioniqa Tech. (10 kton facility)	Ioniqa Technologies (50 kton facility)	Mechanical recycling (20% recycling failure rate[57])	Mechanical recycling (10% recycling failure rate)	Mechanical recycling (0% recycling failure rate)	Conventional PET production
Linear comparison	1.485 tCO_2e	-1.132 tCO_2e	-1.479 tCO_2e	-1.371 tCO_2e	-1.766 tCO_2e	-2.161 tCO_2e	
Multi-cycle analysis		-1.619 tCO_2e	-2.191 tCO_2e	-0.878 tCO_2e			
Product comparison		1.344 tCO_2e	0.997 tCO_2e	0.917 tCO_2e	0.621 tCO_2e		3.963 tCO_2e

Table 3 : Summary of the environmental impacts of several end-of-life technologies assessed in the study from CE Delft (13)

[55] http://poseidonplastics.com/

[56] https://cen.acs.org/environment/recycling/Eastman-build-250-million-plastics/99/web/2021/02 and https://www.eastman.com/Brands/Eastman_Tritan/Pages/tritan-renew.aspx

[57] The recycling failure rate designates waste that has not been treated in mechanical recycling. A 20% recycling failure rate thus means a 80% final yield.

Note: The comparison between end-of-life processes takes into account avoided emissions and are thus negative, whereas when considering the production of a new product, end of life emissions are not accounted for and emissions are thus positive. The avoided emissions taken into account are avoided CO_2 emissions from the production of heat and electricity and the avoided production of PET.
Furthermore, no failure rate is considered for Ioniqa's technology, whereas it is likely that, in reality, some of the feedstock is not converted.

- In the linear comparison, mechanical recycling emits less greenhouses gases than Ioniqa's 10kt plant, regardless of the amount of failure. The emissions of the 50 kton plant are however similar to mechanical recycling if the failure in mechanical recycling is about 15%. If the failure rate is lower, mechanical recycling has less environmental impacts. The results show that Ioniqa's technology is a good option for streams that cannot now be mechanically processed, or which are rejected. If these streams were otherwise incinerated, the environmental benefit would be considerable.
- The results for the multi-cycle analysis show that mechanical recycling has the disadvantage that the output has a lower quality than the output of Ioniqa's technology. Ioniqa's material is used again for food-grade PET bottles and the material from mechanical recycling mainly for fleece sweaters (or other plastic products)[58]. However, it has to be noted that food-grade PET can be produced via mechanical recycling (taking into account that in a perfect closed-loop system, food-grade PET could not be produced more than 3 or 4 times using the same material). Moreover, this assessment assumes that the output is burned after one cycle and not recycled a second time, which is conservative for mechanical recycling technologies. For Ioniqa, it is assumed that the output is high quality (virgin quality) and is used again in PET bottles. A 35% (respectively 5%) ratio is assumed to be incinerated for small bottles (respectively large bottles) because it does not end up with a recycler (lost during the sorting process).
- The latest comparison shows that the production of conventional PET from petroleum is about 2.5 tCO_2e /t of PET. If end-of-life combustion emissions are added, this amounts to just under 4 tCO_2e/t of PET. If Ioniqa is considered to be a PET producer, the result depends on the allocation of the combustion avoided by applying the Ioniqa process. Adding this advantage, the production of Ioniqa-PET provides 1 to 1.3 tCO_2e /t of PET from Ioniqa-BHET, depending on the scale of the plant.

Due to lower energy inputs, PET from mechanical recycling has still less impacts than PET from Ioniqa's technology. The difference depends on the amount of PET that falls out and is burned. The advantage of obtaining a better quality of output is not taken into account.

A study published in 2010 evaluated the impacts of PET bottle-to-fiber recycling of four different technologies: mechanical recycling (using Wellman International Ltd.'s technology), semi-mechanical recycling[59] (using long John Group's process), back-to-oligomer recycling (using Far eastern New Century CO., Ltd.'s glycolysis process) and back-to-monomer recycling (using Patagonia's LCA results on the methanolysis process). As these companies have different locations, it is important to note that the results on mechanical recycling, on methanolysis and on virgin PET fibers are applicable to Western Europe, whereas the results for glycolysis and semi-mechanical recycling are computed with data from Taiwan. This could influence the results. As these companies have different locations, it is important to note that the results on mechanical recycling are dependent on the recycling schemes in place in such regions.

[58] This assumption is conservative as rPET from mechanical recycling of clear bottles is more and more used to produce new bottles.
[59] Semi-mechanical recycling designates the Long John Group's process that produces recycled PET fibre through the flake-pellet-fibre route. As Long John Group adds a small amount of ethylene glycol to meet the final quality requirements, the process is called "semi-mechanical".

The methodology used was the LCA ISO 14040 on a cradle-to-factory gate for second life approach. Two different methodologies were used to quantify the impacts: the "cut-off" methodology[60] and the "waste valuation" methodology[61] (11).

The "cut-off" approach results were as follows (15):

- Mechanical recycling emits 0.96 tCO_2/t of recycled PET fiber
- Semi-mechanical recycling emits 1.88 tCO_2/t of recycled PET fiber
- Chemical recycling through glycolysis emits 2.59 tCO_2/t of recycled PET fiber
- Manufacturing virgin PET fibre emits 4.06 tCO_2/t of virgin PET fiber[62]

The "waste valuation" results were comparable to the "cut-off" approach (11):

- Mechanical recycling emits 2.03 tCO_2/t of recycled PET fiber
- Semi-mechanical recycling emits 2.95 tCO_2/t of recycled PET fiber
- Chemical recycling through glycolysis emits 3.66 tCO_2/t of recycled PET fiber
- Manufacturing virgin PET fibre emits 4.06 tCO_2/t of virgin PET fiber

Indeed, the glycolysis process emits between one and three times the amount of CO_2 than mechanical recycling but is still better than manufacturing virgin fiber. It should however be kept in mind that the properties of recycled material are different in the case of mechanical recycling, which does not give out virgin-like PET contrary to glycolysis. The two types of recycling are thus complementary depending on the use of the recycled material.

Energy costs

The same study goes through the energy use of the different recycling methodologies.

The "cut-off" approach results were as follows (11):

- Mechanical recycling uses 13 GJ of non-renewable energy
- Semi-mechanical recycling uses 23 GJ of non-renewable energy
- Chemical recycling through glycolysis uses 39 GJ of non-renewable energy
- Manufacturing virgin PET fibre uses 95 GJ of non-renewable energy

Thus, the glycolysis process uses three times more energy than mechanical recycling (partly due to the temperatures range needed to complete the process) but is still almost 2.5 times better than manufacturing virgin fibers.

[60] The "cut-off" methodology refers to the omission of not relevant life cycle stages, activity types (e.g. investment goods, storage, ...), specific processes and products (e.g. re-granulating of internally recycled polymer production waste before re-melting) and elementary flows from the system model. Cut-offs are quantified in relation to the percentage of environmental impacts that is approximated to be excluded via the cut-off (e.g. "95 %" relates to cutting off about 5 % of the total environmental impact (or of a selected impact category)). Source: general guide for Life-cycle Assessment – Detailed guidance. In our case, the used bottles from the first life are considered to be waste and not bear any environmental burden from the first life.

[61] The "waste valuation" methodology refers, in our case, to the allocation of the impacts of the first life of the bottles on an economic basis. It was assumed that 32% of the environmental burden of virgin PET bottle grade resin is shifted to the recycled PET fibre.

[62] The difference with Ioniqa's earlier result of 2.5 tCO2e/t resides in the fact that the virgin fibre here takes into account the embedded energy of the virgin PET fibre (which accounts for about 40% its the energy consumption)

<table>
<tr><th colspan="2">GLYCOLYSIS</th></tr>
<tr><td>Technology</td><td>Input
• Suited to polymers from polycondensation, mostly used for PET, PA, and PU.
• Treats mono-material streams with a relatively low level of contamination.
• Pre-sorting or pre-treatment are often necessary (e.g., sorting, washing, grinding, etc.).
Process
• The feedstock is dissolved in Ethylene Glycol.
• The temperature required varies between 200°C and 300°C depending on the feedstock.
• The reaction lasts from 3 to 5 hours.
• Depolymerization yields announced are comprised between 93% and 98%*.
Output and Downstream steps
• The output of total PET glycolysis is BHET. This compound could be used to produce new PET.
• The output of PA6.6 glycolysis consists of hexamethylenediamine. This compound can afterwards be used to produce PA6.6 again. However, adipic acid is lost during the reaction and must be added to complete the repolymerization.
• The output of PA6 glycolysis consists of caprolactam. This compound can afterwards be used to produce PA6 again.
• The output of PUR is diol mixes. This mix could be used to produce new PU.
• In almost every case, purification steps are needed to remove colorants and contaminants.
• The purity obtained is close to the virgin resin one.</td></tr>
<tr><td>Technology scaling-up</td><td>Average Technology Readiness Level
• Estimated TRL = 3-7 (depending on the technology developer)
• Most technology developers are still in the development phase of their technology except for JEPLAN, which is at industrial scale.
Current and future capacities
• Technology advancements and plans for expansion significantly vary from a developer to another.
• PerPETual and JEPLAN are the most advanced technology developers in terms of scaling-up of their technology and/or capacity of their facilities (mainly using clear PET as feedstock).
• Planned capacities ranges from 10 to 160 ktons per year and are mostly planned for the coming years[63].</td></tr>
<tr><td>Economic performance</td><td>• High pre-treatment costs due to sorting and decontamination steps
• Reprocessing of the solvent is an additional cost compared to mechanical recycling
• Equipment needs to be made of noble materials that are resisting corrosion
• BHET (and higher oligomers) obtained from PET glycolysis process can be used as building blocks for the synthesis of polymers, with higher economic value (unsaturated polyesters, PU foams…).
• Lack of public data available</td></tr>
</table>

63 https://www.eastman.com/Company/Circular-Economy/Solutions/Pages/Our-investment-in-France.aspx

Environmental performance	LCA data (or similar studies), notably carbon footprint • Glycolysis avoids the use of methanol, sometimes under supercritical conditions, used in methanolysis, and limits the environmental impact of recycling, since strong acids or bases necessary for PET hydrolysis are not used Comparative analysis between end-of-life processes • Lower environmental impact than combustion but higher impact than mechanical recycling (if the failure rate is inferior to 10%) Energy costs • The glycolysis process uses three times more energy than mechanical recycling (partly due to the temperatures range needed to complete the process) but is still almost 2.5 times better than manufacturing virgin fibers. • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	

Table 4 : Glycolysis recapitulative table (RECORD, 2022)

*Yields can vary depending on the feedstock type and operating conditions. These yields are likely to be overestimated as they have been calculated by technology developers on a lab scale.

2) Methanolysis

a. Technology

Input

This recycling technology is generally used on polymers from polycondensation (such as polyesters or polyamides) as their bonds can be degraded by alcohols reagents (4). Polyesters (such as PET, PBTP, PTMP) are the most easily recyclable through methanolysis due to their ester group that can be easily cut by glycols or methanol (5). The most advanced technologies currently are focusing on PET polymer. The feedstock used are usually PET streams that cannot be mechanically recycled, such as opaque PET and polyester fibre (Loop Industries)[64][65].

To our knowledge, there is no technology developer studied focusing on polyamide or polyurethane recycling through methanolysis.

There is a lack of transparency on feedstock pretreatment from most of the technology developers (notably on the different types of pretreatment needed, their extent and the organization in charge of it). In theory, the technology has been proven successful only on mono-material waste streams and thus the majority of the waste feedstock would need to undergo some kind of presorting and pretreatment.

Process

These technologies are using methanol as a solvent to degrade the bonds and thus go back to smaller molecules (monomers, dimers, or oligomers).

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[64] In France, clear colored PET can be mechanically recycled. Historically opaque PET bottles have been mixed with colored PET and mechanically recycled. There are now ongoing developments on the mechanical recycling of opaque PET as a specific stream. Outside of France, the mechanical recycling of opaque PET is developing but is still at a very early stage.

[65] https://www.loopindustries.com/en/technology/materials

These processes require heat. The quantity of heat is highly dependent on the process and the feedstock chosen. Challenging feedstocks, such as multilayered PET, are usually more heat-intensive (6). The publicly known temperature required by current technologies starts at below 90°C (Loop Industries). This temperature might not be representative of the technology category as the required heat is very dependent on the process chosen and the presence of catalysts for instance. Methanolysis usually occurs at a pressure of 25 bars and a temperature of 180°C, for a residence time of about five hours, in the presence of catalysts (12).
In some cases, methanolysis can be performed under supercritical conditions[66] (Mitsubishi process), to allow for a reduced residence time (about 10 minutes in the absence of catalyst). The pressure necessary for this process is about 150 bars with a 300°C temperature.

Output and downstream steps
When recycling PET, the output obtained is MEG (MonoEthylene Glycol) and DMT (DiMethylTerephtalate).

In all cases, purification steps are needed to remove colorants, contaminants, additives, and impurities. Indeed, during the methanolysis process, other alcohols and polymer derivatives are forming and need to be removed. These steps are often done by the technology developer (such as Loop Industries). The purity of the product obtained is very close to the virgin resin according to Loop Industries[67]. The latter has commissioned an external organism (Kemitek) to test the purity of its output. It was found that the DMT purity was ranging from 99.7% to 100.1% (w/w) and MEG purity was ranging from 98.2% to 98.9% (w/w). Their results have been registered on the European Chemicals Agency under the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH) regulation, which shows that the purity of Loop's products is similar in quality to the products manufactured in Europe[68].

Repolymerization is afterwards needed and often done by a downstream actor. For instance, Loop industries has partnered up with INVISTA, who executes the PET repolymerization process, from Loop's recycled DMT and MEG.

b. Technology scaling-up

Average Technology Readiness Level
The technology developers studied are at demonstration stage. Their TRL thus ranges from 6 to 8. Technologies such as Loop Industries are currently advanced as they are planning their first industrial capacities.

Current and future capacities
The technology developers studied are operating plants of a few hundred tons per year.

Indeed, Loop Industries owns and operates a mini-Pilot (25 L reactor) and pilot scales (6000 L reactor) in Montreal amounting up to a total of 1t/day output. Planned capacities ranges from 40 to 100 ktons per year and are mostly planned for the coming years. Loop Industries is currently building a 40kt/y plant in South Carolina (which was expected to be operational at the end of 2020 and probably delayed due to the Covid-19 crisis as there has not been any update) together with its venture partner Indorama Ventures. Following their first communication in September 2020, Loop Industries and Suez announced the site of their future plant was selected in January 2022. The facility will be located in France and will produce 70kt/y of virgin-like recycled PET, the plant will be operational in 2025. Loop and Suez will invest 250 million euros.
They have also established partnerships (supply agreements) with Danone, L'Oréal, L'Occitane, Coca-Cola, PepsiCo, NPC, and Drinkworks over the last years. The developer plans to further deploy its

[66] A fluid is in supercritical conditions when it is heated above its critical temperature and compressed above its critical pressure. Critical temperature and pressure are the points where a fluid changes its physical state. Above its critical temperature and critical pressure, a fluid cannot change state between gaseous form and liquid form. It is thus called supercritical.
[67] https://www.loopindustries.com/en/technology/materials
[68] https://www.loopindustries.com/en/article/technology-verification

technology through retrofit and licensing to manufacturers. In 2021, SK Geo Centric purchased 10% of Loop Industries' shares at the price of $56 million and created a joint venture with the developer. The joint venture aims at deploying Loop Industries PET recycling technology across Asia. A new 83kt/y plant is planned to be built in South Korea (no deadline specified). Long-term plans additionally include the building of 4 plants across Asia to achieve a capacity of 300kt/y.

As for Eastman, they are executing an engineering feasibility study on the design and construction of a commercial scale methanolysis facility. In January 2021, they announced their plan to build a $250 million polyethylene terephthalate (PET) depolymerization plant at its Kingsport, Tennessee. The facility should be built by the end of 2022 and be able to process 100,000 metric tons (t) per year of post-consumer PET waste[69]. The developer has also established a partnership with California-based Circular Polymers to secure feedstock by sourcing recovered PET carpet fibers. In January 2022, the developer announced the intention to invest $1 billion to build a chemical recycling facility in France. The deadline set for the completion of the project is 2025, while capacity upon competition is expected to reach 160 kt/y. Brand-owners such as LVMH Beauty, The Estée Lauder Companies, Clarins, Procter & Gamble, L'Oréal, and Danone, have already signed letters of intent for multiyear supply agreements for Eastman's new plant[70].

c. Economic performance

There is no information at this stage. We could assume that, as Eastman is vertically integrated, it makes it easier to assume internally the financial cost.

d. Environmental performance

LCA data (or similar studies), notably carbon footprint

Methanol used in the methanolysis process can have a consequent environmental impact.

There are very few publicly available LCA on such processes, but Loop industry asserts that an Infinite Loop™ plant with a 63,000-ton production capacity can claim carbon dioxide savings of 135,500 metric tons, or the equivalent of a medium-sized car driving over 540,000,000 km per year. Loop's technology also shows a 60% reduction of global warming potential when compared to virgin PET produced from fossil fuels[71]. However, the methodology that led to such results has not been disclosed by the company and thus such results should be handled carefully. This LCA was conducted by an independent third party.

However, Loop's technology uses an organic solvent that is usually in the gaseous state. The methanol used in the methanolysis process has an environmental impact associated to it. There is additionally an issue of solvent recovery that could be worrisome in terms of economical or environmental impacts. The company does not elaborate on this treatment (16).

Comparative analysis between end-of-life processes

A study published in 2010 evaluated the impacts of PET bottle-to-fibre recycling of four different technologies: mechanical recycling (using Wellman International Ltd.'s technology), semi-mechanical recycling (using long John Group's process), back-to-oligomer recycling (using Far eastern New Century CO., Ltd.'s Glycolysis process) and back-to-monomer recycling (using Patagonia's LCA results on the methanolysis process). As these companies have different locations, it is important to note that the results on mechanical recycling, on methanolysis and on virgin PET fibers are applicable to Western Europe, whereas the results for glycolysis and semi-mechanical recycling are computed with data from Taiwan. Thus, the following results should be considered carefully.

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[69] https://www.eastman.com/Company/News_Center/2021/Pages/Eastman-and-Governor-Lee-Announce-Plastic-to-Plastic-Recycling-Facility.aspx

[70] https://www.textileworld.com/textile-world/fiber-world/2022/01/eastman-to-invest-up-to-1-billion-to-accelerate-circular-economy-through-building-worlds-largest-molecular-plastics-recycling-facility-in-france/

[71] https://www.loopindustries.com/en/article/invista

The methodology used was the LCA ISO 14040 on a cradle-to-factory gate for second life approach. Two different methodologies were used to quantify the impacts: the "cut-off" methodology and the "waste valuation" methodology (11).

The "cut-off" approach results were as follows (11):
- Mechanical recycling emits 0.96 tCO_2/t of recycled PET fibre
- Semi-mechanical recycling emits 1.88 tCO_2/t of recycled PET fibre
- Chemical recycling through methanolysis emits 3.08 tCO_2/t of recycled PET fibre (high case: 3.44 tCO_2e/t; low case: 2.71 tCO_2e/t)
- Manufacturing virgin PET fibre emits 4.06 tCO_2/t of virgin PET fibre

Indeed, the methanolysis process emits more than three times the amount of CO_2 than mechanical recycling but is still better than manufacturing virgin fiber. It should however be kept in mind that the properties of the recycled material are different in the case of mechanical recycling, which cannot give out virgin-like PET contrary to methanolysis. The two types of recycling are thus complementary depending on the use of the recycled material. Again, the following results should be considered carefully as they are related to different geographical areas.

As for Eastman, the company claims that producing resins containing recycled materials can reduce greenhouse gas emissions up to 20-30% compared to fossil fuel-based feedstocks (further details on how these number were calculated remain unavailable)[72].

Energy costs

The same study goes through the energy use of the different recycling methodologies.

The "cut-off" approach results were as follows (11):
- Mechanical recycling uses 13 GJ of non-renewable energy
- Semi-mechanical recycling uses 23 GJ of non-renewable energy
- Chemical recycling through methanolysis uses 51 GJ of non-renewable energy (high case: 40 GJ; low case: 62 GJ)
- Manufacturing virgin PET fibre uses 95 GJ of non-renewable energy

Thus, the methanolysis process uses almost four times more energy than mechanical recycling (partly due to the temperatures range needed to complete the process) but is still almost two times better than manufacturing virgin fibers.

Moreover, a significant amount of energy is required, for the process in itself as well as for the distillation of ethylene glycol in the case of methanolysis (as for hydrolysis). In this case, the reactor temperature needs to be as high as 350°C during 3 to 5 hours and the EG needs to be distilled at about 340°C (12).

METHANOLYSIS	
Technology	Input • Suited to polymers from polycondensation, mostly used for PET. • Treats mono-material streams with a relatively low level of contamination (Loop technical requirement is more than 80% of PET content[73]). • In general, pre-sorting or pre-treatment are necessary (e.g., sorting, washing, grinding, etc.). Process • The feedstock is dissolved in methanol. • The temperature required varies between 100°C and 200°C depending on the feedstock and the pressure is set around 25 bars. • The reaction lasts about 5 hours with a catalyst.

[72] https://cen.acs.org/environment/recycling/Eastman-build-250-million-plastics/99/web/2021/02
[73] https://refashion.fr/eco-design/sites/default/files/fichiers/Chemical%20recycling%20Making%20fiber-to-fiber%20Recycling%20a%20Reality%20for%20Polyester%20Textiles.pdf

	• In some cases, methanolysis can be performed under supercritical conditions. The residence time is about 10 minutes in the absence of catalyst and the pressure necessary for this process is about 150 bars with a 300°C temperature. Output and Downstream steps • The output of PET methanolysis consists of MEG (MonoEthylene Glycol) and DMT (DiMethylTerephtalate). These monomers can afterwards be repolymerized into PET. • In almost every case, purification steps are needed to remove colorants and contaminants. • The purity obtained is close to the virgin resin one.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 6-8. • Most technology developers are still in the development phase of their technology. • Loop Industries are currently planning their first industrial capacities. • Eastman planned to build an industrial plant in France (160 kt/y). Current and future capacities • The technology developers studied are operating plants of a few hundred tons per year. • Planned capacities ranges from 40 to 160 ktons per year and are mostly planned for the coming years.
Economic performance	• Potential high pre-treatment costs due to sorting and decontamination steps • Reprocessing solvent is an additional cost compared to mechanical recycling • Equipment needs to be made of noble materials that are resisting corrosion (as methanol is used) • Lack of public data available
Environmental performance	LCA data (or similar studies), notably carbon footprint • Methanol used in the methanolysis process can have a consequent environmental impact. • Issue of solvent recovery that could be worrisome in terms of economical or environmental impacts. • The methanolysis process emits more than three times the amount of CO_2 than mechanical recycling but is better than manufacturing virgin fiber. Energy costs • The methanolysis process uses almost four times more energy than mechanical recycling (partly due to the temperatures range needed to complete the process) but two times less than the manufacturing of virgin PET in order to convert PET bottles to fibers. • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
loop INDUSTRIES	EASTMAN

Table 5 : Methanolysis recapitulative table (RECORD, 2022)

3) Aminolysis

Note: Due to the low development of aminolysis technologies on the market, this category is only briefly presented in this report and will not be as detailed as other processes.

a. Technology

<u>Input</u>
The great majority of scientific studies conducted on aminolysis used PET (mostly bottles, fibers, powder) as feedstock. Additional, although limited, studies were also conducted on the application of this technology in the recycling of PU insulators (e.g., foams) (12).

<u>Process</u>
Chemical depolymerization via aminolysis consists of degrading plastics' bonds using a host primary amine solution in aqueous or, less frequently, in gaseous form as solvent (7, 16). Amines are organic bases derived from ammonia through the replacement of one or more hydrogen atoms with organic groups such as alkyl or aryl. This method has gained interest due to amine groups having higher reactivity than hydroxyl groups in the glycol and alcohol environments used in glycolysis or alcoholysis (18). The amines which are most frequently used are methylamine, ethylamine, and butylamine (19).

There is limited available scientific research backing up chemical depolymerization via aminolysis. Although it is generally agreed that this process does not require high pressure, there is a significant lack of detail defining under which conditions the technology can be effectively applied. One of the most popular findings emerging from available literature is that aminolysis generally takes place at temperatures varying between 20°C and 100°C (20). The reported time frame required for this reaction varies from a few hours up to 85 days depending on feedstock used, selected amines, temperature, and preferred catalyst (if any) (15, 17). As an example, PET degradation to a range of oligomers was achieved in only 17 hours using ethylenediamine and operating at 100°C (20). Multiple studies also showed that using a catalyst (such as dibutyl tin oxide, sodium acetate, …) may significantly reduce the reaction's time frame (18). Other techniques such as using ultrasonication, UV radiation, microwave irradiation, and solar energy have also been explored as potential energy sources to make this technology faster, more efficient, cost effective and eco-friendly (21).

<u>Output and downstream steps</u>
When amines are used to depolymerize PET, the output generally consists of corresponding bis(2-hydroxy ethylene)terephthalamide (BHETA) monomers, PTA and EG diamines (8, 16). Available literature reports on aminolysis' output materials being suitable for becoming added-value products to produce polyurethanes or other polyesters, to synthetize plasticizer for PVC, unsaturated polyester resin, polyurethane resin, polyester amide resin, surfactants, etc. (18, 19). Studies also proved that triethylamine is the amine which was able to provide the highest products yield of PTA and EG in the degradation of PET (19). As for the treatment of PU foams via aminolysis, the output generated may consist of degraded products (e.g., substituted polyol, polyamines compounds) (22).

b. Technology scaling-up

<u>Average Technology Readiness Level</u>
This technology has an estimated TRL of 2. Publicly available evidence concerning how this process can be effectively used for chemical recycling purposes is still scattered and limited to a narrow range of feedstocks. Moreover, there is yet no evidence of aminolysis being deployed on an industrial nor on a commercial level (15, 16).

<u>Current and future capacities</u>
This technique of chemical depolymerization is still considerably less developed than recycling via alternative solvents (glycolysis, hydrolysis, …). Toxicity and high cost of amines have been presented as two possible reasons why this process has not yet been further investigated (16).

c. Economic performance

The lack of consistent scientific research and the absence of industrial scale applications leads aminolysis to having a significant economic disadvantage compared to other chemical depolymerization processes (17). Moreover, the high cost of amines was reported to be a deterrent for further scientific research (16).

d. Environmental performance

No information found on this subject

AMINOLYSIS	
Technology	Input • Most studies have been conducted using PET or PU foam as feedstock. Process • Aminolysis uses an amine solution to degrade plastic's bonds. • Methylamine, ethylamine, and butylamine are the amines which are used most frequently. • The lack of available research does not allow to clearly determine operating conditions (pressure, temperature, reaction time, etc.). • It is generally agreed that the process does not require high pressure, and that temperatures may vary from 20°C to 100°C. Output and Downstream steps • When PET is used as an input the outputs obtained are BHETA monomers, PTA and EG diamines. These output materials are suitable for becoming added-value products. • The treatment of PU foams may lead to degraded products. • Triethylamine provided the highest products yield of PTA and EG in the degradation of PET.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 2. • Limited availability of scientific research supporting aminolysis. Available sources are limited to a narrow range of feedstocks. • No evidence of technology developers deploying this technology. Current and future capacities • No forecasting of future capacities due to the absence of technology developers deploying this process • Costs and possible toxicity of amines perceived as part of the reason why this technology is less developed than others.
Economic performance	• High cost of amines. • Economic disadvantage as a consequence of limited research and absence of industrial applications. • *Lack of public data available*
Environmental performance	• Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
No technology developer identified	

Table 6 : Aminolysis recapitulative table (RECORD, 2022)

4) Hydrolysis

This subcategory includes non-catalytic and catalytic hydrolysis (via the use of enzymes or microwaves). Enzymatic depolymerization, which is a subcategory of hydrolysis will be studied into detail on the "enzymatic depolymerization" part.

a. Technology

Input
Such as glycolysis, hydrolysis is used on various resins from polycondensation but is mostly developed for PET. It is mainly used for PET that is difficult to recycle (such as contaminated PET, trays, textile…).

The technology developers reviewed for the purpose of this paper can recycle both post-consumer and post-industrial waste.

As for PA6, Aquafil's technology treats pre- and post-consumer PA6 to produce caprolactam. The latter is then reprocessed to produce nylon yarns for textile and carpet applications. The main sources of feedstock include PA6 fishnets which are collected worldwide, PA6 carpets, and other oligomers or plastic waste generated by the polymer industry. Their feedstock needs to be decontaminated before entering the process[74].

Though, Depoly asserts that its technology does not need any specific sorting as the process can selectively treat PET plastic in the presence of other plastics like polypropylene or polyvinyl chloride.
There is generally a lack of transparency on the subject of pretreatment from most of the technology developers. In theory, the technology has been proven successful on mono-material waste streams and thus the pretreatment step seems to be necessary.

Gr3n's Demeto technology can process PET feedstocks (bottles, trays, textiles, etc.) composed of either 100% polyester or with up to 30% of other materials (PU, cotton, polyether-polyurea, etc.).

<u>Process</u>
Hydrolysis uses the same principle as alcoholysis: a solvent is used to degrade the bonds of the polymer and break it down into smaller molecules (monomers, dimers, or oligomers). The main difference is the solvent used, which in this case is water. The process can be catalyzed with microwaves in the case of Gr3n for example (it is also known that Gr3n uses alkaline media and that the process of PET treatment takes less than 10 minutes to complete).

No figures about energy use or operating conditions have been made public by the technology developers studied. Yet, these electrolytic processes usually are very energy consuming. In the absence of catalysts, the only chemical used is water.

As for the duration of the reaction, it is also very variable depending on the process chosen and its catalyst. Obtaining a total depolymerization requires the application of high temperatures (115 to 420°C) and high pressures (10 to 480 bar), during long times (up to 7h), because of the weak reactivity of water (weak nucleophile) (12). There are three types of hydrolysis depending on the conditions applied during the reaction:

- <u>Alkaline hydrolysis</u>: Hydrolysis is performed in alkaline conditions, which are created by adding sodium hydroxide (NaOH) or potassium hydroxide (KOH) in the process (about 4-20% by weight of hydroxide in water). The conditions required for such a process are a temperature range from 210°C to 250°C under pressure from 14 to 20 bar. The reaction can occur with or without catalysts and takes 3 to 5 hours in a batch reactor (12). No yield has been found at this stage.
- <u>Acid hydrolysis</u>: Hydrolysis is performed in acid conditions, which are generally created by using concentrated sulfuric acid (H_2SO_4). In some cases, other mineral acids, such as nitric or phosphoric acid, can be used as well. The reaction between the polymer and concentrated sulfuric acid takes place at considerably lower temperatures (in a range from 80 to 95°C) than alkaline and neutral hydrolysis (12). The yield of acid hydrolysis has not been found at this stage. However, concentrated sulfuric acid is highly corrosive (> 80 wt.%) which necessitates specific processing equipment (12).
- <u>Neutral hydrolysis</u>: Hydrolysis is performed in neutral conditions. The conditions required for such a process are a temperature range of 200°C to 300°C under pressure of 10 to 40 bar. The reaction can occur with or without catalysts and takes about one hour without catalyst for the batch conversion to be completed at 275°C[75]. Hydrolysis proceeds more rapidly when PET is introduced into the reactor in the molten state than when it is solid. The ratio of PET to water is typically in the range from 1/2 to 1/12. The yield of TPA obtained is about 95% (12). For neutral hydrolysis, the post-reaction mixture has a pH of 3.5 to 4.0 due to the fact that the reaction products, TPA and its monoglycol ester, are acidifying the reaction media.

[74] https://www.econyl.com/assets/uploads/RS19_Aquafil_ENG_web.pdf
[75] It has to be noted that there are divergent views on the duration of the reaction without a catalyst.

Neutral hydrolysis was found to be able to operate as a continuous process in a twin-screw extruder (12).

- Subcritical and supercritical hydrolysis: In these processes, water reaches the sub- or supercritical state, and becomes apolar. The reaction can be assimilated to hydrocracking when it occurs in an oxygen-depleted environment. The conditions needed for this process is a temperature range of 150°C to 400°C and the pressure ranges from 220 to 240 bar. The reaction time is about 30 minutes for a batch process (5). The yield obtained for this process is about 98% (12).

Output and downstream steps

Depending on the feedstock, the hydrolysis process produces:

- MEG and PTA when applied to PET. These two building blocks needs to be repolymerized to produce recycled PET. Contrary to other solvolysis methods and alkaline hydrolysis, this process is the unique solvolysis method that leads directly to the production of terephthalic acid (TPA) and ethylene glycol (EG). This route is then the fastest and PET can be directly reconstituted from these species, without additional steps (12). As for alkaline hydrolysis, it produces Na_2TA that has to be converted into PTA. Indeed, production of PET through the esterification of DMT takes two steps whereas the transesterification of PTA is done in one reactive step.
- Caprolactam when applied to PA6 (9).

Purification steps are afterwards necessary to remove contaminants and colorants and ensure the quality of the product. Most technologies give out monomers that will need to be repolymerized with the help of an external partner. In theory, the output produced could be food grade material.
The quantity of by-products and waste in neutral hydrolysis is considerably lower than for alkaline and acid hydrolysis. In acid hydrolysis, substantial amounts of inorganic salts and aqueous waste are generated as by-products (12).

Aquafil's LDR (Lactam Direct Recycling) process achieves a PA6 conversion rate of approximately 90%[76]. The main output produced by Aquafil's depolymerization process is caprolactam. This material is then polymerized and turned into textile yarns by the developer. The yarn produced (called Econyl yarn) can be used for multiple applications to produce textiles and carpets.

As for Gr3n's Demeto process, the reaction mixture obtained within the reaction chamber is precipitated, filtered, washed, and dried. TA is the main output product obtained, as well as the EG that is recovered and distilled to be reused in the process.

b. Technology scaling-up

Average Technology Readiness Level

Most of the technology developers studied are at their laboratory or pilot stage (such as Depoly, RITTEC with the RevolPET® technology and BP), they are therefore considered to still have a TRL of 3 to 4.
However, Gr3n's technology is more advanced and has an estimated TRL of 6.
Considering PA recycling, Aquafil's technology is at a commercial scale.

Current and future capacities

There is few information about capacities due to the low stage of development for most of the technology developers.
While mainly based in Italy, Aquafil operates a total of 16 facilities (divided across 3 continents and 8 countries – number which includes waste storage and separation, as well as nylon regeneration sites). The two Aquafil recycling plants have respectively a capacity of 40,000 (it is not specified whether this capacity refers to input or output capacity) and 16,000 tons/year (capacity referred to used carpet input, based in Phoenix, Arizona, USA). Aquafil is partnered with Tarkett (which supplies them with post-consumer carpets) and has engaged in supply agreements with a series of companies in the textile industry (Adidas, Volcom, Stella McCartney, Interface, Milliken, Mannington).

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[76] https://www.aquafileng.com/en/polymer-plants/polyamide/continuous/

Gr3n has a lab scale plant in Chieti, Italy (capacity unknown). In 2017, the developer had received a 9.9€ million funding from the EU Horizon 2020 which they intended to use to finalize their first pilot plant[77]. As of January 2022, no news was found on the construction of their facility (expected capacity: 30 kt/y). In the long-term, Gr3n plans to start selling recycling equipment, provide maintenance services, and license its recycling process. Partners include PET producers, municipalities, and equipment producers.
Gr3n additionally created an Industrial Advisory Board composed of brand owners such Adidas, Nestlé, H&M, Unilever, and IKEA, etc... The Board participated in the Demeto project by providing comments and feedback on business development activities[78]. The DEMETO technology was developed with the support of the Danish Technical University and Processi Innovativi srl. As of February 2019, the company needed to raise over 3-4€ million. It is known that this investment was at least partially needed to develop a new full-scale recycling plant. In September 2021, Gr3n announced they received a €6.3 million financing from Chevron Technology Ventures, Standex International and other investors[79].

Depoly has started to build its pilot plant in November 2019. The plant started operating in February 2021, when a pre-testing phase began (capacity unknown)[80].

BP plans to construct a $25 million pilot plant in the US (in Illinois) to prove the technology, before progressing to full-scale commercialization. The plant was planned for late 2020 and probably delayed due to the Covid-19 crisis as there has not been any update. The capacity of this plant is unknown at this stage.

RITTEC has developed a depolymerization process for PET called RevolPET[81]. In 2020, Leistritz and RITTEC signed a letter of intent for the construction of a RevolPET pilot plant (input capacity 10kt/y) which was expected to be built by the end of 2021, no updates were however found on this subject[82]. RITTEC's project partners for RevolPET include the Institutes for Chemical and Thermal Process Engineering, and Machine Tools and Manufacturing at Braunschweig Technical University, the Fraunhofer Institute for Chemical Technology, Reclay Systems GmbH, SCHILLER Apparatebau GmbH, and VTU Engineering Deutschland GmbH (type of partnership not disclosed)[83].

c. Economic performance

These processes come with a relatively high cost, partly due to the significant cost required to purify the TPA (12).
There is no additional information at this stage.

d. Environmental performance

<u>LCA data (or similar studies), notably carbon footprint</u>
There are very few publicly available LCA on such processes, but Gr3n has conducted an LCA that gave a reduction of CO_2 and consumed energy of -60% and -68% respectively compared to the production of virgin PET[84]. As this LCA has not been made public, the methodology and hypothesis chosen are undisclosed and thus not confirmable.

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77 https://textileexchange.org/featured/gr3n-recycling-2017/
78 https://universal-sea.org/inspirations/gr3n-the-new-technology-to-tackle-the-plastic-waste-issue
79 https://gr3n-recycling.com/media.html
80 https://network.changemakers.com/challenge/creating-shared-value-prize/refinement/depoly
81 https://bmbf-plastik.de/sites/default/files/2021-06/FactSheet_revolPET_EN_06_0.pdf
82 https://www.chemicalrecycling.eu/news/revolpet-strategic-partnership-rittec-umwelttechnik-with-leistritz-construction-of-a-pilot-plant-for-chemical-pet-recycling/
83 https://www.rittec.eu/solutions/revolpet-r.html
84 http://gr3n-recycling.com/#tab-id-7

In the declaration of the environmental performance of its products[85], Aquafil asserts that producing raw PA6 from recycled PA waste emits 1.7 tCO_2e/t of product. According to PlasticsEurope, producing virgin PA6 in Europe emits 6.7 tCO_2e/t of product[86]. As this LCA has not been made public, the hypothesis and the methodology chosen are undisclosed and thus not confirmable.

The technology developer Depoly estimates that, when fully operational, for each recycled tons of PET they will save up to 7.7 tons of CO_2, which would be equivalent to 30,000 tons of CO_2 saved each year (further details unavailable)[87].

<u>Comparative analysis between end-of-life processes</u>
A study conducted in 2020 on publicly available information found that, depending on the catalyst used and the different proportion of solvents, hydrolysis of PET waste could save emissions compared to incineration. Complex PET streams such as multi-layered PET, trays or films could benefit from this technology (23).

RITTEC claims that its RevolPET process saves up to 60% CO_2 compared to virgin production of PET from crude oil, details behind the calculation are however not disclosed[88].

<u>Energy costs</u>
A significant amount of energy is required, for the process in itself as well as for the distillation of ethylene glycol in the case of hydrolysis (as for methanolysis). In this case, the reactor temperature needs to be as high as 350°C during 3 to 5 hours and the EG needs to be distilled at about 340°C (12).

Aquafil has made public the energy consumption of its process in Slovenia. The renewable energy use (mainly hydropower) amounts to 31 MJ. Out of the total energy consumption 9 MJ is used for upstream steps[89], 22 MJ for the core process, and less than 0,02MJ for the downstream[90] steps). The non-renewable energy use amounts to 976 MJ (of which 865 MJ for upstream, 105 MJ for the core process and less than 6MJ for the downstream steps)[91].

A study found that more than 55% of the emissions allocated to hydrolysis are due to energy consumption (23). It was also stated that addition of excess water during purification of monomers affects the GHG emissions adversely due to higher energy consumption during the recovery of ethylene glycol. Indeed, the study thus recommends using selective filtration without excess water to limit the environmental impact of the process.

HYDROLYSIS	
Technology	Input • Suited to polymers from polycondensation, mostly used for PET, PA, and PU. • Treats mono-material streams with a relatively low level of contamination from post-industrial or post-consumer waste. • Pre-sorting or pre-treatment are often necessary (e.g., sorting, washing, grinding, etc.). Process

[85] Aquafil (2013) ENVIRONMENTAL PRODUCT DECLARATION for ECONYL POLYMER, December 2013
[86] PlasticsEurope (2014) Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers: Polyamide 6 (PA6), February 2014
[87] https://network.changemakers.com/challenge/creating-shared-value-prize/refinement/depoly
[88] https://bmbf-plastik.de/sites/default/files/2021-06/FactSheet_revolPET_EN_06_0.pdf
[89] Upstream steps include: extraction of non-renewable resources, additives and auxiliaries production, transportation, secondary raw materials that are entering into pretreatment plant (PA6 fishnets, PA6 carpet, oligomers), Polymer production, ECONYL® plant operation (depolymerisation step & purification step of caprolactam, polymer production.
[90] Downstream steps include : transportation to average distribution platform or retailer.
[91] https://www.aquafil.com/assets/uploads/EPD-FOR-ECONYL-YARN.pdf

	• The feedstock is placed in water in alkaline, acid, neutral or subcritical/supercritical conditions. • Alkaline hydrolysis requires temperatures from 210°C to 250°C under pressure from 14 to 20 bar. The reaction can occur with or without catalysts and takes 3 to 5 hours in a batch reactor. • Acid hydrolysis requires temperatures from 80°C to 95°C. • Neutral hydrolysis requires temperatures from 200°C to 300°C under pressure of 10 to 40 bar. The yield of TPA obtained is about 95%*. • Subcritical/supercritical hydrolysis requires temperatures from 150°C to 400°C under pressure of 220 to 240 bar. The reaction time is about 30 minutes for a batch process. The depolymerization yield obtained for this process is about 98%*. Output and Downstream steps • The output of PET Hydrolysis consists in MEG and PTA. These two building blocks needs to be repolymerized to produce recycled PET. • The output of PA6 Hydrolysis consists in caprolactam that needs to be repolymerized to produce recycled PA6. • In almost every case, purification steps are needed to remove colorants and contaminants. • The purity obtained is close to the virgin resin one.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 3-4. • Most technology developers are still in the development phase of their technology. • Gr3n's technology is more advanced and has an estimated TRL of 6. • Aquafil's technology is at a commercial scale. Current and future capacities • Aquafil is operating two plants of 40,000 and 16,000 tons/year. • Gr3n has completed the construction of a pilot plant (capacity unknown) which will be used as a testing center for the construction of future industrial plants (30kt/y).
Economic performance	• These processes come with a relatively high cost, partly due to the significant cost required to purify the PTA • Lack of public data available
Environmental performance	LCA data (or similar studies), notably carbon footprint • Gr3n has conducted an LCA that gave a reduction of CO_2 and consumed energy of -60% and -68% respectively compared to the production of virgin PET. These figures are only indicative. • Aquafil asserts that producing raw PA6 from recycled PA waste emits 1.7 tCO_2e/t of product. According to PlasticsEurope, producing virgin PA6 in Europe emits 6.7 tCO_2e/t of product. These figures are only indicative. Energy costs • More than 55% of the emissions allocated to hydrolysis are due to energy consumption • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
bp · AQUAFIL synthetic fibres and polymers · DePoly · RITTEC UMWELTTECHNIK · gr3n	

Table 7 : Hydrolysis recapitulative table (RECORD, 2022)

*Yields can vary depending on the feedstock type and operating conditions. These yields are likely to be overestimated as they have been calculated by technology developers on a lab scale

5) Hydrolysis catalyzed with enzymes

This part focuses on enzymatic depolymerization, which is a subcategory of hydrolysis.

a. Technology

Input

Applications of enzymatic depolymerization currently focus on PET resin. Petrobras, a Brazilian company, is focusing exclusively on PET bottles as a feedstock and is thus competing with mechanical recycling. As such, a presorting step is necessary to ensure that the feedstock is not contaminated and contains only PET bottles.

As for Carbios, a French startup, they are using any kind of plastic products containing PET as feedstock. This process can apply to plastics or textiles[92]. Indeed, they claim that even *"contaminated PET plastic waste can also be processed by this technology, as the enzyme only targets PET".* It seems that contaminants (such as colorants, carbon black, TiO_2, cyclohexanedimethanol - CHDM, other polymers: PA, PE, PVC) are not inhibiting the enzyme. According to the company, the technology *"does not require sophisticated sorting as the enzyme has been specifically designed to target PET, therefore allowing to recycle complex plastic waste usually not recyclable through mechanical recycling".*

Process

Carbios states that its technology (C-Zyme) is efficient at low temperature and atmospheric pressure[93].
Carbios announced a 97% depolymerization yield in a 16-hour process processing PET bottles[94].
Petrobras' process seems to confirm this statement as they are announcing that their process occurs at moderate pressure and temperature as well[95].

Output and downstream steps

The process uses an enzyme to biologically break down PET into the monomers MEG and TPA. These monomers afterwards need to be purified and repolymerized to produce recycled PET. Carbios is stating that this recycled PET is virgin-like and suitable for food grade applications. Moreover, its depolymerization process was validated by its partner Michelin[96].

b. Technology scaling-up

Average Technology Readiness Level

Carbios' technology is at pilot scale, using a 1000 liters reactor[97] and has completed the construction of a demonstration plant in 2021. Their current TRL is thus about 7.

As for Petrobras, there is few information available about their facilities. They were in optimization phase in 2018 and their TRL is probably at 3-4.

Current and future capacities

Carbios started the construction of the demonstration plant developed in partnership with Technip FMC. The plant (capacity unknown), based in Clermont-Ferrand (France), was inaugurated in November 2021. This facility will be used to collect technical, economic, and environmental data on the technology. Carbios is additionally planning an industrial rollout by 2025 by constructing a facility with a reference unit capacity of 40kt/y. Since 2019, the technology developer has achieved a total capital increase of

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[92] Textile PET has been validated in November 2020: https://www.foodpackagingforum.org/news/carbios-to-produce-pet-bottles-from-textile-waste.

[93] https://www.carbios.com/carbios-obtient-de-nouveaux-brevets-en-europe-et-au-japon-apres-une-delivrance-aux-etats-unis/

[94] https://www.carbios.com/carbios-produit-les-premieres-bouteilles-en-pet-a-partir-de-dechets-de-plastiques-100-biorecycles-grace-a-sa-technologie-enzymatique/

[95] https://agenciabrasil.ebc.com.br/en/geral/noticia/2018-11/petrobras-designs-technology-disintegrate-pet-bottles

[96] https://www.carbios.com/carbios-et-michelin-pneu-100-durable

[97] https://carbios.fr/

155€ million. At the end of 2021, they received a 3,3€ million support from the EU Life program[98]. It is known that the company is part of a Consortium with L'Oréal, Nestlé Waters, Suntory Food & Beverage Europe, and PepsiCo. The purpose of the Consortium is to increase the recycling of PET products using Carbios' enzymatic technology[99]. It has also established partnerships with Novozymes (production of the proprietary enzyme for PET degradation), Technip energies (engineering and construction support), INRA (R&D partnership), CNRS (R&D partnership), and INSA Toulouse (R&D partnership). A five-year partnership was additionally signed at the end of 2017 with L'Oréal for the production of colored or opaque recycled PET bottles. Finally, in 2021 Carbios signed an agreement with Michelin to include PET bottles and textile waste as recycled content into the production of PET yarns used in tires[100].

Petrobras was expected to enter pilot phase in 2021, no further updates have been found on the subject.

c. Economic performance

No information found on this subject

d. Environmental performance

Carbios and Petrobras have not made public any environmental data on their respective processes.

[98] https://www.carbios.com/fr/carbios-commission-europeenne-life/
[99] https://www.carbios.com/en/nestle-waters-pepsico-and-suntory-beverage-food-europe-join-consortium-founded-by-carbios-and-loreal-to-support-the-worlds-first-enzymatic-technology-for-the-recycling-of-plastic/
[100] https://www.carbios.com/en/carbios-and-michelin-developing-100-sustainable-tires/

HYDROLYSIS CATALYZED WITH ENZYMES	
Technology	Input • Focus on PET. • Competition with mechanical recycling if the feedstock is composed of bottles (such as Petrobras). • Treats mono-material streams with a relatively low level of contamination from post-industrial or post-consumer waste. • No sophisticated sorting necessary claimed as the enzyme targets PET feedstock. Process • The feedstock is put in solution in the presence of an enzyme. The enzymatic process biologically breaks the chain into monomers that after purification could be recycled to make PET polymer again. • Atmospheric pressure and low temperature claimed. • 97% depolymerization yield* announced in a 16-hour process. Output and Downstream steps • The output of PET hydrolysis consists in MEG and PTA. These two building blocks needs to be repolymerized to produce recycled PET. • The purity claimed is close to the virgin resin one.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 5. • The technology developers are still in the development phase of their technology. Current and future capacities • Carbios concluded the construction of the demonstration plant (capacity unknown). Industrial roll-out (40kt/y) is planned for 2025.
Economic performance	• Lack of public data available
Environmental performance	LCA data (or similar studies), notably carbon footprint • Lack of public data available Energy costs • Lack of public data available
STUDIED TECHNOLOGY DEVELOPERS	
CARBIOS	PETROBRAS

Table 8 : Hydrolysis catalyzed with enzymes recapitulative table (RECORD, 2022)

*Yields can vary depending on the feedstock type and operating conditions. These yields are likely to be overestimated as they have been calculated by technology developers on a lab scale

VI. Dissolution

Note: the terms *dissolution* and *selective dissolution* are used interchangeably.

a. Technology

Input

One of the primary advantages of selective dissolution is its ability to treat an extensive range of plastic resins. Although not suited for the recycling of thermosets as their chemical structure does not allow them to dissolve, this type of technology has proven adaptable to practically all types of thermoplastics (PS, PET, PVC, PA, PP, PMMA, ABS, etc.). The input used by technology developers may consist of contaminated mono-material streams or mixed plastic flows, including multi-layered packaging (the economics may limit the acceptance of mixed plastics, in order to avoid the management cost of non-reactive plastics contaminated with the solvent used for the dissolution) (24). Both post-consumer and post-industrial wastes are likewise admissible as feedstock. As of today, the great majority of technology developers operate using a feedstock composed of contaminated mono-material streams. Examples include PureCycle Technologies[101] using recovered PP waste, Polystyvert[102] focusing on post-consumer PS (including expanded PS, extruded PS, high-impact PS, and products containing flame retardants - HBCD), and PolyStyreneLoop[103] processing post-industrial waste such as PS foams containing HBCD.

Given that most of the feedstocks used in these processes are usually not mechanically recyclable, dissolution can be considered as a complementary solution to mechanical recycling. This statement is reinforced by the existence of developers such as Polyloop[104] and APK AG[105]. By importing Vinyloop's technology, Polyloop will be able to recycle postproduction soft PVC. Indeed, it is challenging to treat soft PVC through mechanical recycling (notably in terms of quality), mainly because of inherited substances in post-consumer waste, which are now restricted under Reach regulation. In 2021, the developer Polyloop additionally disclosed that they have begun a process of adaptation of their dissolution technology to also recycle polycarbonates. On the other hand, APK AG has been successfully processing PE/PA multi-layer films. The start-up is planning to extend its operations to the processing of other types of pre- and post-consumer waste that are normally not mechanically recyclable such as PET/PE and PE/Alu films, post-consumer, and post-industrial plastics from WEEE, and other types of mixed plastic waste fractions (e.g., LDPE, HDPE, and PP, no additional information is available on the treatment of these types of plastics). Out of the technology developers that have been analyzed, APK AG is the only one with the ability to process mixed waste in the form of multi-layered packaging. CreaCycle can recycle plastic resins that are found in waste mixed with another material (e.g., in multilayer packaging). The process requires a pre-sorting step to divide waste by polymer type based on the plastic that is being targeted (such as (E)PS, PVC, ABS, PC/ABS, HIPS, and PP issued from plastic packaging, electronic plastic waste, and plastic insulation foam)[106].

Pre-sorting of waste is a common practice among recyclers operating via selective dissolution. Other than being sorted by polymer type (e.g., in the CreaCycle process[107]), plastics are often prepared for further processing also through washing and grinding (5). Polystyvert has implemented a coarse filtration system that allows large contaminants (e.g., cardboard, paper, other plastics, metals) to be easily removed to obtain the desired quality of feedstock[108]. APK AG pre-treats waste by mechanically separating plastics from textiles, sand, metal particles, and other unwanted materials. Plastics are then air screened and divided between light (film particles, fibers, corks) and heavy fractions (hard plastics and heavy impurities). Different plastics within the heavy fraction are then separated by density (12).

[101] https://purecycletech.com/
[102] http://www.polystyvert.com/en/
[103] https://polystyreneloop.eu/
[104] https://polyloop.fr/
[105] https://www.apk-ag.de/en/
[106] https://www.creacycle.de/en/the-process.html
[107] https://www.creacycle.de/en/the-process.html
[108] http://www.polystyvert.com/en/technology/

Polyloop shreds its waste and, depending on the feedstock used, pre-sorts it and/or cleans it as well[109]. PolyStyreneLoop also pre-treats its waste by removing impurities found within PS foams[110]. Other developers such as PureCycle Technologies do not specify whether they carry out pre-sorting or pre-treatment of plastic waste.

<u>Process</u>

Once the nature of the input (contaminated mono-stream vs. mixed plastics) has been established, either an essential oil or another solvent capable of targeting the selected resin/additive is selected. The majority of technology developers do not disclose which type of solvent is used within their recycling process. It is however known that Polystyvert's technology is based on the use of a non-toxic cymene essential oil and that PureCycle Technologies[111] (technology developed and licensed by Procter & Gamble) also uses a non-toxic solvent (12). As for CreaCycle and PolyStyreneLoop, their technology relies on a specific CreaSolv Formulation which is customized for the type of resin treated. Although no details are provided about this formulation, CreaCycle claims to always prioritize the use of solvents which are considered safe, are biodegradable, are not harming marine species and do not fall in the category of volatile organic compounds/solvents[112] .

In general, dissolution processes work through the pre-treatment of waste (washing, crushing, separating unwanted materials, please refer to "input" for further details), dissolution of plastics in a solvent, filtration, precipitation, and distillation of the solvent (please refer to "output" for further details) (5). The input and the solvent used are the two factors that determine what happens within the dissolution phase. When the input consists of a contaminated mono-material stream, two options are possible. In one case, the solvent only dissolves the targeted resin leaving additives in their solid state. This is the case for Polystyvert and CreaCycle. Polystyvert's process is very quick and can be conducted at low temperatures. During the process, the oil will only dissolve PS. Depending on their density, remaining materials will either float or sink (12). The other available option is for the solvent to only dissolve specific additives and impurities, leaving the resin in its solid state (24). It is through these processes that selective dissolution enables plastic recyclers to remove certain contaminating substances that are restricted by existing regulations and, in some cases, to recycle valuable non-plastic substances (24).

On the other hand, when the input consists of a plastic mix or of multi-layered plastics, the choice of the solvent allows to determine which of the available resins will be dissolved, maintaining the other polymers in their solid form. This step is sometimes referred to as "chemical filtration" due to its ability to separate plastics that are soluble in the solvent from those that are not. After the targeted resin has been dissolved, a filtration system allows to recover the remaining solid waste and, in some cases, to eliminate certain insoluble additives that may be contaminating the selected resin. Once cleaned from certain impurities and from solid residuals, a non-solvent/anti-solvent is added to the selected polymer in its liquid form. This step allows to precipitate the selected polymer, which is then recovered through an additional filtration system that allows to further remove impurities (24). It is known that CreaCycle uses a specific CreaSolv precipitation agent to precipitate polymers[113].

APK AG, is one of few technology developers processing mixed waste via selective dissolution (16). Their solvent-based process, known as Newcycling, was developed based on CreaCycle's CreaSolv technology. Following the pre-treatment of PA/PE multi-layer films (see previous paragraph for further details), PE is dissolved in a solvent bath. The dissolved PE is divided from solid PA using a standard solid-liquid separation system. From this moment on, the two polymers are processed separately. The PA is introduced into a Coperion ZSK twin screw extruder, where it is melted and processed into to then be pelletized into PA recyclate. The solid PE is also introduced into a ZSK twin screw extruder together

[109] https://polyloop.fr/strap-recycling/process/?lang=en
[110] https://polystyreneloop.eu/technology/
[111] https://solarimpulse.com/efficient-solutions/purecycle-technologies
[112] https://www.creacycle.de/en/knowhow/creacycle-gmbh-eng.html
[113] https://www.creacycle.de/en/the-process.html

with a solvent. Then, intensive devolatilization of the liquid takes place, the solvent is removed, and the remaining PE melt is pelletized[114].

The most favorable option for technology developers would be to create a process that is simultaneously able to remove all harmful substances and impurities, and to separate mixed plastics. This however poses numerous challenges. To provide an example, Vinyloop/Texiloop did not succeed in this attempt because phthalates were getting dissolved with the PVC and they could not be removed during the rest of the process (24). After being shut down, Vinyloop reopened under the name Polyloop on a smaller scale. The Polyloop process, also known as STRAP (solvent-targeted recovery and precipitation), is initiated by adding shredded waste into a “metal basket” of up to 300 kg which is then inserted into the Polyloop recycling unit. Here the dissolving process begins. A mixture of solvents is added into the reactor and solubilizes PVC and the constituents of its formulation. The metal basket is equipped with openings (size of the openings selected according to the type of waste), which serve as a primary filter by retaining the charges of the composites during the draining phase. The mixture of solvent and PVC solution is then purified further using a series of other filters. The insoluble materials that are recovered are then returned to the basket, while PVC is precipitated. Precipitation consists of heating up the solution of solvent and PVC using steam within a reactor. The solvent is gradually replaced by water in which the PVC is not soluble. Agitation allows small grains of r-PVC to form compounds in the boiling water. These compounds are then dried[115].

The European project NONTOX, which will come to an end in May 2022, is currently exploring ways to recover waste plastics from WEEE (Waste from Electrical and Electronic Equipment), ELV (End-of-Life Vehicles) and C&DW (Construction & Demolition Waste) sectors. The focus of this study is to treat resins containing additives and other undesired impurities[116]. The CreaSolv process is of the technologies which are being explored for this purpose. The project is being conducted with the participation of the VTT Technical Research Centre of Finland, the Italian WEEE PRO (Producer Responsibility Organization) ECODOM, Fraunhofer IVV, UNIVAN, Treee, the IMDEA Energy Institute, and several other partners invested in the recycling of WEEE[117] (24).

It is relevant to mention that a critical advantage of dissolution technologies is that they allow to recover targeted polymers with low alteration of their chemical structure. While solvolysis involves the breaking down or the modification of polymer chains, selective dissolution procedures are used to either dissolve one resin, multiple resins, or certain additives and impurities (24). It is relevant to specify that, when used to recover resins, this process does not require to bring the polymer back to its monomer stage (5).

Detailed information concerning temperature, volume of solvent used, energy source, and total time of the reaction are usually not disclosed by the technology developers. In general, the dissolution phase (following pre-sorting/pre-treatment, before letting the melted polymers cool down) have an estimated duration of 30 minutes and are conducted at a temperature that is lower than the solvent’s boiling point (12). It is known that the volume of solvents used by CreaCycle is less than 1%[118] in relation to the processed plastic[119]. However, this percentage does not apply to other technology developers which, as previously mentioned, do not disclose the amount of solvent required by their processes.

From an environmental point of view and for safety purposes, the solvents used are selected for their low flammability and low toxicity (5). However, this does not exclude that certain solvents may be toxic or explosive (24).

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[114] https://www.coperion.com/en/news-media/newsroom/2020/apk-relies-on-coperion-zsk-extruder-technology-for-newcycling
[115] https://polyloop.fr/strap-recycling/process/?lang=en
[116] http://nontox-project.eu/?page_id=18
[117] http://nontox-project.eu/?page_id=20
[118] It is not specified whether this quantity refers to the the volume of fresh solvent required in addition of recycled solvent, or if it consists of the actual amount of solvent in contact with plastic.
[119] https://www.creacycle.de/en/the-process.html

A fundamental step for this technology to perform efficiently is to recover and regenerate the solvents used (24). This outcome is achieved through distillation of the solvent that has been used during the recycling loop. Another necessary step that is necessary to carry out at the end of the recycling process is to dispose of all unrecovered/unrecoverable substances that cannot be reused and that are therefore classified as waste (16).

<u>Output and downstream steps</u>
Once the polymers have been precipitated or impurities have been removed from the selected resins, the output of this process generally consists of high-quality recyclates and, in some cases, of valuable recovered substances (such as certain additives or contaminants) (16). Since selective dissolution does not usually modify the targeted polymers' chemical structure (or involves low alteration of the structure), the type of recyclate obtained depends on the input materials used. Developers processing PS waste produce r-PS (Polystyvert, PolyStyreneLoop), those recycling PP obtain r-PP (PureCycle Technologies), those treating PA deliver r-PA (APK AG), etc... New additives may be added to the plastic output or further processing may be applied to obtain a newly recycled product. As an example, Polystyvert's unique recycling process allows for the purified polystyrene to be re-introduced into a polymerization reactor to regenerate expanded polystyrene (EPS) and high-impact polystyrene (HIPS) (12). Solvents' recovery is also a key component of dissolution processes.

In terms of quality of the output, dissolution is likely to deliver recycled materials with higher quality and purity than mechanical recycling (5). Mono-streams feedstocks are usually preferred over mixed waste to achieve high quality and yields (24). As previously mentioned, one of the advantages of dissolution is its ability to remove certain contaminants and additives from plastics. Doubts however remain on the applicability of these recycled resins in the food industry (24). PureCycle Technologies has claimed for its output (Ultra-Pure Recycled Polypropylene - UPRP) to be suitable for food-grade applications. In this context, the developer announced the submission of a request for its output to receive a non-objection letter from the US Food and Drug Administration (FDA) in September 2021[120]. As of January 2022, it is unknown whether the request has been approved and if PureCycle additionally sent its application to receive the European Food Safety Authority (EFSA) approval. Although producing high purity and virgin like polymers, developers such as PolyStyreneLoop (virgin-like r-PS free of impurities), and CreaCycle technologies (efficiently removing odorous, substances, contaminants) have not yet been declared suitable for the production of plastics used in the food industry. Polystyvert claims for its output (high-purity r-PS free of inks, flame retardants, and pigments) to be suitable for food-grade applications. However, no information was found on whether their recyclates have obtained an official regulatory approval for this purpose[121].

a Technology scaling-up

<u>Average Technology Readiness Level</u>
This technology is not yet fully mature. Most technology developers are still at the stage of technology development and have not yet launched operations on a commercial scale. Thus, the TRL is estimated to be around 5.

<u>Current and future capacities</u>
Technology advancements and plans for future expansion of commercial facilities significantly vary from one developer to another.

Polystyvert has a current input capacity of 600 tons of PS per year[122]. Back in 2018, the company had announced its objective of building eight recycling plants in Europe (no deadline specified), each of them

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[120] https://www.marketscreener.com/quote/stock/PURECYCLE-TECHNOLOGIES-I-120780777/news/PURECYCLE-TECHNOLOGIES-INC-Other-Events-Financial-Statements-and-Exhibits-form-8-K-36594638/
[121] https://www.canplastics.com/canplastics/polystyvert-gets-new-round-of-financing-to-develop-full-scale-polystyrene-recycling-plant/1003456580/
[122] https://resource-recycling.com/plastics/wp-content/uploads/sites/4/2018/08/2018-08-20-EN-Press-Release-plant-inauguration-FINAL.pdf

with a capacity of 20-30kt of PS per year. In 2019, Polystyvert planned to start commercial deployment through licensing across the Europe and North America, to then proceed expanding on a global scale (no further updates have been published since). The company has established strategic partnerships with multiple organizations, including: Total (industrial partnership), Cycle Capital (investor), Anges Québec (investor), BDC Capital (investor), Quadriam (investor), Energy Foundry (investor), and COEXPAN (partnership aimed at validating the use of rPS for Form Fill Seal (FFS) used in yoghurt packaging applications). INEOS Styrolution and Polystyvert have also initiated a joint development agreement which aims at advancing a circular economy for PS (news from February 2021). At the end of 2021, the developer received a grant of $3.5 million by Sustainable Development Technology Canada (SDTC)[123].

PolyStyreneLoop's opened its first demonstration plant in June 2021[124]. The plant is located in Terneuzen (Netherlands) and has an input capacity of 3,300 tons/year and an output capacity of approximately 3,000 tons/year. Construction works for the demonstration plant had begun in November 2019[125]. The PolyStyreneLoop Cooperative is a non-profit organization under Dutch law. The Cooperative formed by 3 core partners, 53 members (among which Suez and Soprema), 12 supporters (among which Shell, Total, and BASF), and 9 allies. Key actors include Fraunhofer Institute for Process Engineering and Packaging IVV and CreaCycle (technology partners for the building of the pilot plant), National Groen Fonds (investor), VERAS (Dutch demolition company, partnership created to enhance the recycling of EPS from construction), and Kingspan Unidek and Renewi (studying the separation and sorting of waste containing EPS). PolyStyreneLoop also signed agreements with Knauf, GCC and Afipeb to collect demolition waste produced in France[126]. The developer has secured its funding through the EU LIFE Programme (subsidy of € 2.7 million over 4 years, date unknown), and RABO Bank (loan of € 4.5 million). In October 2021, they received approval to transport PS-foam from demolition waste containing HBCD[127]. In March 2022, PolystyreneLoop announced they stopped the project due to numerous constraints (including delays because of the COVID-19 pandemic, surge in energy prices).

PureCycle Technologies currently holds a lab-scale unit at the facilities of its testing partner Phasex, which is located in Andover (Boston area). The construction of the company's first commercial plant in Ohio, USA has already commenced. Once fully operational, the plant is expected to reach the capacity of over 105 million pounds (approximately 48ktons) per year. Production is expected to start in late 2022 with full capacity to be reached in 2023. The developer is currently undergoing the pre-engineering phase for the design of five additional commercial lines in the USA. Once completed, these facilities should be capable of producing over 165 million pounds (approx. 75 ktons) of UPRP each[128]. In 2021 PureCycle Technologies reached an agreement with The Augusta Economic Development Authority by which one of their plants will be located in the Augusta Corporate Park, USA[129]. The company additionally announced a partnership with SK Global Chemical to build a 55kt/y recycling plant in South Korea[130]. A partnership was also signed with Mitsui & Co. to build a recycling plant in Japan, details on the facility have not yet been disclosed[131]. Other strategic partners can be mentioned such as Phasex (testing partners), TOTAL (supply agreement), L'Oréal (supply agreement), Nestlé (R&D partner), Gulfspan (construction partner), and Milliken & Company (providing additives for the production of r-

[123] https://www.canada.ca/en/innovation-science-economic-development/news/2021/11/government-of-canada-supports-leading-edge-company-specializing-in-polystyrene-recycling-that-helps-protect-the-environment.html
[124] https://www.businesswire.com/news/home/20210602005924/en/Innovative-PolyStyreneLoop-Plant-Will-Recycle-Polystyrene-Foam-Demolition-Waste-and-Recover-Valuable-Resources
[125] https://polystyreneloop.eu/
[126] https://mailchi.mp/515fa6306404/ps-loop-update-october-13407485
[127] https://mailchi.mp/515fa6306404/ps-loop-update-october-13407485
[128] https://ir.purecycletech.com/news-events/press-releases/detail/8/roth-ch-acquisition-i-to-combine-with-purecycle
[129] https://purecycle.com/2021/07/purecycle-to-build-new-recycling-facility-in-augusta-georgia/
[130] https://www.prnewswire.com/news-releases/purecycle-partners-with-sk-global-chemical-to-open-ultra-pure-recycling-plant-in-south-korea-301354405.html?tc=eml_cleartime
[131] https://purecycle.com/2021/09/purecycle-announces-partnership-with-mitsui-to-develop-ultra-pure-recycled-polypropylene-plant-in-japan/

PP). The company has the (ambitious) goal of building 50 more recycling plants across the world within the next 15 years.

Launched in 2019, Polyloop (which treats PVC inputs) is still within its lab scale phase to improve its efficiency (current capacity unknown). However, the developer already plans the upscaling of its technology. In 2020, their process began testing in a laboratory pilot unit owned by Kem One (Balan, France). By 2022, the developer plans to install its first operational unit in the facilities of its partner Serge Ferrari (no news as of January 2022)[132]. Polyloop claims that its equipment is able to process 300kg batches in 3 hours, with a maximum of 6 batches per day. Additional business partners include MTB recycling (installing and maintenance partner), CETHIL, CGI (Commissariat Général à l'Investissement, investor), BPI (investor), and the ADEME (Polyloop was selected as part of the "Circular Economy and Waste Recovery" call for projects launched in February 2019). The developer is part of the ReSol project together with Chomarat and the University of Claude Bernard Lyon 1 (UCBL). ReSol aims at recycling PVC-coated textile composites. In November 2021, the project received 540 000€ of public funding within the program R&D Booster 2021[133].

APK AG successfully produced the first pre-commercial quantities of recycled PE, PA, and aluminum in 2016. In 2018, the developer expanded its commercial plant in Merseburg (Germany), reaching a capacity of 8,000 t/year (it is not specified whether it refers to input or output capacity). It is known that the plant will focus on the recycling of PE/PA multilayer films. In 2019, the company had received around 19€ million as investments for the expansion of their operations. A great share of the investment (almost 4€ million) came from the state of Saxony-Anhalt [134]. In 2019, the developer communicated its intention to build another commercial plant with a capacity of 25,000 t/year in 2021. It is known that, by 2025, the company aims to build further plants across Europe and Asia. No further updates are available as of January 2022 (12). APK AG is owned by MIG Fonds and AT Newtech. The company has also established a strategic partnership with MOL Group (for technology development and plant construction) and is a member of a series of global networks including the Circular Plastics Alliance, Plastic Recyclers Europe, CEFLEX, and the Ellen MacArthur Foundation.

Although there is no information concerning the existence of CreaCycle's property plants, this developer has been successfully deploying its patented technology via business partners. In 2018, the first pilot plant in which the CreaSolv process is used was opened in partnership with Unilever in Indonesia. The plant can recycle up to 3 tons of packaging waste daily and it is the only facility in the world where this technology is being used to recycle sachets (60% of PE composition). In 2019, Unilever announced that the CreaSolv process had been successfully proven to be effective for the recycling of sachets through industrial scale trials[135]. However, due to technical, financial, and logistical challenges, the plant has been closed[136]. CreaCycle is also collaborating with PolyStyreneLoop, the MultiCycle Project[137] (Horizon 2020 project focus on plastic recovery in the packaging and automotive sectors, overall budget of 9.7€ million, almost 80% of which is funded by the EU), the European project NONTOX (Horizon 2020 project), and Circular Packaging[138]. Circular Packaging is a project supported by the German Federal Ministry of Education and Research (Bundesministerium für Bildung und Forschung) to provide alternative end-of-life solutions for multi-layer laminates from household waste (3.12€ million investment). The project was supposed to begin with the construction of a pilot plant (to be located at Lober GmbH & Co. Abfallentsorgungs KG's premises) to improve the recycling of multi-layer laminated waste. This first phase was going to be followed by an up-scaling of the technology to an industrial demonstration plant and testing at this facility. The project began in 2018 and was supposed to reach completion in 2021. As of January 2022, no updates have been found concerning the progress attained

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[132] https://polyloop.fr/polyloop-heberge-par-kem-one/
[133] https://polyloop.fr/projet-resol-enfin-du-pvc-recycle-pour-les-enducteurs/
[134] https://www.apk-ag.de/unternehmen-profitieren-von-einer-nachhaltigen-wirtschaftsfoerderung-des-landes-sachsen-anhalts-pressetermin-bei-apk-ag/
[135] https://www.creacycle.de/en/projects/packaging/unilever-sachet-recycling-2015.html
[136] https://www.no-burn.org/investigation-reveals-unilevers-expensive-plastic-sachet-chemical-recycling-failure/
[137] https://www.creacycle.de/en/creasolv-plants/multicycle-2018-en.html
[138] https://www.creacycle.de/en/creasolv-plants/circular-packaging-2018.html

so far. While the state of advancement of these facilities and their capacities are still unknown, it is acknowledged that the smallest plants built by CreaCycle have a capacity between 2-4,000 tons annually[139].

b Economic performance

Although a wide range of solvents are available on the market and, therefore, easily accessible, recovery and reuse of solvents is a necessary procedure for dissolution to be economically profitable. It is estimated that for the technology to be viable, the solvent used must have a good extractive activity and at least 70% of it must be recycled at the end of the process. High level of impurities within the input used may additionally threaten the economic viability of this technology due to potential need for cascade selective dissolutions when treating mixed plastics (24).

In terms of economic competitiveness of the recyclates, the price of r-PP recycled by PureCycle Technologies is claimed to be comparable to that of virgin polypropylene[140]. As of Polyloop, the developer claims that its output needs to have a minimum sales price of 1000€/tons for the process to be economically profitable[141].

Dissolution processes have recently been drawing attention of several actors in the EEE sector in Europe who wish to find effective ways to treat brominated plastics (24). The ability of this technology to treat plastic mixes which contain harmful additives may therefore be interpreted as a driver of increasing investments in the development of dissolution processes.

c Environmental performance

<u>LCA data (or similar studies), notably carbon footprint</u>
There is a lack of information on this topic.

<u>Comparative analysis between end-of-life processes</u>
Selective dissolution has a lower environmental impact than chemical recycling technologies which require for the polymer to be brought back to its monomer stage and then be repolymerized (24). No further information is currently available on this topic. No information was found on the environmental impact of the different solvents used by technology developers.

<u>Energy costs</u>
The energy consumption of selective dissolution technologies is generally lower than in traditional solvolysis, which requires heating, purification and repolymerization (5). Yet, while necessary to achieve economic profitability, the recovery of solvents by distillation may require a significant consumption of energy (24).

It is claimed that PureCycle Technologies' requires 60-85% less energy compared to the production of virgin polypropylene[142][143]. No further information was provided concerning the means (context, methodology, etc.) by which these numbers where estimated.

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[139] https://www.creacycle.de/en/the-process.html
[140] https://solarimpulse.com/efficient-solutions/purecycle-technologies
[141] https://www.lesechos.fr/pme-regions/innovateurs/polyloop-recycle-le-pvc-au-pied-des-usines-de-plastique-1292980
[142] Please note that this range is based on a forecasted utility demand for a commercial-scale purification plant which has been designed but not yet built.
[143] https://solarimpulse.com/efficient-solutions/purecycle-technologies

DISSOLUTION	
Technology	Input • Practically suited to all types of thermoplastics. Most projects on PS, PVC, and polyolefins. • Treats either mono-material contaminated streams (majority of technology developers) or mixed plastics. Some of the additives contained in the contaminated feedstock, like phthalates in PVC, may be dissolved with the polymer. This means that additional pre-treatment steps would be required. Pre-sorting or pre-treatment are often necessary (e.g., sorting, washing, grinding, etc.). Process • Dissolution has the advantage of almost not altering the chemical structure of the recovered polymer. • The nature of the process and the solvent used vary depending on the type of input. Usually, the type of solvent is not disclosed by the technology developers (confidential information). • Option A: the solvent added dissolves the targeted plastics. Melted polymers are then recovered and filtered to remove the remaining impurities. • Option B: the solvent added dissolves the unwanted additives/contaminants/plastics. The targeted polymer remains in its solid state, other substances may either be recovered or disposed of. • A non-solvent/anti-solvent is needed at the end of the process to bring either liquid polymers or other substances back to their solid form. • The process has an estimated duration of 30 minutes and is conducted at a temperature that is lower than the solvent's boiling point. Output and Downstream steps • The output consists of high quality recyclates and, in some cases, of valuable recovered substances (e.g., certain additives). • New additives may be added to the plastic output. • No food grade approval at the moment
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 5. • Most technology developers are still in the development phase of their technology. Current and future capacities • Technology advancements and plans for expansion significantly vary from a developer to another. • CreaCycle (up to 4,000 t/y per facility) and APK AG (8,000 t/y) are the most advanced technology developers in terms of scaling-up of their technology and/or capacity of their facilities. Other developers are still in the lab or demonstration phase. • Several technology developers (PureCycle Technologies, PolyStyreneLoop, Polyloop) claimed that they would have started operating their demonstration plant or commercial facilities in 2021/22. No further details have so far been found concerning the advancement of these operations.
Economic performance	• The recovery/recycling of solvents is necessary to achieve economic profitability. • The ability of dissolution to treat plastics containing additives may drive investments in this type of technologies. • Lack of public data available

Environmental performance	LCA data (or similar studies), notably carbon footprint • Most solvents have low flammability and low toxicity. • Some solvents may be toxic or explosive. Comparative analysis between end-of-life processes • Lower environmental impact than technologies bringing plastics back to the monomers to then repolymerize them. Energy costs • High energy consumption requirements for solvents' distillation. • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
Polystyvert, APK, PURECYCLE, POLYLOOP, PolyStyreneLoop, CreaCycle GmbH, VinyLoop	

Table 9 : Dissolution recapitulative table (RECORD, 2022)

*PolystyreneLoop stopped their project in March 2022.

VII. Thermal treatment

1) Non catalytic pyrolysis

a. Technology

Input
Pyrolysis is a process conducted in the absence of oxygen which can handle relatively mixed waste streams. However, it is more suited for polymers from polyaddition (polyolefins, PS and PMMA). Some resins such as PVC, PET or PU should previously be removed from the feedstock. Indeed, PVC can release hydrochloric acid, which is highly corrosive and causes harmful toxic fumes. As for PET, it increases the solid residue rate and consequently reduces the final yield. PET also contains oxygen, which is released in the reactor and interferes with the reaction media (24).
Moreover, some non-plastic additives such as fiberglass should be avoided as well as they generally cause operational problems in pyrolysis units (24).
Among the technology developers studied, most feedstocks were mixed plastic-rich waste (Agilyx, Plastic Energy, Recycling Technologies UK), post-consumer (Agilyx, Enval, OMV, Indaver) and post-industrial waste (Enval, OMV) feedstocks containing polyolefins (HDPE, LDPE, PP, PE), polystyrene, ABS, PB, PMP, PDMS and other polymers. PVC and PET can be processed by some technologies as well (Arcus Greencycling).
MMATwo is a four-years project launched in 2018 with the aim of recycling PMMA through non-catalytic thermal depolymerization. The feedstock used consists of post-industrial scraps and end-of-life waste (WEEE and ELV). The chemicals company ARKEMA is amongst the core members of this project.
The developers are concentrating their efforts on hard to recycle plastics such as soft and flexible packaging (e.g., films), multi-layered and laminated plastics (e.g., crisp packets), complex or even contaminated plastic (e.g., food trays). For instance, Enval is focusing on flexible pouches with an aluminum foil layer[144].
Some developers are also focusing on feedstock such as tires shreds. Examples of such companies include Enviro in Scandinavia[145].

Usually, a first sorting step is necessary to remove non-processable inputs and mechanically recyclable materials. The preprocessing steps also depend highly on quality standards needed. For instance, Agilyx is preprocessing waste in the plant to meet the quality control standards[146].
On the contrary, Arcus Greencycling asserts that no sorting is necessary[147].

Process
Pyrolysis is a thermal treatment process in the absence of oxygen. The aim of pyrolysis is to obtain a predominantly liquid faction.
Pyrolysis processes occur in an atmosphere without oxygen (the concentration of O_2 is inferior to 1%). Usually, they are carried out between 350 and 650°C (12). Most of the technology developers studied assert being in this range of temperature.
Enval uses microwaves to bring the energy needed. The plastic waste thus goes through a shredder, an airlock and then enters the reactor where it undergoes a micro-wave induced pyrolysis. Carbon black is added in the reactor to heat up the plastic, the carbon gets hot and transfers heat to the plastic. When the carbon is exposed to microwaves, it reaches temperatures of up to 1000°C in just a few minutes[148].
Other technology developers use non-condensable gases combusted (Arcus Greencycling, Plastic Energy, ITERO) or steam (Splainex) to supply energy to the pyrolysis reactor.

144 http://www.enval.com/
145 https://www.envirosystems.se
146 https://www.agilyx.com/
147 https://www.arcus-greencycling.com/
148 https://www.enval.com/plant/

Plastic Energy's process is also known as Thermal Anaerobic Conversion (TAC) and achieves a conversion rate of 85%. The remaining output (residual 25%) consists of tars and gas which are used to power the process[149].
Yields obtained are highly dependent on the feedstock and thus actual yield can be lower than theoretical or announced yield depending on the facility. The technologies studied claim to reach yields from 70% to 85% (mass yield from plastic waste to oil). Additional purification steps would result in further losses (approximately 3%)[150].
When going back to the monomer, the theoretical yield in styrene can go up to 85% (in the case of depolymerization of PS) and in MMA up to 90% (in the case of PMMA depolymerization) (12). The MMATwo project claims a yield between 64% and 85%.

Output and downstream steps
Depending on the feedstock, pyrolysis processes, under certain conditions, can produce the monomer, for example for PS, PMMA and Polyamide 6. It is thus a thermal depolymerization for these polymers.
In the case of other polymers as feedstocks, such as polyolefins (PE, PP), such a process could be considered as thermal cracking and will lead to three different fractions with different molecular weights.
Non catalytic thermal depolymerization gives out three main outputs:

- A liquid phase, oil, composed of hydrocarbon mix, that can be reprocessed and refined to obtain a petrochemical base of naphtha type or more generally polyolefins with C5-C10 chains. Depending on the process, C20 to C50 chains can be present in this phase. This fraction can afterwards be separated in a petroleum-type steam cracker (12).
- A gas mixture that can be thermally cracked to produce a gas free of condensable fractions (tars). After purification, this gas can be used directly in gas engines or gas turbines (12).
- A solid phase coke (or char), that can be:
    - either burnt to provide the thermal input necessary for pyrolysis (pyro gasification) (12).
    - or used as a secondary fuel, if it is not too loaded with pollutants (the pollutants of the waste remain in the majority) (12).
    - Pollutants, such as heavy metals, remain mainly in the coke because of the low treatment temperatures (washing and ash removal operations are generally necessary) (12).
    - or gasified in a separate device, after purification (12).

BASF, through its ChemCycling project, is feeding the oil fraction in their process BASF Verbund to produce r-PA resins. The input used can consist of recycled mixed plastic household waste, scrap tires, or industrial waste from polyamide production and processing[151].

Enval also produces aluminum foil from its pyrolysis process, as it has a commercial value and can be separated during the pyrolysis process[152].

The MMATwo project claims for its process to convert PMMA waste into high quality (>99 %) MMA monomer, also thanks to a purification phase carried out by Speichim. Different types of purification techniques are being tested to treat crude MMA and obtain a virgin like MMA. Distillation, pervaporation[153], reactive distillation with catalyst are among the techniques that are being tested[154].

Plastic Energy currently supplies TACOIL (pyrolysis oil) to Repsol, which converts it into virgin resins, and to Sabic, which transforms them into "circular certified polymers". Sabic and TESCO are working

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[149] Chemical Recycling in Asia Pacific conference, 14/09/2021
[150] https://plasticenergy.com/
[151]https://chemicals.basf.com/global/en/Monomers/polyamide_intermediates/sustainable_products/Ultramid_Ccycled.html
[152] https://www.enval.com/
[153] Pervaporation is a technique which uses a membrane within a partial vaporization process to separate mixed liquids.
[154] https://www.mmatwo.eu/wp-content/uploads/2020/10/MMAtwo-Virtual-Workshop_F-Boutros_P-De-Groote.pdf#:~:text=Speichim%20is%20specialized%20in%20toll%20purification%20%3B%20mainly,crude%20MMA%20to%20obtain%20a%20virgin%20MMA%20like.

jointly on a process transforming TACOIL into food grade r-PP[155]. Unilever, Tupperware and Mondelez are also already integrating TACOIL in the production of some of their products (including some food-grade applications).

OMV produces gas, synthetic crude oil (Syncrude) and petrochemical feedstock which are used for virgin plastics production at Borealis (OMV's partner).

Recycling Technologies UK's output consists of a hydrocarbon mix called Plaxx. Targeted final applications are plastic production (70%) and waxes (30%).

It is known that in 2020 the developer Fuenix Ecogy Group has completed the REACH registration for its Premium Circular Feedstock (naphtha, paraffin, LPG)[156].

b. Technology scaling-up

<u>Average Technology Readiness Level</u>
Most of the technology developers studied are at demonstration stage and thus their TRL range from 5 to 7.
Some particularly well-developed technologies are Plastic Energy, Enval and Splainex, which are close from industrial phase and whose TRL range from 7 to 9.

<u>Current and future capacities</u>
Current plants are able to produce from a few thousand tons a year to 35 000 tons per year (Splainex) of oil or monomers.
Planned capacities for the non-catalytic pyrolysis processes ranges from 15 ktons per year to 350 ktons per year in a time horizon from 2021 to 2025.
Plastic Energy is currently operating two plants in Sevilla and Almeria (first plant in the European Union having obtained a REACH certification) with a capacity of 7,000 tons/year input each, operating respectively since 2014 and 2017. They aim at expanding the production of their Sevilla plant by 2022 and of start building 10 chemical recycling plants by 2021 (across Europe and Asia). There is no news on whether this target has been reached. However, several projects are ongoing:

- Plastic Energy has contracted a partnership with ExxonMobil to build a plant in France (announced in 2021). The companies finalized the investment decision at the end of 2021 with start-up anticipated in 2023. The initial capacity of the plant is about 25,000 t/y of plastics waste, to be scaled up to 33,000 t/y in the future[157].
- A first large-scale plant was planned to start operations in 2021 on Sabic's Netherlands-based project in Geleen but it is now expected for 2022. The input capacity of this plant would be about 20,000 t/year. It is known that Sabic has invested approximately €30 million in the development of the facility.
- A plant with Ineos is expected to reach completion towards the end of 2023, although the companies have not announced a location for the plant. This plant would be able to process up to 30,000 tons of input per year.
- A plant in Pengerang, Malaysia is expected with Petronas. The agreement was signed in 2019, the plant is scheduled to operate in 2024 and to reach a capacity of 33kt/y (it is not specified whether it refers to input or output capacity). The facility will process municipal solid waste (MSW), rejects of mechanical recycling centers and other collected recyclables (composition not specified).

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[155] https://www.icis.com/explore/resources/news/2020/09/17/10553991/first-commercially-available-chemically-recycled-food-grade-r-pp-pellets-enter-market
[156] https://echa.europa.eu/registration-dossier/-/registered-dossier/31769
[157] https://plasticenergy.com/plastic-energy-announces_fid_and_start_of_construction_works_for_advanced_recycling_plant_in_france/

- A plant is expected with Total Energies which construction agreement was signed in 2020[158]. The plant will have a capacity of 15,000 t/y and will be located at Total's *zero crude* facility in Grandpuits, France. In January 2022, the two companies also announced the construction of a second plant in Sevilla, Spain. The recycling plant is expected to be completed by 2025 and to reach a final input capacity of 33,000 t/y[159].
- The developer signed a Memorandum of Understanding (MoU) in Indonesia with West Java for the construction of 5 plants with an average capacity of 20-33kt/y.[160]
- In October 2020, Nestlé additionally declared its intention to assess the opportunity of building a plant with Plastic Energy in the UK (no additional information provided).

In December 2021, Plastic Energy and INEOS Olefins & Polymers Europe announced a partnership to develop a solution to turn hard-to-recycle plastics into recycled resins suitable for food-grade and hygiene applications[161]. A strategic collaboration to increase the rate of plastics' recycling had also been signed in November of the same year with Axens[162].

Recycling Technologies UK currently owns a lab-scale demonstration facility (capacity 100kg/h), and it is in the building phase of their first pilot plant (no further details available). The construction of this facility is partly funded through a €10 million investment from Neste and Mirova (investment company specialized in sustainability) and a grant from Zero Waste Scotland (non-profit environmental organization). The developer plans to install 1300 machines by 2027, producing 7 million tons of Plaxx, which is their proprietary output of the oil fraction, annually. This is a rather ambitious goal.
In October 2020, the developer announced a joint project in collaboration with Neste and Unilever for the development of a recycling process able to produce virgin quality plastics[163].
Other Recycling Technologies' strategic partners include: Kerax (supply agreement), ecosurety (EPR scheme), Binn Group (waste management company), Innovate UK (funding). Research partners include: Wood Research and Development (testing and certification lab), University of Brimingham, Cranfield University, University of West of England, University of Surrey. It is known that INEOS Styrolution and Trinseo are working with Recycling Technologies UK to build multiple plants for the recycling of PS. To begin with, a pilot plant will be built it the UK in 2022. INEOS Styrolution plans to build a 15kt/y (input) commercial facility in Wingles, France (timeline not disclosed). Trinseo also announced they will build a plant with the same capacity in Tessenderlo, Belgium, which will be completed in 2023[164].

Enval uses modules that can be accolated to plants and to each other's. A typical Enval module operates at a feed rate of up to 350 kg per hour, which equates to a nominal capacity of 2,000 tons per year[42]. Enval partnerships include The Kraft Heinz Co. and Sonoco (to explore the deployment of plastic recycling solutions in the United States), Little Freddie, SAIREM, (supplier of microwave generators that power the recycling process), Resource Association, CIWM, and Cambridge Cleantech.

Fuenix Ecogy Group owns a pilot plant and is in its scaling-up phase. In 2020, the developer had received a € 4 million investment from Brightlands Venture Partners (with the participation of Koobra Invest, Bolsius and Fimavest as investors)[165]. Together with Dow Chemicals, the developer established

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[158] https://plasticenergy.com/total-and-plastic-energy-announce-a-strategic-partnership-and-the-construction-of-the-first-chemical-recycling-plant-in-france/#:~:text=Paris%20%E2%80%93%20Total%20and%20Plastic%20Energy%20announce%20the,new%20Total%20platform%20z%C3%A9ro%20crude%20in%20Grandpuits%2C%20France.
[159] https://www.packaging-gateway.com/news/plastic-energy-totalenergies-spain-recycling/
[160] Chemical Recycling in Asia Pacific conference, 14/09/2021
[161] https://plasticenergy.com/ineos-and-petroineos-at-grangemouth-partner-with-plastic-energy-in-an-important-breakthrough-in-the-recycling-of-plastic/
[162] https://plasticenergy.com/plastic-energy-axens-strategic-collaboration/
[163] https://recyclingtechnologies.co.uk/2020/10/recycling-technologies-neste-and-unilever-combine-expertise-to-test-and-validate-systems-to-chemically-recycle-waste-plastics/
[164] https://recyclingtechnologies.co.uk/2021/04/ineos-styrolution-recycling-technologies-and-trinseo-progress-plans-for-the-first-polystyrene-recycling-plants-in-europe/
[165] https://brightlandsventurepartners.com/nieuws/fuenix-raises-e-4-million-to-scale-up-its-technology-to-recycle-mixed-plastic-waste/

a partnership for the supply of pyrolysis oil to Dow's production facilities in Terneuzen, Netherlands (partnership ongoing since 2019). In 2021, the two partners extended their agreement with the goal of building a second plant in Weert, the Netherlands plant (20 kt/y input capacity, date of completion unavailable)[166].

ITERO owns a pilot plant in the UK and has a first commercial plant under construction. The R&D pilot plant is located in the UK (unknown capacity). The commercial plant is due in 2023 and will be located in Brightlands Chemelot Campus, Geleen, Netherlands and will require an investment of about 25 € million. The plant will consist of a single-module 27 kt/a facility (input)[167]. In February 2021, ITERO signed an agreement with COUNT Energy Trading. The agreement established that COUNT Energy Trading will purchase an annual share of the produced liquid output (up to 19kt/y). In June 2021, another partnership was initiated with Kerax (wax manufacturer) to increase the recycling of plastic waste. As part of the collaboration, Kerax will purchase up to 5kt/y of recycled wax produced by the commercial plant in the Netherlands.

OMV owns a pilot plant located in Schwechat, Austria which is planned to start operating by the end of 2022 (capacity of 16kt/y). The aim is to reach final industrial-scale capacity (200kt/y) by 2025 at the latest. OMV has invested approximately 10€ million in the project as a whole, 10% of which has been subsidized by FFG (Austrian Research Promotion Agency) (as of 2018). OMV also holds 75% interests in Borealis, which is currently working on a project (Borecycle C) to develop circular polymers derived from chemical recycling.

Of the MMATwo project, it is known that they aim to secure a supply of minimum 12.2kt of recycled materials from the input of 27kt of PMMA and other types of end-of life waste (not specified)[168].

The technology developer Indaver announced in 2021 that they had received permits to build a 15 kt/y plant in Antwerp, Belgium. Since 2017, the company had been working on a lab scale to develop the technology with Ghent University and the University of Antwerp. The announced facility is meant to bring Indaver from lab to pilot scale, yet, as of January 2022 no news on the subject were found[169].

Arcus Greencycling currently has an input capacity of 250 kg - 800 kg plastic waste per hour. While no details were found on this developer's recycling facilities, it is known that the North Channel Bank financed the construction of a first pilot system. The company has also partnered with Infraserv höchst (infrastructure partner, first prototype installed in their facilities), KIT (technology partner), Sphera (with whom they conducted a LCA assessment), and Sulzle (engineering partner).

Agilyx currently operates a 50-100 t/day (it is not specified whether it refers to input or output capacity) facility in Tigard, USA, under a joined venture with AmSty. As of July 2019, Agilyx was planning to build a commercial recycling facility in Europe with an input capacity up to 50t/day. No updates have however been found on the subject. The developer additionally has strategic partnerships with General Electric (development of an artificial intelligence technology), Go Beyond Racing (partnership to recycle single-use PS generated during events), Styrenics Circular Solutions (joint industry initiative), Technip Energies (to market and license Agilyx's depolymerization and Technip Energies' purification technologies), NextChem (technology and EPC partners to develop advanced chemical recycling facilities globally), ExxonMobil (established together Cyclyx Joint Venture to supply the plastics recycling industry), Braskem (deploy advanced recycling for PP in North America), Mitsubishi Chemical Methacrylates (developing solutions for the recycling of PMMA). In December 2021, Agilyx announced a partnership with Toyo Styrene for the building of a recycling plant (10t/d capacity) in Japan[170].

166

167 https://www.itero-tech.com/projects

168 https://www.persistencemarketresearch.com/market-research/methyl-methacrylate-market.asp

169 https://www.indaver.com/en/news-media/news-detail/press-release-indaver-receives-permit-to-build-a-new-plant-for-the-chemical-recycling-of-end-of-lif/

170 https://news.cision.com/agilyx/r/toyo-styrene-enters-into-the-construction-phase-of-chemical-recycling-facility-in-japan-utilizing-ag,c3483797

c. Economic performance

An economic analysis of rapid pyrolysis conducted by Gerard Antonini concluded that the technology could provide a positive return on investment after approximately 6 years (12). The following paragraph is a translation of his work. Please note this is a theoretical analysis.

This analysis focused on a Dense Fluidized Bed (DFB) installation allowing the rapid pyrolysis of plastic waste. This unit operates 8 000 h/year and can treat an incoming flow of used plastics of: 6,000 t/year.

d. Environmental performance

LCA data (or similar studies), notably carbon footprint

Among the technologies studied, some have undergone a study of their environmental impacts. However, as these evaluations have not been made public, the hypothesis and the methodology chosen are undisclosed and thus not confirmable.

Indeed, Fuenix Ecogy Group asserts that plastic made from their feedstock reduces CO_2 emissions by 65% compared to virgin plastic.

BASF conducted an LCA of their ChemCycling process. They compared CO_2 emissions of plastic production from pyrolysis oil and naphtha, using a mass balance approach. The process chosen was the production of ethylene in steam cracker and the polymerization to LDPE (low-density polyethylene). The feedstock either comes from naphtha from crude oil or from oil from pyrolysis of mixed plastic waste from German yellow bag. It was found that:

- "Conventional production of 1t LDPE emits, in total, 1894 kg CO_2e.
- For the production of 1t LDPE via pyrolysis a negative number of -477 can be accounted for the overall CO_2 emissions."
- BASF thus concludes that "1 ton of LDPE produced from pyrolysis oil under a mass balance approach, emits 2.3 t less CO2 than 1 ton LDPE produced from fossil naphtha"

This study relies on several hypothesis which are:

- The fact that the study is based on projections of future development if the waste sector in Germany (carbon footprint of electricity, etc.)
- The previous result is calculated using a mass balance approach.
- Negative emissions are taken into account in the calculation using a reference scenario for plastic waste treatment which is incineration.

Some methodological choices regarding this study are also debatable. Indeed, lower yields on the recycling process give out better environmental benefits. This is due to the fact that more feedstock is needed to produce the same quantity of recycled plastics. As the study takes into account avoided emissions of the end of life of plastics (incineration assumption in this case), if the quantity of material used increases, the environmental benefits also increase. Moreover, deducing end of life emissions is particularly decisive for the results obtained, even though it can be difficult to compute. Without deducing end-of-life emissions, the GHG impacts of the production of one kilogram of chemically recycled LDPE is greater than that of a kilogram of virgin LDPE[171].

In September 2020, Plastic Energy published a report in partnership with Quantis focusing on the life-cycle assessment of chemical recycling (pyrolysis) of plastic waste[172]. The study analyses chemical recycling using two different approaches:

- Approach 1 – Waste perspective: Comparison of different end-of-life options (landfilling, incineration, and chemical recycling) for 1kg of sorted mixed plastic waste (composition not specified)
- Approach 2 – Product perspective: Comparison of the production of 1kg of virgin LDPE with production of virgin-like LDPE via both mechanical recycling and chemical recycling

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[171] *Approche « Mass balance » et recyclage chimique des plastiques*, ADEME

[172] https://plasticenergy.com/sustainability/lca-report/#:~:text=Plastic%20Energy%20contracted%20independent%20sustainability%20consultancy%2C%20Quantis%2C%20to,is%20available%20to%20download%20on%20the%20link%20below.

The analysis was conducted within a European scope both for waste perspective and product perspective calculations. The waste perspective scenario considers an average European energy mix as baseline. The efficiency considered in the incineration with energy recovery plant are respectively 10.1% for electricity and 31% for heat. No further details are available on the data used to conduct calculations nor concerning the limits of the study.

Regarding the Approach 1, the results highlight that, in terms of climate change impact (kg $CO_{2\text{-eq}}$), chemical recycling is the second-best option after landfilling. In terms of resources use, chemically recycled LDPE proved to be the best option due to the prevented production of virgin naphtha. The study concludes that incineration is the scenario with highest climate change impacts (GHG emissions from incineration are not entirely compensated by energy recovery). Although landfilling has relatively low climate change impacts, the risk of materials being dispersed in the environment is not considered within the applied LCA calculations. Moreover, this end-of-life options hinders circularity as it does not allow to recover any materials in the process. Consequently, the report suggests that, in the long-term, chemical recycling will become a preferable solution to incineration with energy recovery from a waste management perspective.

Indicator (Units)	Chemically recycled LDPE (pyrolysis)	Incineration with energy recovery	Landfill
Climate change (kg $CO_{2\text{-eq}}$)	0.55	1.60	0.15
Resources use, fossil (MJ)	-31.10	-26.54	0.36

Table 10: LCA results for 1 kg of sorted mixed plastic waste

Regarding the Approach 2, the results highlight that mechanically recycled LDPE performs better in terms of climate change impact (kg $CO_{2\text{-eq}}$) than chemically recycled LDPE and virgin (fossil) LDPE. The results of this section take into consideration the prevented impacts of alternative end-of-life waste treatments. The results show that mechanical recycling performs better than chemical recycling, which however remains a better option that virgin LDPE production.

Indicator (Units)	Chemically recycled virgin-like LDPE (pyrolysis)	Virgin (fossil) LDPE	Mechanically recycled virgin-like LDPE
Climate change (kg $CO_{2\text{-eq}}$)	0.86	1.90	-0.45
Resources use, fossil (MJ)	39.54	80.08	22.14

Table 11: LCA results for 1 kg of produced virgin and virgin-like LDPE

In order to validate the reliability of the study's calculations, Plastic Energy and Quantis run a series of sensitivity tests. The following parameters were varied to verify the sensitivity of the obtained conclusions:

- Electricity mix used in the chemical recycling facility, for both the product and waste perspective approaches (i.e., EU mix vs 100% renewable one).
- Assuming, instead, that the entire plastic waste used in the chemical recycling process, alternatively, would have been incinerated (product perspective approach).
- Assuming, instead, that the entire plastic waste used in the chemical recycling process, alternatively, would have been sent to landfill (product perspective approach).
- Different distances travelled by truck (100 km, 500 km, 1000 km) to transport plastic waste to sorting facility for chemical recycling scenario (product and waste perspective approach).
- Electricity utilization for pyrolysis (± 20% compared to the baseline) at the chemical recycling facility.
- Different amounts of naphtha needed to produce 1 kg of LPDE (baseline: 1.6 kg Naphtha /kg LDPE; additional amounts tested include 1.4, 1.2 and 2.0 kg Naphtha / kg LDP).
- Efficiency of chemical recycling process in terms of the ratio of TACOIL produced and feedstock processed (baseline: 69.6%; additional efficiencies of 65% and 75% assessed).

- Amount of energy (i.e., electricity and heat) recovered from waste plastic in the incineration process (baseline: average EU energy recovery rate; other scenarios assessed include no energy recovery, and high energy efficiency).
- Mechanical recycling quality ratio from the Product Environmental Footprint (PEF) guidance has been tested to integrate the quality of the plastic as a parameter in the study.

Specific findings of the sensibility analysis have not been included within the public version of the report. However, the results of the study point out that, to achieve higher efficiency from an LCA perspective, chemical recycling technologies should decrease their energy consumption while increasing output yields. Renewable energy sources are suggested as a mean to further reduce carbon emissions.

<u>Comparative analysis between end-of-life processes</u>
The emissions calculated by Arcus Greencycling amount to 140 kg CO_2eq./t mixed plastic waste.

Recycling technologies UK asserts that their technology could save 1.4tCO2e per ton of plastic processed compared to an incineration facility.

The BASF LCA gives out favorable environmental performances for pyrolysis compared to incineration. The pyrolysis process taken into account is the production of oil as feedstock for the chemical industry (with a material yield of 70%, and almost no need of external energy due to internal energy recovery). It was compared to the incineration process, generating electricity and steam that substitutes electricity from national grid and steam from national average. The feedstock used is one ton of mixed plastic waste from packaging (German yellow bag) in both cases. It should be noted that *"the study is based on an assumed future development of pyrolysis and the waste sector in Germany in 2030"*[173]. It was found that:

- "Pyrolysis of 1t mixed plastic waste emits, in total, 739 kg CO_2e.
- Incineration of 1t mixed plastic waste emits, in total, 1777 kg CO_2e."

In conclusion, pyrolysis of mixed plastic waste emits 50 percent less CO_2 (or 1t less CO_2) than the incineration of mixed plastic waste.

Gerard Antonini conducted a similar analysis on a flash pyrolysis installation (12). This installation can treat about 6 000 tons of waste plastic by year and can function continuously for 8 000 hours/year. His conclusions were that:

- The rapid pyrolysis process (including sorting, electric consumption, and indirect emissions) emits about 1 039,7 t CO_2/year. These emissions only relate to the treatment of the plastic waste and not the latter steps from pyrolysis oil.
- Incineration of this quantity of plastics would emit 15 553,5 t CO_2/year.

The results of the different analyses should be considered carefully as they are very variable depending on the methodology chosen and the assumptions for the calculation. Gerard Antonini's assessment was conducted for a French facility using thus the French electricity emission factor and waste composition.

<u>Energy costs</u>
Pyrolysis is a very energy intensive process compared to other recycling technologies, but some technology developers assert that by incinerating the gas fraction produced during the process, it can be self-sustaining. A case study of a pyrolysis plant confirmed this analysis by revealing that the process was autothermal (12). However, the process still needs an external energy supply to function at a certain moment. Plastic Energy uses produced tars and gas to power the recycling process.

In November 2021, Agilyx announced that its Tigard, Oregon facility has transition to an energy supply sourced entirely from renewable sources[174].

[173] Critical review statement LCA for Chemcyling
[174] https://news.cision.com/agilyx/r/agilyx-and-amsty-joint-venture-transitions-to-100--renewable-energy-at-its-tigard--oregon-facility,c3454985

NON-CATALYTIC PYROLYSIS	
Technology	Input • More suited for polymers from polyaddition (polyolefins, PS, ABS and PMMA). • Treats relatively mixed plastics waste streams but acceptable polymers ratio is very high • Usually, a first sorting step is necessary to remove non-processable inputs (PVC, PET, PU…) and mechanically recyclable materials. Process • Pyrolysis processes occur in an atmosphere without oxygen (the concentration of O_2 is inferior to 1%). • They are carried out between 350 and 650°C. Some technologies (such as Enval) use microwaves to bring the energy needed. • Yields obtained range from 70% to 85%* (mass yield from plastic waste to oil). Additional purification steps would result in further losses (approximately 3%). • When going back to the monomer, the theoretical yield in styrene can go up to 85%* (depolymerization of PS) and in MMA up to 90%* (PMMA depolymerization). Output and Downstream steps • Pyrolysis processes, under certain conditions, can produce monomers of polymers input, for example for PS, PMMA and Polyamide 6. • In the case of other polymers as feedstocks, such as polyolefins (PE, PP), it will lead to three different fractions: an oil fraction, a gas mixture and coke or char. • The oil fraction can be reprocessed into naphtha or polyolefins and be separated in a petroleum-type steam cracker. • The gas mixture is usually used to supply heat for the process.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 5-8. • Most technology developers are still in the development phase of their technology. • Enval and Splainex are close from industrial phase. Plastic Energy is at commercial scale. Current and future capacities • Current plants are able to produce from a few thousand tons a year to 35 000 tons per year (Splainex) of oil or monomers. • Planned capacities for the non-catalytic pyrolysis processes ranges from 15 ktons per year to 350 ktons per year in a time horizon from 2021 to 2025.
Economic performance	• An economic analysis of rapid pyrolysis as conducted by Gerard Antonini concluded that the technology could provide a positive return on investment after less 3 years. • Lack of public data available
Environmental performance	LCA data (or similar studies), notably carbon footprint • BASF found that 1 ton of LDPE produced from pyrolysis oil under a mass balance approach, emits 2.3 t less CO_2 than 1 ton LDPE produced from fossil naphtha. These figures are only indicative. • The BASF LCA gives out favorable environmental performances for pyrolysis compared to incineration (even though it is computed with strong methodological choices, see VII.d). Energy costs • Pyrolysis is an energy intensive process compared to other recycling technologies, but some technology developers assert that by incinerating the gas fraction produced during the process, it can be self-sustaining. A case study of a pyrolysis plant confirmed this analysis by revealing that the process was autothermal. This

	means that a part of the output is used for the energy of the site. However, the process still needs an external energy supply to function at a certain moment. • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
OMV, INDAVER, MMAtwo, fuenix, PLASTIC ENERGY, ARCUS, Recycling Technologies, ETIA Ecotechnologies, agilyx, ITERO, BOREALIS, enval, ARKEMA, clariter, Splainex Ecosystems	

Table 12 : Non-catalytic pyrolysis recapitulative table (RECORD, 2022)

*Yields can vary depending on the feedstock type and operating conditions. These yields are likely to be overestimated as they have been calculated by technology developers on a lab scale.

2) Catalytic pyrolysis

a. Technology

Input

Catalytic pyrolysis is able to treat waste that is rejected by centers treating household waste for recycling, light automotive shredder residue (ASR) (plastic films, foams, etc.), and mixed waste resulting from the production/transformation of plastics. The source of the feedstock can be post-consumer or post-industrial depending on the requirements of the technology developer.

Some technology developers favor the use of homogeneous feedstocks (GreenMantra Technologies[175] or Pyrowave[176] relying on PS input streams), while others process mixed plastic waste (24). It should be noted that the term "mixed plastic waste" may not refer to all type of polymers. Most technologies are not capable of treating all types of plastics, which is why developers only accept a mix of selected polymers as input. As an example, Quantafuel[177] and Pryme[178] only process mixed plastic waste composed of PE, PP and PS. GreenMantra Technologies[179] owns a technology capable of treating post-consumer and post-industrial waste (either PP & PE, or PS mixed waste).
In October 2021, BioBTX announced its involvement in the Circular Foam project together with Covestro, RWTH Aachen University, ETH Zürich and Rijksuniversiteit Groningen. The project aims at the design and demonstration of chemical recycling solutions for PU rigid foams into high quality products suitable for closed-loop applications (it was not yet disclosed whether Bio BTX's technology is the one that will be used within the project)[180].

PVC feedstocks are frequently avoided as there is evidence of this material reducing the process performance due to a strong decrease in the activity of the catalysts in the presence of sulphur and acid vapors, with a subsequent decrease in the yield of the reactions (5). Cassandra Oil[181] and Anellotech are able to treat different types of waste (e.g., end of life tires, oil contaminated soil and oil sludge, electronic scrap). These developers however do not accept PVC in their feedstock. In general, PET

[175] http://greenmantra.com/
[176] https://www.pyrowave.com/en/
[177] https://quantafuel.com/
[178] http://www.pryme-cleantech.com/about-us/
[179] Please not that Geenmantra Technologies treats both PS and a mixture of PP and PE. Although processed by the same technology developers, these two feedstocks are recycled separately.
[180] https://biobtx.com/making-pur-foam-circular/
[181] http://cassandraoil.com/en/

waste is not accepted either by the technology providers. Yet, some of them tolerate a certain PET fraction in the feedstock.

Feedstocks containing a high level of contaminants (such as paper, chlorinated products, heavy metals) may lead to a significant reduction of the reaction yields or, in some cases, even to the deactivation of the catalyst (such as in the presence of certain metals). That is why pre-treatment steps might be required (8, 9). As an example, the benefits of adding a catalyst in the pyrolysis process may rapidly decline also due to the presence of chlorine or nitrogen in the carbon residues. That is why catalytic pyrolysis may require the pre-sorting or the pre-treatment (e.g., pre-pyrolysis) of waste (12). Pyrowave and GreenMantra Technologies both include a step of input's preparation at the beginning of their recycling process. Pyrowave removes contaminants and impurities from its feedstock during a phase of preparation and shredding of feedstock (details not disclosed)[182], GreenMantra Technologies removes impurities by extrusion (12).
Of the developer Carboliq, it is known that the size of its input feedstock should not exceed the following measures: 40mm for 2D, and 5mm for 3D. Metals, stones, glass, ceramics, and porcelain also have to be removed, while humidity should be kept below 18%. Yet, Carboliq's process was also designed to handle significant quantities (not specified) of PVC and brominated ABS waste contamination[183].
For some actors such as Quantafuel, Carboliq, and KIT, which only treat specific resins, it remains unclear whether the technology developers are responsible for the sorting and purification of their own input.

Process

Catalytic pyrolysis features the presence of a catalyst (e.g., metal oxides, cobalt complexes, silicate zeolites, etc.), which is added to achieve results such as increased reactivity of the reaction, lower operating temperatures, better selectivity, and reduction of by-products (24). Catalytic pyrolysis can take place either in a liquid (melted) or in a solid form (12). The first case consists of a one-level approach in which the catalyzer and the polymer are directly in contact with each other while the polymer is in its liquid form. The other option is to use a two-step system beginning with the thermal degradation of the polymer, followed by a catalytic processing of the produced vapors (5). In the second scenario, the catalyst is in contact with the formed vapors in its gaseous form (12). The two-step approach can be used to prevent a deactivation (poisoning) of the catalyst due to the presence of impurities such as certain metallic traces. This treatment can be carried out in line or decoupled (pyrolysis then condensation of the vapors then catalytic treatment) (24). Information concerning the type, quantity, and recovery of the catalysts used by each technology developer is usually not publicly disclosed (16).

Regarding operating conditions, the presence of a catalyst reduces processing temperatures to around 300°C compared to approximately 400-450°C for non-catalytic pyrolysis (24). As an example, using a catalyst (MgO, CaO, …) to depolymerize PS can reduce the reaction temperatures from 550-600°C to 380-400°C (12). Catalytic pyrolysis conducted at temperatures as low as 200°C is often referred to as slow catalytic pyrolysis (5). Another variant of catalytic pyrolysis is catalytic microwave pyrolysis. In this case, plastic waste is mixed with a highly microwave-absorbent dielectric material to improve plastics' naturally poor dielectric strength. The choice of the added material determines the resulting magnitude of heating and heating efficiency. Once the dielectric material has been added to the plastics mix, the heat absorbed from the microwaves is transferred to the plastics by conduction. Advantages of using this treatment include even heat distribution, higher heating rates, increased control over the process and improved production speed when compared to conventional pyrolysis (10). The Canadian developer Pyrowave bases its chemical recycling operations on this process.

GreenMantra Technologies process uses a thermochemical process in which PP (with less than 10% of PE) is preheated and fed into a pyrolysis reactor where it is depolymerized. This step can include catalysts to target specific end products.

Carboliq (subsidiary of Recenso GmbH, Germany) developed a Catalytic Tribochemical Conversion (CTC), which is a one-stage liquefaction process. This process uses a mechanical shear imposed on

[182] https://www.pyrowave.com/medias/iw/pyrowave-process-ENG.pdf
[183] http://www.carboliq.com/pdf/1910_CARBOLIQ-flyer-K-2019.pdf

the reaction medium to overcome the limitations of heat and mass transfer. The shear also lowers the required reaction temperature, bringing it below 400°C while operating under atmospheric pressure levels. The catalyst used by the developer is not disclosed. Carboliq claims that the only source of energy used within the process is generated through friction[184].

Quantafuel has developed a unique two-stage catalytic process (type of catalyst not disclosed). Following pyrolysis, the developer purifies the gas from impurities (ash, chlorine, sulphur, etc.), then condenses it and separates oil fractions through distillation[185]. This two-stage process is used to maximize the valorization of plastic waste and increase the quality of desirable hydrocarbons.

The Karlsruhe Institute of Technology (KIT) and LyondellBasell have been cooperating on a joint research venture since 2018. The goal of the agreement is to develop a new catalytic thermal depolymerization technology. KIT contributes to the partnership through its expertise in thermal conversion processes, while LyondellBasell focuses mainly on the development of the catalyst. This collaboration led to the development of the MoReTec technology (no further details provided).

<u>Output and downstream steps</u>
Composition of the feedstock, selected catalyst and processing techniques have therefore direct implications on the outputs of catalytic pyrolysis (12). Plastic waste recycled via this reaction leads to outputs which nature is similar to those of non-catalytic pyrolysis. These include:

- <u>A liquid fraction</u>: the reaction leads to the production of a pyrolysis oil. In general, the presence of a catalyst favors the production of oligomers with chains containing between 5 and 10 carbon atoms (fuel compounds like diesel or gasoline) (12). Very selective catalysts can lead to the production of specific hydrocarbons with high commercial value and prevent the formation of chlorinated hydrocarbons (in the case of waste containing PVC). Depending on the nature of the process and feedstock used, the refining of pyrolysis oils can either lead to monomers (depolymerization, possible with PA6, PS, PET, or PMMA) or to a hydrocarbon mix (cracking, necessary for polyolefins) (12). Following post-treatment steps (such as purification) the final outputs obtained by developers consist of products such as crude oil (Cassandra Oil), olefins (Anellotech), naphtha (Pryme), kerosene (Pryme), BTX (Bio-BTX, Anellotech), styrene (Pyrowave; Greenmantra produces both a primary up-cycled low molecular weight polystyrene and a secondary recycled styrene monomer)[186], waxes (GreenMantra Technologies, Pyowave) and hydrocarbon mixes suitable for fuel applications (Carboliq).
- <u>A gaseous fraction:</u> another product is syngas, which can be composed of a mixture of hydrogen, methane, and various hydrocarbons. Further catalytic treatment of syngas also allows to obtain ammonia, ethanol, or methanol.
- <u>Solid residues:</u> a mixture of organic compounds and recycled fibers. Coke (or char), that can be used for energy recovery, fuel production, or gasified (12).

Different catalysts can be used to direct the products, improve the outputs' quality, and yields of this process compared with non-catalytic pyrolysis (24). Using a catalyst to depolymerize PS allows to reach a yield close to 79% in styrene (Pyrowave's yield reaches up to 95% in monomer production) (7,8). The conversion of polymers into monomers is more significant when the catalyst is added to the polymer in its liquid form (the polymer direct contact with the catalyst favors the reaction compared to when the vapors formed are put in contact with the catalyst in its gaseous form) (12). Examples of technology developers' liquid output yields include Quantafuel – 84%[187], Pryme – over 90% liquid output, 10% non-condensable gases. No further information was provided concerning how these yields were calculated.

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[184] http://www.carboliq.com/en/technology-en.html
[185] https://www.quantafuel.com/our-solution/technology/
[186] https://www.ineos.com/businesses/ineos-styrolution/news/ineos-styrolution-and-greenmantra-sign-jda-to-advance-polystyrene-chemical-recycling/#:~:text=GreenMantra%20utilizes%20its%20existing%20proprietary%20and%20patented%20catalytic,molecular%20weight%20polystyrene%20and%20secondary%20recycled%20styrene%20monomer.
[187] https://www.basf.com/global/en/who-we-are/sustainability/we-drive-sustainable-solutions/circular-economy/mass-balance-approach/chemcycling/FAQ_ChemCycling.html

Specific studies conducted on PE proved that the larger the polymer's pore size, the higher the yield of PE conversion to liquid hydrocarbons. In this case, less acidic catalysts would yield lighter gas and liquid fractions, thus facilitating an easier return to the associated monomers or oligomers after steam cracking (12).

In the case of KIT and Lyondell Basell, the oil obtained through pyrolysis is cracked into C2 and C3 gas, which are used to produce respectively transparent PE and PS[188]. The technology developers produce multiple output products (e.g., Quantafuel's output consists of 10% ash, 16% light fraction, 56% diesel fraction, 8% heavy fraction). Low temperature and microwave catalytic pyrolysis can lead to good quality output materials (e.g., recycled fibers with good mechanical and surface characteristics) (5). Catalysts can also be used to address the presence of brominated flame retardants in plastic waste. However, while some catalysts can reduce bromine levels in the oil, they can also significantly reduce the amount of oil or alter its composition (24).

Anellotech's technology, known as Plas-TCat™ process, can be controlled to either generate an output with a high yield of BTX or a high yield of olefins. Other minor components found within the output include paraffins, H_2, other C5+ liquids, and wax. The desired output products (BTX, ethylene, propylene, paraffins) are produced directly within the reactor and are ready to undergo the purification step. The amount of CO and CO_2 produced depends on the oxygen content of the feedstock.

In cases where a hydrocarbon mix is produced, the latter can be further purified/distilled to become eligible for integration into higher value applications (Quantafuel, GreenMantra Technologies, Anellotech). GreenMantra's final output consists of PE and PP polymer additives, waxes, styrene polymers, which can be used in asphalt, polymer reprocessing, and plastic composites.

As a general comment, it is relevant to mention that although it might be possible to obtain virgin-quality equivalent recyclates (including feedstock suitable for food-grade applications), significant losses (details currently unavailable) might occur during each recycling loop aiming to achieve this high-quality output (16).

b. Technology scaling-up

<u>Average Technology Readiness Level</u>
Most of the reviewed technology developers had an estimated TRL of 6-7. An exception is represented by low temperature catalytic pyrolysis as this process has a lower maturity level.

<u>Current and future capacities</u>
The current production capacities of the reviewed technologies significantly vary from one developer to another. Most of the technology developers already possess a pilot (Anellotech, Bio-BTX) or a demo plant (Carboliq - output of 2500 tons/year; Cassandra Oil demo plant - One Cassandra 1500kW-reactor is expected to produce approximately 300 000 barrels of oil per year).

Some players have already begun construction for their commercial recycling facility. Developers such as Pryme, Carboliq, Bio-BTX have announced that their new plants are expected to begin production within the next 2 to 3 years (2022-2023). Pryme has a planned input capacity of 40,000t/year for their future commercial plant located in Rotterdam, Netherlands (commissioning expected Q2 2022) which is expected to be increased of 50% by 2023[189]. Pryme additionally claimed that they will select five European locations and start the permitting process to build more plants by the end of 2021. As of 2021, Pryme established a feedstock supply agreement with Suez and signed a Letter of Intent (LOI) with Shell Chemicals for off-take and downstream development. In the same year, the developer secured a NOK 287 million investment through private placement which will be used to develop its plant in Rotterdam.

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[188] https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/chemical-recycling-via-conversion-to-feedstock/start-up-of-lyondellbasells-moretec-plant-underlines-ambitious-plastic-waste-targets
[189] https://pryme-cleantech.com/

Pyrowave owns a small-scale unit in Canada processing 400-1200t/y (news as of 2019). The developer works in partnership with Ineos (buyer of its output) and ReVital Polymers (recycling partner). Furthermore, in November 2020, Michelin and Pyrowave agreed to work together to fast-track the industrialization of Pyrowave's technology (focus on certification and international commercial roll-out). The joint development agreement will ultimately account for an investment of more than €20 million[190].

GreenMantra Technologies started the construction of a 1100 t/y demonstration plant in 2018. As of end 2019, GreenMantra owned a commercial facility containing 3 production lines. A fourth production line was announced by the end of 2019 - no additional information is however available on the status nor the capacity of the plant. The facilities that are currently run and operated by GreenMantra focus on the processing of PE and PP. In 2019, the developer announced its intention to start building a demonstration plant for PS recycling, keep expanding its existing facilities, and further deploy its technology on a global level (no additional information available). GreenMantra's strategic partners include INEOS Styrolution (joint development agreement), HARKE GROUP (distribution partnership), Western Technologies and Innovation LLC (aiming to expand its presence into Middle East and Africa, and in the Indian subcontinent), Crayola (the company will supply discarded plastic markers which will be turned into high-value polymers for industrial applications). In 2021, the company additionally received a funding of $1 million from Bioindustrial Innovation Canada and of $1 million from the Canadian government.

In September 2020, KIT and LyondellBasell announced the successful start-up of the first MoReTec molecular recycling facility in Ferrara, Italy. The facility has a capacity of 5-10 kilograms of household plastic waste per hour, which is equivalent to an output of approximately 17 t/y. While no further information was found as of January 2022, it is known that the deployment of MoReTec's technology is part of LyondellBasell goal of producing 2 million metric tons of recycled and renewable-based polymers annually by 2030.[191]

In 2020, Anellotech partnered with R Plus Japan, a new joint venture of 16 Japanese cross-industry partners aiming at developing Plas-TCat™ to commercialize an eco-efficient recycling technology by 2027 (end of a 4-year development program being run by Anellotech). Two plants are under construction. The engineering phase for the first plant began in June 2019, the plant will have an input capacity of 500 tpd, producing 40 kt/y of BTXN (benzene, toluene, xylene, and naphthalene) & 30 kt/y of CO. The second commercial plant (planning under way) will have an input capacity of 2,500-3,000 tpd, producing 200-250 kt/y of BTXN & 150 kt/y of CO. Its research and development partners are Johnson Matthey and Intercat (specialized in catalyst technologies), IFP Energies Nouvelles (IFPEN) (process development and scaling-up), Axens (process and plant design, licensing). The developer is also partnered with Toyota Tsusho Corporation (strategic equity investor and corporate partner for the supply chain of renewable aromatic chemicals).

Quantafuel is amongst the developers with highest capacity thanks to its commercial plant in Skive (Denmark), which was recently scaled-up and has now an input capacity of 20 000 t/y[192]. The developer has also another plant in Kristiansund (pilot plant developed with BASF used to test commercial scalability)[193], and other plants planned in Esbjerg in 2022 (80,000 ton per year), Antwerpen w/VITOL & VTTI in 2022-2023 (100,000 ton per year), Amsterdam with VITOL & VTTI in 2022-2023 (100,000 ton per year), and a first plant with BASF in 2023 (100,000 ton per year)[194]. In 2021, the company purchased

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190 https://www.michelin.com/en/press-releases/michelin-and-pyrowave-join-forces-to-industrialize-an-innovative-plastic-waste-recycling-technology/

191 https://cefic.org/a-solution-provider-for-sustainability/chemical-recycling-making-plastics-circular/chemical-recycling-via-conversion-to-feedstock/start-up-of-lyondellbasells-moretec-plant-underlines-ambitious-plastic-waste-targets

192 https://www.quantafuel.com/skive

193 https://www.quantafuel.com/Kristiansund

194 https://www.quantafuel.com/plants-and-projects#:~:text=Quantafuel%E2%80%99s%20pilot%20plant%20in%20Kristiansund%20is%20part%20of,plant%20to%20be%20built%20on%20the%20same%20premises.

a site to build the Esbjerg plant, which will become of one of the biggest plastic waste sorting plants in Europe as well as their future chemical recycling plant. As of June 2021, Quantafuel invested in a plastic pre-sorting line in Aalborg. The sorting line is being built in cooperation with Geminor and it will increase control over feedstock quality for the Skive and Esbjerg plants[195].
Quantafuel has additionally established partnerships with VTTI (energy partner), Grønt Punkt Norge AS (partnership to increase the material recycling rate in Norway), Plastpiratene (organization involved in plastic collection activities which will send waste to Quantafuel), Vitol (funding of its first plants), and BASF (invested 20 million € to secure the pyrolysis oil for the ChemCycling project)[196].

The capacities of other developers (such as Bio-BTX) were not disclosed. The first pilot plant of BioBTX was opened in partnership with Zeton, Tebodin-Bilfinger, University of Groningen, KNN Advies B.V., and Syncom B.V. It is known that Bio-BTX has secured funding from multiple investors (Carduso Capital, Vries Beheer, Lynnovation, Groeifonds, NOM) which will be used mainly for the construction of the first commercial plant. The technology developer is also part of the iCarePlast project which aims to turn plastic into aromatics using BioBTX's technology. Other than BioBTX, the iCarePlast consortium is composed of the Agencia Estatal Consejo Superior de Investigaciones Científicas (CSIC), the Universitat Politècnica de València, the Technische Universität Braunschweig, iPoint-Systems gmbh, the National Laboratory of Energy and Geology (LNEG), University of Twente, Imperial College London, KERIONICS S.L., URBASER, S.A.[197].

c. Economic performance

Although little information is available, it is relevant to point out that the profitability of these processes is directly impacted by the cost, type, quantity, and lifespan of the catalyst used (24).

Quantafuel has developed a financial model which allows the company to receive a payment both for accepting waste plastic and for the final output sold. This technology developer is receiving a payment around 50-80$ for each ton of plastic collected for recycling. Moreover, the developer has established a partnership with BASF, which has committed to buying all of their output [198] [199]. The estimated market price of their output is of 1000$ per ton (24).

Pryme has a projected CAPEX of 700€ per ton of output (oil).

The technology developer Carboliq published the following financial information on its website[200]:

- Targeted sales price > 550€/to oil, > 50€/to fuel
- Negative cost (gate fee) for feedstock delivery: -50€/to
- Cost of production <400€/to oil

Additional information on economic performances is currently unavailable as these details are usually not publicly disclosed by developers.

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195 https://www.marketscreener.com/quote/stock/QUANTAFUEL-ASA-103374361/news/Q3-21-36981840/
196 https://www.quantafuel.com/our-solution/our-partners#:~:text=Quantafuel%20and%20Plastpiratene%20aim%20to%20establish%20an%20environmental,tonnes%20of%20plastic%20waste%20from%20the%20marine%20environment.
197 https://www.icareplast.eu/consortium/
198 https://seekingalpha.com/article/4378135-quantafuel-global-leader-in-chemical-recycling-of-plastic-backed-basf-and-vitol-potential-to
199 https://d1kc1xo119v43s.cloudfront.net/1613912399/qfuel-annual-report-2019.pdf
200 https://carboliq.com/en/contributions-en.html

d. Environmental performance

<u>LCA data (or similar studies), notably carbon footprint</u>
In terms of environmental impact, Pryme claims for its process to present the opportunity to reduce CO_2 emissions up to 100% when compared to traditional forms of crude oil extraction[201] (no further information was provided concerning the methodology and context that were used to estimate this number). As for Pyrowave, each ton of processed plastics is estimated to prevent the release of more than 2 tons of greenhouse gases[202] (no further information was provided concerning the methodology and context that were used to estimate this number). Little information is available assessing the reusability or recyclability of catalysts. Additional details concerning the means by which these numbers have been calculated is currently unavailable as this information is usually not publicly disclosed by developers.

<u>Comparative analysis between end-of-life processes</u>

No information found on this subject

<u>Energy costs</u>
By reducing the temperatures required for depolymerization to occur, the presence of a catalyst has the potential to reduce the energy required for catalytic pyrolysis compared to non-catalytic pyrolysis (16). As an example, using a catalyzer in the processing of PP and PE can reduce the activation energy respectively from 276 kJ/mol to 106 kJ/mol and from 394 kJ/mol to 178 kJ/mol (12).

Pyrowave claims for its process to have a (low) energy consumption of roughly 1 to 1.5 kWh/kg of processed materials), which is approximately 10 times less energy than making styrene from virgin resources[203].

Pryme claimed that they intend to source 100% of their energy from renewable sources (no further details provided).

CATALYTIC PYROLYSIS	
Technology	Input • Input can consist of homogeneous feedstocks (GreenMantra Technologies or Pyrowave relying on PS input streams) or of mixed plastic waste (Quantafuel, Pryme, Cassandra Oil). • Pre-sorting/pre-treatment may be required to remove contaminants that may lead to a significant reduction of the reaction yields or, in some cases, even to the deactivation of the catalyst (Pyrowave, GreenMantra Technologies, Anellotech). Process • The presence of a catalyst leads to an increased reactivity of the reaction, lower operating temperatures, better selectivity, and reduction of by-products. • Information concerning type, quantity, and recovery of the catalysts used is usually not publicly disclosed. • Option A: one-level approach in which the catalyzer and the polymer are directly in contact with each other while the polymer is in its liquid form (Carboliq). • Option B: two-step system beginning with the thermal degradation of the polymer, followed by a catalytic processing of the produced vapors (option often used to prevent the deactivation of the catalyst) (Quantafuel). • Processing temperatures to around 300°C.

[201] https://www.pryme-cleantech.com/solutions/
[202] https://www.pyrowave.com/medias/iw/Brochure-PYROWAVE_2020_ENG_PDF.pdf
[203] https://www.pyrowave.com/medias/iw/Brochure-PYROWAVE_2020_ENG_PDF.pdf

	• Variants of this process: low temperature catalytic pyrolysis; and catalytic microwave pyrolysis (Pyrowave). Output and Downstream steps • Like in non-catalytic pyrolysis, output is composed of a liquid fraction, a gas fraction, and solid residues. • Different catalysts can be used to direct the products, improve the outputs' quality, and yields of this process compared with non-catalytic pyrolysis. • Depending on the selected process, catalytic pyrolysis can lead to the formation of monomers (depolymerization) or to a hydrocarbon mix (cracking). • The presence of a catalyst favors the production of oligomers with chains containing between 5 and 10 carbon atoms (with the exception of developers such as Clariter who also targets wax production, i.e., product with more than 10 carbons). • Further processing (purification/distillation) of the obtained hydrocarbon mix can make this output eligible for integration into higher value applications (Quantafuel, GreenMantra Technologies, Anellotech). • Examples of technology developers' liquid output yields include Quantafuel - 84%, Pryme - over 90%.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL: 6-7. • Low temperature catalytic pyrolysis (approximately 200°C) represents an exception as it has a lower maturity level. Current and future capacities • Current capacities significantly vary from one developer to another. • Quantafuel is the developer that currently has the highest capacity thanks to its commercial plant (20,000 tons of plastic processed per year). • Several technology developers (Pryme, Carboliq, Bio-BTX, Quantafuel) claimed that by 2022/23 they will begin production in a commercial facility. No further details have so far been found concerning the advancement of these operations.
Economic performance	• Cost significantly impacted by the price, type, quantity, and lifespan of the catalyst used. • Lack of public data available
Environmental performance	LCA data (or similar studies), notably carbon footprint • Pyrowave claims that for each ton of processed plastic they prevent the release of over 2 tons of greenhouse gases. This figure is only indicative. • Little information available concerning the reusability/recyclability of catalysts. Comparative analysis between end-of-life processes • Lack of public data available Energy costs • As the catalyst reduces operating temperatures, energy consumption should be lower than for traditional non-catalytic pyrolysis. • Lack of public data available on the environmental impact of the process
STUDIED TECHNOLOGY DEVELOPERS	
QUANTAFUEL, CASSANDRA OIL, BioBTX, carboliq, Anellotech, GREENMANTRA TECHNOLOGIES, PYROWAVE	

Table 13 : Catalytic pyrolysis recapitulative table (RECORD, 2022)

3) Hydrothermal cracking

Note: This section presents the hydrothermal cracking technology Cat-HTR™ developed by Licella Holdings. As of today, Licella Holdings mainly operates via a series of partnerships and subsidiaries (including Mura Technology and Renew ELP).

a. Technology

Input
In terms of feedstock, Cat-HTR™ uses mixed plastics as input, including certain types of multi-layered plastics (composition not specified). It should however be noted that the quality of the output is directly affected by the input. As an example, the quantity of aromatics found within the feedstock directly impacts the output's quality (no further details provided). That is why, Licella Holdings is currently working with refineries (using their infrastructure) to test how to best extract impurities from their input.[204] It is also known that Mura Technology is already cleaning and shredding plastic waste before processing it.

Process
Mura Technology and ReNew ELP processes operate using Licella Holdings' Cat-HTR™ technology. This process uses supercritical water (water above 374°C and 218 bars), heat and pressure via hydrothermal liquefaction to break long-chain hydrocarbons, donating hydrogen to produce shorter-chain, stable hydrocarbon products. First, the raw material is prepared by being crushed to produce a mixture which also contains water and oil (paraffinic oil, crude oil, bio-oil, etc.). In this phase, non-plastic contaminants are removed. Plastic waste is then melted, pressurized, and mixed with supercritical water. The mixed plastics and water mixture are then inserted into the Cat-HTR™ reactors for approximately 20 minutes at high temperatures (around 450°C) and high pressure (not specified) [205]. Depending on the feedstock used, catalysts can be added to the process. Finally, the products obtained are cooled under atmospheric pressure and the outputs are separated and stored (no further details provided on these last steps).

Output and downstream steps
Liquid yields are estimated at approximately 80-85%[206]. Mura Technology and ReNew ELP produce the following output fractions:

- Naphtha
- Distillate Gas Oil
- Heavy Gas Oil
- Heavy Wax Residue

However, they do not carry out additional repolymerization steps. Indeed, these steps should thus be conducted by downstream partners.

After being used in the process and following a depressurization phase, supercritical water goes back to being normal water. The water used in the process can be collected and recycled through a purification stage allowing to remove contaminants that were acquired throughout the recycling process. The rest of the output products (non-liquid fraction) are made up by methane and other gases, which are used within the process to produce a calorific effect. The remaining collected contaminants (such as inks) are also considered as reusable (no further details on how these materials are reused). Hence, no output of the Cat-HTR™ process is labelled as waste.

[204] Chemical Recycling in Asia Pacific conference, 14/09/2021
[205] https://www.licella.com/wp-content/uploads/2021/11/2021_Licella_Report_FINAL_1Nov_spreads_EMAIL.pdf
[206] Chemical Recycling in Asia Pacific conference, 14/09/2021

b. Technology scaling-up

Average Technology Readiness Level
With regards plastic waste recycling, the technology developers studied, ReNew ELP and Mura Technology, are at demonstration stage with a TRL of 6-7.

Current and future capacities
The standard Licella module has an initial capacity of 20kt/y (it is not specified whether it refers to input or output capacity). Licella Holdings currently has multiple plants in the pipeline through its partnerships and subsidiaries. Information was found on the following plants[207]:

- Project development in the UK: ReNew ELP is in the final stages of development on the first of four chemical recycling processing lines, with each line processing 20kt of plastic waste a year. The Northeast England plant in Teesside, which will be the first, is planned to start operating by end 2022. Once completed (deadline unknown), the plant is expected to reach a capacity of 80kt/y[208].
- Under iQRenew Pty, Licella Holdings also owns a pilot plant located on the NSW Central Coast in Australia. No further details found on the capacity and opening date of this plant.
- Licella has proposed the construction of a Cat-HTR™ site at an under-utilized manufacturing site which belongs to Dow Chemicals. The site, located in Australia, would be powered by 100% renewable electricity. Supported by Amcor, Coles, iQ Renew, LyondellBasell, and Nestlé, Licella conducted a feasibility study for the construction of a new plant[209]. The status of advancement of this project remains unknown for the time being.
- One plant in the USA planned for 2024 (no further details available).
- One plant in MCC's Ibaraki Plant, Japan to be completed by 2023: This plant will have an input capacity of 20kt/y and will be deployed by Mura Technologies in partnership with KBR (exclusive licensing partner of Mura, providing engineering and technical services and equipment) and Mitsubishi Chemicals. Mura Technologies and KBR are exploring multiple projects across Asia, Europe, and the USA to meet Mura's target of 1,000,000 tons of annual recycling capacity in operation or development by 2025. This seems rather ambitious when compared to their current capacity[210].

Mura has been operating in a partnership with Dow Chemicals, which provide financial support and materials science expertise (no further details available)[211].

c. Economic performance

According to Mura Technology, the prices of the recycled fraction are comparable to fossil oil. No additional information was found concerning the price of Renew ELP's output. Licella claimed that the costs of this technology compared to other forms of chemical recycling are low and that the company aims to offer cheaper solutions than its competitors (prices and names of competitors not specified).[212] It has to be noted that this information could not be checked.

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[207] Chemical Recycling in Asia Pacific conference, 14/09/2021
[208] https://muratechnology.com/sites-projects/renew-elp/
[209] https://www.licella.com/wp-content/uploads/2021/11/2021_Licella_Report_FINAL_1Nov_spreads_EMAIL.pdf
[210] https://www.bioplasticsmagazine.com/en/news/meldungen/20210813-Mura-Technology-KBR-and-Mitsubishi-Chemical-Corporation-announce-innovative-new-plastics-recycling-project-a-first-for-Japan.php
[211] https://investors.dow.com/en/news/news-details/2021/Dow-and-Mura-Technology-announce-partnership-to-scale-game-changing-new-advanced-recycling-solution-for-plastics/default.aspx
[212] Chemical Recycling in Asia Pacific conference, 14/09/2021

d. Environmental performance

LCA data (or similar studies), notably carbon footprint

ReNew ELP has conducted an independent LCA study that shows a +70% reduction in GHG emissions compared to a traditional fossil resource[41]. However, the methodology and hypothesis taken by this LCA have not been made public and are thus unverifiable.

Licella Holdings has also conducted an LCA study (geographic scope: Australia) to compare the Cat-HTR™ process with the production of virgin oil and to evaluate its environmental benefits. Disclosed results reported on a reduction of particulate emissions (air pollution) and water usage compared to landfilling and energy recovery. The methodology and hypothesis considered in this LCA have not been made public and are thus unverifiable.

	Particulate Matter (g $PM_{2.5}$ equivalent)	**Consumptive Water Use** (L)
Cat-HTR™	-90.0	0.13
Landfill	2.74	0.29
Waste-to-energy	2.48	2.36

Table 14 : Benefits of Cat-HTR™ vs. landfill and waste-to-energy[213]

Comparative analysis between end-of-life processes

Mura Technology mentions that this technology could save approximately 1.5 tCO_2/t of plastic processed when compared to incineration. However, there is no further indication on the source of this information[42].

The LCA study conducted by Licella Holdings in Australia reported on a 64% reduction of GHG emissions during the production of 1 ton of Cat-HTR™ oil vs fossil crude oil (kg CO_2e) (with the GHG emissions of Cat-HTR™ being estimated at 203 kg CO_2e per ton of oil)[214].

Energy costs

The technology developers have not made public the quantity of energy required for this process though they claim that the use of supercritical water allows to heat the feedstock rapidly and thus avoids excessive cracking[43]. Licella additionally supports the statement by which the presence of water helps better control the process and, by doing so, it makes the process more energy efficient due to the lower operating temperatures[215].

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213 https://www.licella.com/wp-content/uploads/2021/11/2021_Licella_Report_FINAL_1Nov_spreads_EMAIL.pdf
214 https://www.licella.com/wp-content/uploads/2021/11/2021_Licella_Report_FINAL_1Nov_spreads_EMAIL.pdf
215 https://www.licella.com/wp-content/uploads/2021/11/2021_Licella_Report_FINAL_1Nov_spreads_EMAIL.pdf

HYDROTHERMAL CRACKING	
Technology	Input • Mixed plastic waste Process • Supercritical water, heat, and pressure via hydrothermal liquefaction to break long-chain hydrocarbons, donating hydrogen to produce shorter-chain, stable hydrocarbon products. Output and Downstream steps • Naphtha • Distillate Gas Oil • Heavy Gas Oil • Heavy Wax Residue
Technology scaling-up	Average Technology Readiness Level • Estimated TRL = 6-7 (for the developer studied). Current and future capacities • ReNew ELP is in the final stages of development on the first of four chemical recycling processing lines, with each line processing 20,000 tons of plastic waste a year. The Northeast England plant in Teesside, which will be the first, is slated to launch mid- to end 2021. • Licella has several other projects in the pipeline, details on the advancement on these projects are however unavailable for the time being.
Economic performance	According to Mura Technology, the price of the recycled material is comparable to fossil oil.
Environmental performance	LCA data (or similar studies), notably carbon footprint • ReNew ELP has conducted an independent LCA study that shows a +70% reduction in GHG emissions compared to a traditional fossil resource*. • A LCA conducted by Licella Holdings shows that in Australia Cat-HTR™ would lead to a 64% GHG emissions reduction compared to the production of virgin oil. The technology would produce less particulate matter and consume less water than landfilling and energy recovery. • Mura Technology mentions that this technology could save approximately 1.5 tCO_2/t of plastic processed when compared to incineration*. • Please note the above figures are only indicative. Energy costs • The use of supercritical water would allow to heat the feedstock rapidly and thus avoids excessive cracking • The presence of water within the process reduces operating temperature and, subsequently, energy consumption • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
Licella™ MURA ReNew ELP	

Table 15 : Hydrothermal treatment recapitulative table (RECORD, 2022)

*Unverifiable statements from technology developers.

4) Hydrocracking (or catalytic depolymerization through hydrocracking – in the presence of hydrogen)

Note: The information contained in this section has been sourced from scientific papers reviewing hydrocracking technologies in general. These papers do not always specify whether the information provided refers to plastic-to-fuel or plastic-to-plastic applications. Given that most of the existing research on this topic has been conducted on hydrocracking for plastic-to-fuel applications, it is likely that some of the documents used to write this report may have been built on literature referred to plastic-to-fuel experiments.

The ECHA refers to this technology also using the term hydrogenation.

a. Technology

Input

Research has proven that different resins react in diverse manners to hydrocracking. The estimated hierarchy of feedstocks' suitability for the degradation of plastic materials via hydrocracking is as following: PIP[216]>PS>PET>PP≈PBD>LDPE>HDPE[217] (23). PVC resins are not included in the ranking as they are usually excluded from selected feedstocks due to their poisoning effects (10). Although little information is available on the topic, this technology is considered to be capable of treating both mono-streams and mixed plastics (12). The absence of developers deploying this recycling process[218], together with limited publicly available information, does not allow to determine which type of polymers are most often used, nor whether pre-sorting or pre-treatment of plastic waste is common practice for this technology. It is however known that hydrocracking processes have proven highly sensitive to impurities and contamination of input resins (10). Pre-treatment steps may therefore be required to achieve an optimal output.

Process

The term "hydrocracking" refers to a specific type of catalytic cracking, one that is realized under a hydrogen (H_2) atmosphere. Hydrocracking processes are used to shorten the length of polymer chains (23). In hydrocracking, plastic waste is first subjected to a low temperature pyrolysis. Then, the core reaction takes place and turns plastics into a liquid stage free from non-distillable matter. The liquid obtained is then moved to the catalyst bed (10). During the core reaction, C-C bonds are split to then be hydrogenated on a monofunctional acid catalyst or on a bifunctional catalyst (bifunctional hydrocracking) (12). Whether monofunctional or bifunctional, any catalyst used in this process must have both hydrogenation-dehydrogenation and cracking abilities. A typical hydrocracking catalyst is composed of a metal site and an acid site. The acidic support within the catalyst (e.g., silica-alumina, crystalline zeolite, a strong solid acid, etc.) activates cracking and isomerization reactions, while the metal (noble metal, non-noble metal of group VI-A or group VIII-A of the periodic table) performs the hydrogenation-dehydrogenation function. Bifunctional catalysts are generally considered the best option for the hydrocracking of plastics. Catalysts with a hydrotreating ability or with low sensitivity to the presence of impurities are preferred for the treatment of plastic waste (23).

As for other technologies, one of the reasons why catalysts are used in hydrocracking is to reduce processing temperatures. Hydrocracking generally occurs at temperatures between 375°C and 500°C. When hydrocracking is conducted at low temperatures, catalysts with weak acidic properties (e.g., alumina/silica) or weak hydrogenation-dehydrogenation functions (e.g., Fe) should be avoided as they have proven unable to crack plastics in the presence of limited heat. Increasing reaction temperatures may lead both to an increase in plastics' conversion and to a decrease in the output's quality (23). In general, temperatures over 400°C are not recommended for hydrocracking as more gases and coke

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216 PIP = polyisoprene

217 Resins are ranked based on the highest liquid conversion yields obtained (please refer to the following paragraphs for further details)

218 This statement refers to the findings of the background research that was conducted for this study. Technology developers may exist although they have not been considered within this analysis.

may result due to higher temperatures (23). It should additionally be noted that the type and presence of a catalyst does not have a significant impact if the process is conducted at high temperatures (10).

In terms of other operating requirements, hydrocracking usually requires hydrogenated pressures reaching up to 70 bars (10). The effects of different hydrogen pressures in the process have however not been thoroughly explored by researchers. As for reaction times, increasing the length of the reaction may both favor the reaction by increasing plastics' conversion rates and lead to an increased production of gas. Optimal times to achieve the maximum oil yield should be determined based on the type of polymer treated and the other reaction conditions. A reaction time of more than 60 minutes is usually not advised for an active catalyst at moderate temperatures (23).

Output and downstream steps

Other than reducing operating temperatures, adding a catalyst in the process leads to an increased oil quality and improved conversion yields (10). Similarly, the presence of hydrogen allows to obtain higher quality outputs compared to conventional catalytic pyrolysis. Compared with conventional and catalytic pyrolysis, hydrocracking can reduce the formation of olefins, aromatics, and coke in the reaction products. Moreover, the presence of hydrogen allows for the removal of heteroatoms such as chlorine, bromine, and fluorine that may be found in waste plastic (23). As previously mentioned, the estimated order of ease for the degradation of various individual plastic materials is the following: PIP>PS>PET>PP≈PBD>LDPE>HDPE. This ranking should be interpreted as PIP giving the highest liquid yield and the lowest yield of gas, while HDPE gives the lowest liquid yield and the highest yield of gas. A desired quality of oil may be produced by selecting a specific composition of the plastic feed. Although hydrocracking has been studied for the production of recycled feedstock, most of the information available of this process and the majority of its current applications are related to the production of high quality and ready-to-use fuels (12, 13). This process produces in fact highly saturated liquid products which do not need further upgrading if used for transportation fuel or energy production (23).

b. Technology scaling-up

Average Technology Readiness Level

The technology has an estimated TRL of 7 for plastic-to-fuel applications. However, when it comes to plastics-to-plastics applications, the technology is still at a research/pilot scale. No evidence was found of the technology being applied at a commercial scale or of industry players having publicly invested in the development of this technology. Thus, the estimated TRL could be 2-3.

Current and future capacities

Hydrocracking has not yet been tested on an industrial scale for waste management purposes. While several scientific studies have been conducted to assess the efficiency of hydrocracking processes to treat plastic waste, further research is required to better understand under which conditions (temperature, pressure, feedstock, catalyst, reaction time) the process achieves highest efficiency. As of now, hydrocracking remains more popular in plastic-to-fuel applications (12 ,13).

c. Economic performance

Hydrocracking is usually expensive due to the investments needed to generate high pressures (12) and elevated operating costs associated for example with the consumption of hydrogen (which costs around €2500 per tons when electrically produced) (14). The hydrocracking of some types of waste (such as PVC) may produce hazardous substances. Dealing with such materials has an impact on the process' cost as it requires additional control operations and removal of impurities from the end products. Applying very high pressure might additionally fail to provide added benefits when considering the cost associated with a high-pressure process. Significant investments in research and development are required due to the technology still being in its early stages. Operating costs will also have to be optimized for hydrocracking to become a more attractive recycling solution (10).

d. Environmental performance

No information found on this subject

HYDROCRACKING	
Technology	Input • Estimated hierarchy for feedstock suitability: PIP>PS>PET>PP≈PBD>LDPE>HDPE. • PVC is usually avoided as input due to its poisonous effects. • Technology considered as capable of treating both mono-streams and mixed plastics. • Pre-treatment/pre-sorting may be required due to the high sensitivity to impurities of these processes. Process • Specific type of catalytic cracking realized under a hydrogen atmosphere. • The presence of a catalyst reduces the required operating temperatures which, for hydrocracking, descend between 375°C and 500°C. Temperatures above 400°C are however not recommended (more gases and coke may result due to higher temperatures). • The catalyst used can either be a monofunctional acid catalyst or a bifunctional catalyst. The type of catalyst should be selected based on other operating conditions (e.g., temperature, desired output, etc.). • Further research is necessary to determine optimal operating temperatures, pressure, catalyst, and reaction time. Output and Downstream steps • Outputs are comparable with those of catalytic pyrolysis but with a reduced formation of olefins, aromatics, and coke. • Reaction used to reduce the length of polymer chains. • Adding a catalyst to the reaction increases oil quality and improves conversion yields.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL: 2-3. Current and future capacities • Not yet deployed on a commercial scale for plastic-to-plastic applications. • Further research required to determine optimal conditions for hydrocracking.
Economic performance	• High investments needed to generate high pressures. • Elevated costs of electrically produced hydrogen (€2500 per tons). • Significant investments still required to further develop this technology. • Lack of public data available
Environmental performance	• Lack of public data available
STUDIED TECHNOLOGY DEVELOPERS	
No technology developer identified	

Table 16 : Hydrocracking recapitulative table (RECORD, 2022)

5) Gasification

Note: Some experts consider gasification as indirect recycling of plastic waste. That is because the syngas produced using this process is an intermediary product which requires further conversion steps. The building blocks produced in this process could be used both for plastics and for fuel applications. For the purpose of this study, chemical recycling through gasification only refers to plastic-to-plastic applications.

Variants of gasification processes already exist (such as plasma gasification); however, they are still undergoing a research and development phase.

a. Technology

<u>Input</u>
One of the main advantages of gasification is its ability to treat all type of polymers and almost all feeds composed of organic materials (2,3). Although this technology can treat mixed and soiled plastics, gasification still requires stable waste composition. It is generally preferable to free the input from metals, fermentable composites, and moisture (2,3). This makes the pre-processing of the feedstock often necessary. Pre-treatment steps for gasification can involve waste screening, shredding, and classification (no further details provided on any of the pre-treatment steps).

The technology developer Enerkem treats mixed plastics, woody biomass, textiles, agricultural granulates, and material recovery facility residues. Their input comes from industrial, commercial, or municipal sources[219]. Enerkem prepares its feedstock through sorting to remove recyclable materials and inert materials, then they are shredded, and dried (if needed)[220].

Synova Tech treats waste composed of biomass, ash, moisture, and plastics that are not suitable for mechanical recycling[221]. The developer claims that there is no need to separate nor to wash the feedstock (mixed plastic municipal solid waste). Yet, their recycling process begins with a preparation step consisting of sizing of the feedstock and dosing the input via the feed bin to ensure a consistent throughput (no further details are available concerning this process). Materials which are excluded from the selected feedstock are sent to incineration[222].

<u>Process</u>
Gasification is a thermal treatment cracking process that is conducted in the presence of limited quantities of oxygen (6). This process works by partially oxidating the waste that is inserted in the reactor. There are different types of gasification which happen at different temperatures and under different operating conditions (such as the use of different gasifying agents). Medium temperature gasification features temperatures ranging between 900°C-1650°C, while low temperature gasification takes place at 700°C-900°C (6). The main gasifying agents used are air, steam, and oxygen. Different gasifying agents determine the final composition of the output produced and its suitability for different applications (10). Following the production of syngas, many recycling processes include a syngas cleaning phase.

Enerkem is the most well-known technology developer operating via gasification mainly for waste-to-fuel, but also for plastic-to-plastic applications[223]. Following pre-sorting and pre-treatment, waste is fed into the gasification vessels. Here, the input is broken down in the presence of steam and under specific operating conditions (no further details provided). To improve the purity and quality of its output, the developer has implemented a unique bubbling fluidized bed gasification reactor. To be eligible for chemical-grade applications, the produced syngas also has to undergo a further cleaning and conditioning treatment. This process is conducted directly by Enerkem (details not provided). After having been processed, the syngas is subjected to catalytic conversion, which produces liquid methanol and possibly fuel-grade ethanol as final output[224].

Synova Tech's technology MILENA-OLGA (developed through a joint venture with TNO), works by inserting feedstock, steam, and combustion air into a MILENA gasifier, which converts the input into

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[219] https://enerkem.com/feedstock/flexibility/
[220] https://enerkem.com/process-technology/carbon-recycling/
[221] https://synovatech.com/our-technology-platform/
[222] https://synovatech.com/wp-content/uploads/2021/11/CE_Delft_200456_Carbon_footprint_Synova-T_FINAL-public-version-2.pdf
[223] Although Enerkem produces more waste-to-fuel outputs, some of its outputs (e.g. syngas) can be used to make new plastics.
[224] https://enerkem.com/process-technology/carbon-recycling/

solids (char and tars[225]) and product gas. The solids formed are then transported to a combustion chamber, where their latent energy is captured and used to drive the production process. At the same time, gas and tars are transported into a product gas cooler. The heat energy recovered within the gas cooler is used in the production of process steam. The cooled gas is then moved into a cyclone where it is spun to remove particulate matter. The spun gas is inserted into OLGA. OLGA is a clean-up train which cleans the product gas by removing up to 99.9% unwanted tars using a cooled collecting oil, an electrostatic precipitator, and a cooled absorbing oil[226]. The OLGA process is able to clean the gas of residual heavy tars through the use of a cooled collecting oil (collected tars are sent back to the MILENA reactor). Other fine particles as aerosols are removed through the use of an electrostatic precipitator. Finally, a cooled absorbing oil is used to further filter the gas and remove remaining light tars (which are also sent back to the MILENA reactor together with the heavy tars). All tars that are collected by OLGA, are broken down and used as fuel to power up the whole process.

A gasification technology known as Ebara Ube Process (EUP) is being deployed in Japan. The process was developed by Ebara Corporation and Ube Industries in 2000. It uses a mixture of oxygen and steam as agents to produce syngas from plastic waste. No further details were found concerning the operating conditions of this technology[227]. It is however known that the process is currently being used by Showa Denko within their chemical recycling facility.

Output and downstream steps

Gasification converts inputs into a synthesis gas (syngas), which is a gaseous mixture of carbon dioxide, carbon monoxide, hydrogen, methane, water, and other light hydrocarbons (16). The output of this process often contains impurities such as char, NH_3, H_2S, NOx, alkali metals and tars (6). The quantity of impurities and by-products produced depends on the input used and operating conditions (such as the operating temperature or the selected gasifying agent). High-volatility feedstocks such as PS, PVC, and PET, lead to low char yields but high tar formation. Higher amounts of char are found in waste containing materials such as biomass and fibers (10).

Different types of syngas are suitable for diverse purposes (e.g., energy, fuels, chemicals, plastics). Output obtained via low temperature gasification is only suitable for energy applications, while that obtained via medium temperature gasification can be used for plastic applications. Turning syngas into final products requires a phase of catalytic conversion and distillation. There are at least 4 different paths to close the loop with plastic production: 1. Direct conversion of syngas to produce olefins; 2. Syngas used to produce methanol which is converted into olefins (Methanol-to-Olefins process, MTO); 3. Syngas used to produce ethanol which is converted into ethylene; 4. Syngas used to produce hydrocarbons (obtained via Fischer Tropsch) which are converted into olefins in a steam cracker.

The crude syngas that is produced by Enerkem consists of carbon monoxide, carbon dioxide, water, and hydrogen. As previously described, transforming syngas into building blocks suitable for plastic applications requires additional purifications steps meant to improve its quality (6) and downstream conversion steps. After having been processed, Enerkem's syngas is subjected to catalytic conversion, which produces liquid methanol and possibly fuel-grade ethanol as final output[228].

The process developed by Synova Tech is capable of directly producing olefins. Once the syngas has been processed through OLGA, Technip Energies (strategic partner) carries out an additional step of

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[225] Chars are carbonized products produced during pyrolysis or gasification processes. Tar is a dark brown or black dense liquid made of hydrocarbons and free carbon. Tar is obtained from organic materials.
[226] https://synovatech.com/our-technology-platform/
[227] https://www.ube-ind.co.jp/ube/en/news/2019/20190828_01.html
[228] https://enerkem.com/process-technology/carbon-recycling/

hydrocarbon treatment and purification of the output produced using a steam cracker unit[229]. The olefins produced through this process can be used to in plastics, renewable fuels, and for utilization in turbines. The following data are an example of the outputs produced by Synova Tech starting from a plastic rich feedstock[230]:

Synova/Technip Energies (later as T.En) feedstock composition (input):

- Plastic 590 kg (pure, dry materials excluding inert material and moisture)
- Biomass 291 kg (pure, dry materials excluding inert material and moisture)
- Ash 109 kg
- Moisture 10 kg

High Value Chemicals (HVCs) and fuel gas production (valuable outputs):

- Ethylene 198 kg
- Propylene 70 kg
- 1,3-Butadiene 26 kg
- Benzene 67 kg
- Toluene 16 kg
- Fuel gas 189 kg

b. Technology scaling-up

<u>Average Technology Readiness Level</u>
Gasification has an estimated overall TRL of 6. The technology is well-developed for waste-to-fuel applications (TRL 9); yet plastic-to-plastic value chain is still under development.

Developers owning advanced gasification technologies include:

- Enerkem, a Canadian company currently close to commercial scale, with an overall TRL of about 8 (including both waste-to-plastics and waste-to-fuels applications).
- Synova Tech, a Dutch company currently running a pilot plant and has an estimated TRL of about 5-6 for its waste-to-plastics applications.
- Showa Denko, a Japanese company using the EUP technology and running a commercial plant since 2003. Their estimated TRL is 9 (output's applications not specified).

<u>Current and future capacities</u>
Enerkem is currently operating a plant in Edmonton (Canada) able to process 100,000 dry tons of waste per year and produce 38 million liters of methanol per year (not specified to what extent the output is used for plastic applications). In the long-term, Enerkem aims to license its technology and start deploying prefabricated modular systems internationally. Its investors include Chinese Sinobioway Group and BlackRock. Other partners for the development of recycling plants include Alberta Innovates, Government of Alberta, Air Liquide, Nouryon, Suez, Port of Rotterdam, Waste Management of Canada, Investissement Quebec, Cycle Capital. Disclosed upcoming projects include:

- A plant in Rotterdam (Netherlands) to process 360 000 tons of waste per year and produce 220 000 tons of jet fuel per year.
- A plant in Varennes (Canada), which is currently under construction and scheduled for 2023. The planned capacity is about 125M liters of biofuels and renewable chemicals (input 200k metric tons of waste). This plant, which is worth C$875 million, is being built with strategic partners including Shell (lead investor), Suncor (investor), Proman (investor), Hydro-Québec

[229] https://synovatech.com/synova-and-technip-energies-announce-strategic-partnership-in-advanced-plastic-recycling-technology/#:~:text=Synova%E2%80%99s%20patented%20thermochemical%20recycling%20technology%20closes%20the%20gap,olefin%20monomers%20and%20co-products%2C%20to%20produce%20circular%20plastics.
[230] https://synovatech.com/wp-content/uploads/2021/11/CE_Delft_200456_Carbon_footprint_Synova-T_FINAL-public-version-2.pdf

(renewable hydrogen and oxygen supplier) and with the support of the governments of Quebec and Canada.
- A plant in Tarragona (Spain), which is in development and pending final investment decision. The input would amount to 400kt of waste per year and the output to 270M liters per year of methanol

Synova Tech operates a joint venture with TNO and has a strategic partnership with Technip Energies. The developer installed its first lab-scale unit in 2004 (unknown capacity). A pilot unit (unknown capacity) followed in 2008 in the Netherlands. However, their full integrated technology (MILENA-OLGA) started being tested in 2009 when OLGA was coupled with MILENA in their pilot plant. The technology developer additionally built two small scale plants in India and Portugal, each of which has a capacity of 25 tons per day (approximately 7.5 kt/y, it is not specified whether it refers to input or output capacity). The developer has not yet disclosed future plans for the upscaling of its technology.

Showa Denko owns a plant with a capacity of 70kt/y plastic waste, which has been operating since 2003. The plant is based in Japan and runs using the EUP technology. In 2019, Showa Denko, JGC, Ebara Environmental Plant, Ube Industries, started drafting a licensing contract for the deployment of the EUP technology in Japan as well as other countries (geographic scope not specified). No recent updates were found on the advancement of their joint operations[231].

c. Economic performance

Feedstock's pre-treatment, large amounts of input required, use of pure oxygen, high energy consumption, and need for final purification steps of syngas, significantly increase operational costs associated with gasification.

d. Environmental performance

LCA data (or similar studies), notably carbon footprint
In a Delft study (25), the impacts of gasification were studied. The inputs of this data were various publications and insights from confidential projects as well as TNO's publications.
It was found that gasification of 1 ton of plastic waste emits about -0,2 tCO_2e/t input of DKR350[232] or waste refused by mechanical recyclers, taking into account avoided products and energy. However, due to the screening nature of the studies and the differences in processed waste streams, the results should be considered indicative. Moreover, data from industrial-scale processes are not available and thus these results are only estimated.

Comparative analysis between end-of-life processes
In the same study, it was found that:
- Incineration emits about 1.5 tons of CO_2e./ton of input of DKR 350 (mixed plastic stream) or recycling failures.
- Mechanical recycling of DKR 350 to plastic recyclate for thick-walled applications ('dkr 350') provides a climate impact of approximately -0.5 tons of CO_2e./ton of input material. This is the case, among other things, because the application of the recyclate prevents the production of steel and virgin plastic. Indeed, in this assessment, the following scenario for processing DKR 350 has been retained*: "The mixed plastic flow (DKR 350) produced from household plastic is currently mainly processed in Germany. It is washed and converted into recycled plastic, which is mainly used in thick-walled applications. This is for example garden furniture, tiles, and roadside bollards. According to research conducted by TNO, this recyclate replaces 1/4 concrete, 1/4 plastic, 1/4 steel, 1/8 tropical hardwood, and 1/8 impregnated wood (TNO, 2017)."* (Translated from Dutch).

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[231] https://www.nsenergybusiness.com/news/jgc-ube-industries-showa-denko-begin-study-on-gasification-chemical-recycling-of-plastic-waste/
[232] DKR 350 specification in Netherlands is a category of waste where various types of plastics end up together. This stream makes up circa 35% of the total volume of sorted plastic packaging materials and is difficult to recycle mechanically. Source: Netherlands institute for sustainable packaging.

- Pyrolysis emits about 0 tons of CO_2e./ton of input of DKR350 or recycling failures.
- Gasification emits about -0.2 tons of CO_2e./ton of input of DKR350 or recycling failures.

In August 2021, Synova Tech published the results of a LCA study conducted by CE Delft. The analysis was conducted in the Netherlands using a feedstock containing 560 kg of plastics and 291 kg of (dry) biomass per tons of waste (with the remaining 119 kg composed of ash and moisture). A plant with a capacity of 50kt/y (input/output not specified) was used as a reference. The study considered both the production and the waste management functionality of the Synova process[233]:

- From a production perspective, the process was compared with virgin production of High-Value Chemicals (HVCs). The total virgin production of HVCs was estimated at 1.5 tons CO_2e./ton HVCs (European average). While the Synova's process itself has a higher footprint than virgin production, it was considered that the process involves co-production of fuel gas, avoids waste incineration credits, and that biogenic carbon is present in the products. Adding these factors into the calculation as saved emissions resulted in a footprint net reduction of 2.5 kg CO_2e./ton HVCs compared to virgin production.
- From a waste perspective, Synova Tech's technology was compared to incineration with energy recovery (Dutch Municipal Solid Waste Incinerator). Waste incineration results in a footprint of 0.8 tons CO_2e./ton waste. By taking into account emissions avoided from virgin fossil based HVCs production, the process results in a net 0.9 tons CO_2e./ton waste saving compared to incineration.

<u>Energy costs</u>
This technology is known for having the disadvantage of requiring high energy consumption compared to other recycling processes (further details currently unavailable) (6). However, it should be noted that non condensable light fractions could be used to have an autothermal process[234].

Synova Tech is able to power its process by transforming unwanted tars into fuels and by recovering the heat produced by solid flows and by gas in the cooling process.

[233] https://synovatech.com/wp-content/uploads/2021/11/CE_Delft_200456_Carbon_footprint_Synova-T_FINAL-public-version-2.pdf
[234] An autothermal process refers to a system in which some of the output produced are used to heat-up the process itself. However, the process still needs an external energy supply to function at a certain moment.

GASIFICATION	
Technology	Input • Input can consist of all types of polymer and almost all feeds composed of organic materials. • Gasification can treat mixed and soiled plastics. It is however preferable to free the input from metals, fermentable composites, and moisture using pre-sorting or pre-treatment processes. Process • Process conducted in the presence of limited flow of oxygen. • Medium temperature gasification 900°C-1650°C. • Low temperature gasification: 700°C-900°C. • Enerkem is the most well-known technology developer operating via gasification for notably waste-to-fuel but also for plastic-to-plastic applications. Output and Downstream steps • The output consists of synthesis gas (syngas) that can be transformed into energy, plastics, fuels, and chemicals through further treatment. • Syngas often contains impurities and by-products such as char, NH_3, H_2S, NOx, alkali metals and tars. • Plastic-to-plastic applications require medium temperature gasification. • Synova Tech's process include a purification phase run by Technip Energies.
Technology scaling-up	Average Technology Readiness Level • Estimated TRL: 6 (as plastic-to-plastic value chain is not fully mature) Current and future capacities • Enerkem is currently processes 100,000 dry tons of waste per year and produces 38 million liters of methanol per year. The developer has multiple additional projects in the pipeline for the upcoming years. • Showa Denko owns a plant with a capacity of 70kt/y plastic waste,
Economic performance	• High costs of feedstock pre-treatment, energy, and final purification steps of syngas. Downstream steps are also needed to convert syngas into chemicals and subsequently into polymers. • Lack of public data available
Environmental performance	LCA data (or similar studies), notably carbon footprint • Process was found less impactful than incineration and pyrolysis but more emissive than mechanical recycling. • Synova Tech's LCA showed emission saving compared to virgin production of HVCs and to incineration with energy recovery. Energy costs • High energy consumption compared to other recycling processes. However, non-condensable light fractions could be used to have an autothermal process. • Lack of public data available on the environmental performance of the process
STUDIED TECHNOLOGY DEVELOPERS	
Enerkem SYNOVA SHOWA DENKO	

Table 17 : Gasification recapitulative table (RECORD, 2022)

VIII. Downstream steps

1) Introduction on downstream steps

Downstream steps are usually required after chemical recycling to remove residual impurities, contaminants and perform one or several conversion steps to produce recycled polymers with the proper specifications. These downstream steps depend on the technology, the output's quality, and the targeted end-application.

Impurities can represent an issue for downstream applications, especially if a high-quality material is required. Downstream steps can include separation of gases, distillation, selective aromatics removal by distillation or adsorption in pyrolysis' case. In many cases, existing facilities could be adapted so that they could carry out downstream steps.

A few examples are presented below:
- In the case of the production of monomers via solvolysis, purification and repolymerization steps are needed.
- Regarding pyrolysis, oil purification and further treatment is needed to make it suitable to enter a steam cracker, as would a virgin feedstock. Steam cracking represents the last step to having a virgin-like product.

2) Example of downstream step: vapocracking (Steam cracking)

a. Technology

Input

This process takes as an input the condensable fraction originating from pyrolysis and gasification processes. Indeed, the input is thus comparable to these processes and consists in plastics that are left in the waste stream after mechanical recycling and that otherwise would end up in landfill (such as flexible, multi-layer films).

Process

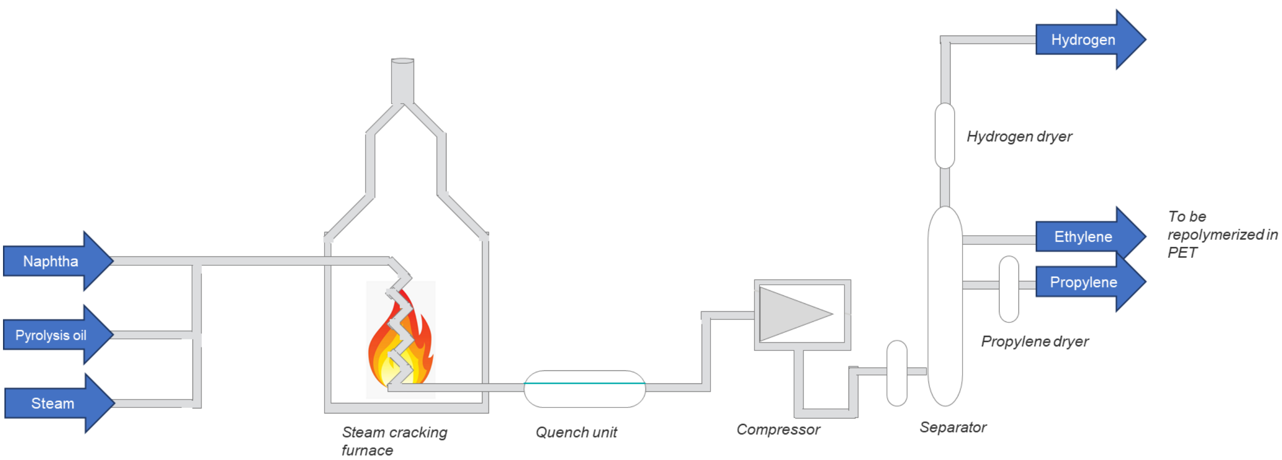


Figure 6 : Steam cracking process (RECORD, 2022)

Steam cracking or vapocracking is a petrochemical process that consists in obtaining, from petroleum fractions (such as ethane, propane, butane, gas oil or naphtha) alkenes (ethylene, propylene) that are better valorized. These alkenes are mainly used in the plastics industry to produce polymers (polyethylene, polypropylene, etc.). The fractions used can be replaced by the oil produced in pyrolysis or gasification processes, which is similar to naphtha in its composition.

These naphtha cuts, resulting from the thermal treatment of plastics, are introduced into the steam cracker under high temperature (around 700°C), and in the presence of steam (around 30 to 100% by weight). The steam allows to reduce the "residence time" and to prevent the formation of coke.

Under these conditions, the hydrocarbon molecules in the naphtha split into several fractions (gases, raffinate and olefins) giving rise to different outputs (12).

<u>Output and downstream steps</u>
Steam cracking gives out several products:

- Olefins, such as ethylene, propylene, butadiene, isobutene, and other unsaturated products. These components will need to undergo additional treatments (chlorination, oxidation, polymerization, etc.) to recuperate ethylene (C_2H_4) and propylene (C_3H_6). These two molecules are the origin of many plastics and can be repolymerized afterwards to create other components such as Polyethylene, Polypropylene, PET, PVC (12).
- Gases (dihydrogen, methane, ethane, etc.) (12). The process gases are reused in the process to generate supercritical steam40.
- A fraction called "raffinate", which is used for fuel applications.

b. Technology scaling-up

<u>Average Technology Readiness Level</u>
As previously mentioned, steam cracking is already used at commercial scale in the petrochemical industry.

<u>Current and future capacities</u>

No information found on this subject

c. Economic performance

No information found on this subject

d. Environmental performance

<u>LCA data (or similar studies), notably carbon footprint</u>

No information found on this subject

<u>Comparative analysis between end-of-life processes</u>

No information found on this subject

<u>Energy costs</u>

No information found on this subject

<table>
<tr><th colspan="2">STEAM CRACKING</th></tr>
<tr><td>Technology</td><td>Input
Condensable fraction originating from pyrolysis and gasification.
Process
Naphtha cuts, resulting from the thermal treatment of plastics, are introduced into the steam cracker under high temperature (around 700°C), and in the presence of steam (around 30 to 100% by weight)
Output and Downstream steps
Three types of output produced:
Olefins and other unsaturated products - These components will need to undergo additional treatments (chlorination, oxidation, polymerization, etc.) to recuperate ethylene (C_2H_4) and propylene (C_3H_6).
Gases: The process gases are reused in the process to generate supercritical steam.
A fraction called "raffinate", which is used for fuel applications.</td></tr>
<tr><td>Technology scaling-up</td><td>Average Technology Readiness Level
Steam cracking is already used at commercial scale in the petrochemical industry.
Current and future capacities
Lack of publicly available data</td></tr>
<tr><td>Economic performance</td><td>Lack of publicly available data</td></tr>
<tr><td>Environmental performance</td><td>Lack of publicly available data</td></tr>
<tr><th colspan="2">STUDIED TECHNOLOGY DEVELOPERS</th></tr>
<tr><td colspan="2">No technology developer - Steam crackers are already operated by petrochemical industries at commercial scale.</td></tr>
</table>

Table 18 : Steam cracking recapitulative table (RECORD, 2022)

IX. Key learnings

A table of the main advantages and drawbacks of the studied technologies is presented below.

Recycling process	Input[235]	Main advantages	Drawbacks
Glycolysis	PET, PA, PU	• Production of high-purity, virgin-like material. • Suitable for food-grade applications (EFSA, FDA approval needed) • Solvent limits the environmental impact compared to other solvolysis processes.	• Mono-material waste streams required (presorting necessary). • Low level of contaminants required (pretreatment necessary). • The use of corrosive chemicals in the process might necessitate noble materials for equipment. • Production of monomers that need to be reintegrated into an existing polymerization value chain.
Methanolysis	PET	• Production of high-purity, virgin-like material • Suitable for food-grade applications (EFSA, FDA approval needed)	• Mono-material waste streams required (presorting necessary). • Low level of contaminants required (pretreatment necessary). • The use of corrosive chemicals in the process might necessitate noble materials for equipment. • Production of monomers that either need to be reintegrated into an existing polymerization value chain or to be repolymerized on site by the addition of a dedicated polymerization unit. • Methanol used in the methanolysis process can have a consequent environmental impact.
Aminolysis	PET	• No high pressure and relatively low temperature range compared to other chemical recycling technologies.	• Not a very developed process. • High costs of amines. • Possible toxicity of amines. • Production of monomers that need to be reintegrated into an existing polymerization value chain.

[235] Note: The list of resins presented in this table is based on the inputs used by the technology developers which have been analysed within this study. Therefore, this table does not include all the resins that could potentially be processed using a given technology.

Hydrolysis	PET, PA	• Production of high-purity, virgin-like material • Suitable for food-grade applications (EFSA, FDA approval needed) • In the absence of catalyst, the only chemical used is water for neutral and sub/supercritical hydrolysis. • Unique solvolysis method that leads directly to the production of terephthalic acid (TPA) and ethylene glycol (EG). This route is then the fastest and PET can be directly reconstituted from these species.	• Mono-material waste streams required (presorting necessary). • Low level of contaminants required (pretreatment necessary). • Significant cost to purify PTA • Strong bases required for alkaline hydrolysis. • Strong acids required for acid hydrolysis. • Production of monomers that need to be reintegrated into an existing polymerization value chain.
Hydrolysis catalyzed with enzymes	PET	• Production of high-purity, virgin-like material. • Suitable for food-grade applications (EFSA, FDA approval needed) • Less stringent conditions than other chemical recycling processes due to the use of enzymes (atmospheric pressure and low temperature claimed). • No sophisticated sorting necessary claimed as the enzyme targets PET feedstock only.	• Mono-material waste streams required from various sources (textiles included). • Low level of contaminants required (pretreatment necessary). • Production of monomers that need to be reintegrated into an existing polymerization value chain.
Dissolution	PS, PP, PVC, PE	• Production of high-purity materials • Can treat contaminated streams and mixed plastics. • Low alteration of the structure of the polymer. • Can usually treat plastics containing additives. However, it may be difficult to separate them (for instance phthalates in plasticized PVC). • Direct production of polymer, no repolymerization needed. • Lower environmental impacts than depolymerization (if the solvent is recovered).	• Pre-sorting or pre-treatment are often necessary (e.g., sorting, washing, grinding, etc.). • Use of solvents to be recycled • No food grade approval at the moment
Non catalytic and catalytic pyrolysis	PS, PE, PP, PMMA, Mixed plastics	• High-purity, virgin-like recycled resin using pyrolysis oil • Suitable for food-grade applications. • Treats relatively mixed waste streams • Process could be autothermal • Process seems to be able to removes contaminants and additives.	• Additional sorting steps necessary to remove non-processable inputs (PVC, PET, PU…) • For catalytic pyrolysis: potential poisoning effects on the catalyst to be considered • High energy consumption compared to other recycling processes

		• For catalytic pyrolysis: catalyst leads to an increased reactivity of the reaction, lower operating temperatures, better selectivity of the end-products, and reduction of by-products.	• Numerous downstream steps needed to produce a recycled polymer (purification of the hydrocarbon mix, integration in virgin value chains). PS and PMMA produce monomers that need to be repolymerized. • Purification of the output necessary before it can be reintegrated in a steam cracker. • Liquid fraction obtained needs to be mixed with virgin feedstock in a steam cracker (via a mass balance approach). • Significant losses in each recycling loop. • No direct link between wastes and recyclates
Hydrothermal cracking	Mixed plastics	• High feedstock flexibility compared to other technologies • Supercritical water allows to heat the feedstock rapidly and thus avoids excessive cracking	• Numerous downstream steps needed to produce a recycled polymer (purification of the hydrocarbon mix, integration in virgin value chains). • Liquid fraction obtained needs to be mixed with virgin feedstock in a steam cracker (via a mass balance approach).
Hydrocracking	Mixed plastics	• Production of high-purity, virgin-like material. • Suitable for food-grade applications. • Can treat both monomaterial waste streams and mixed plastics. • Process removes contaminants and additives. • Limited formation of coke.	• Low level of development • Pre-treatment/pre-sorting may be required due to the high sensitivity to impurities of these processes. • High investments needed to generate high pressures • Numerous downstream steps required to produce a recycled polymer (purification of the hydrocarbon mix, integration in virgin materials value chains) • Significant losses in each recycling loop
Gasification	Mixed waste	• Production of high-purity, virgin-like recycled resin • Suitable for food-grade applications. • Can treat all type of polymers and almost all feeds composed of organic materials. • Can treat mixed and soiled plastics.	• Pre-sorting required to free the input from metals, fermentable composites, and moisture • High temperatures needed • The process releases impurities such as coal, alkali metals and tars, or NH_3, H_2S, NO_x from the syngas.

		• Process removes contaminants and additives. • Syngas is a valuable intermediate product suitable for different applications.	• Numerous downstream steps required to produce a recycled polymer (purification of the hydrocarbon mix, integration in virgin value chains). • Significant losses in each recycling loop.

Table 19: Advantages and drawbacks of steam cracking (RECORD, 2022)

Downstream process	Input	Main advantages	Drawbacks
Vapocracking (steam cracking)	Mixed plastics	• Production of high-purity, virgin-like material. • Suitable for food-grade applications. • Vapocracking step is necessary for the conversion of pyrolysis and gasification output.	• Valuable fraction from pyrolysis and gasification needs to be mixed with virgin feedstock in a steam cracker (via a mass balance approach)

Table 20 : Recapitulative table on technologies (RECORD, 2022)

The current output capacities of the studied technology developers (as of January 2022) are presented below as well as the additional capacities announced by the start-up companies by 2025. Please note there may be a high level of uncertainties as the technology developers have announced ambitious capacities in the coming years.

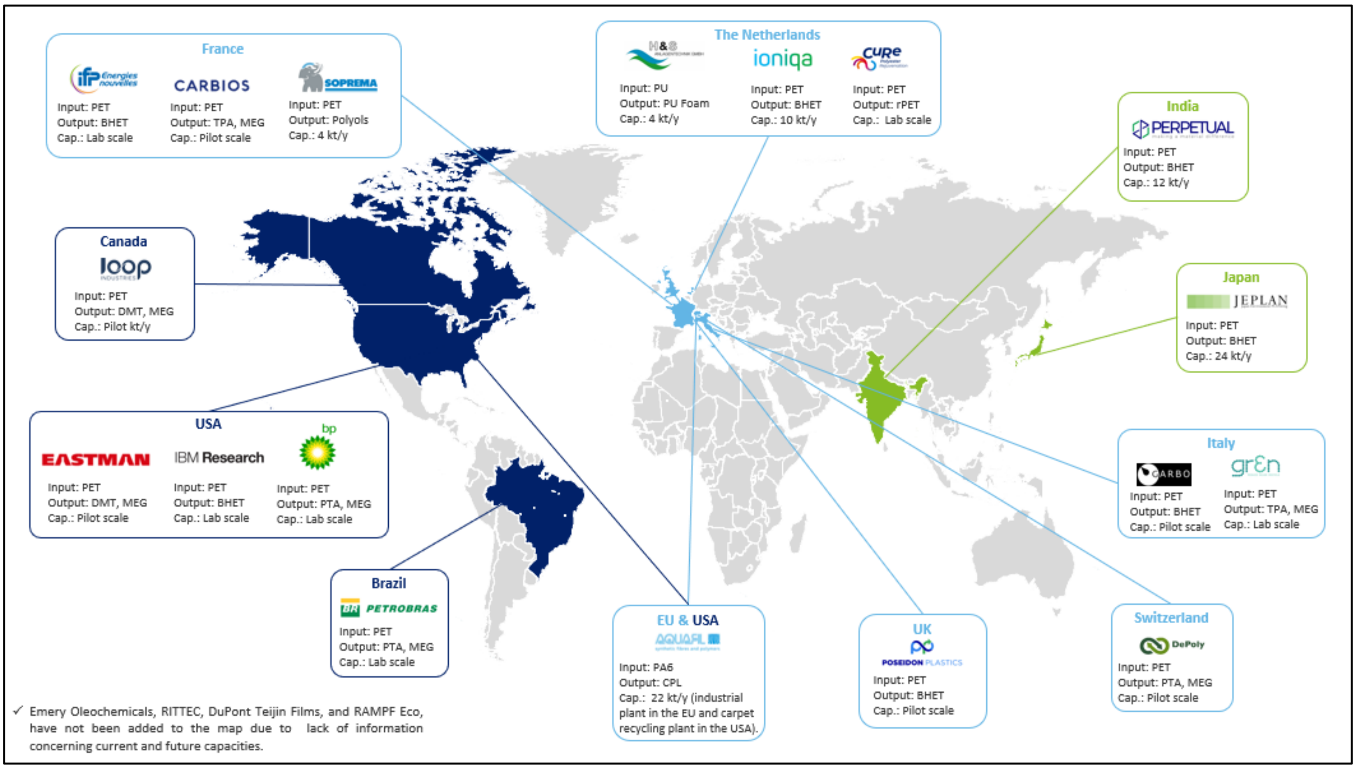


Figure 7 : Capacities of chemical depolymerization technologies in 2021 (RECORD, 2022)

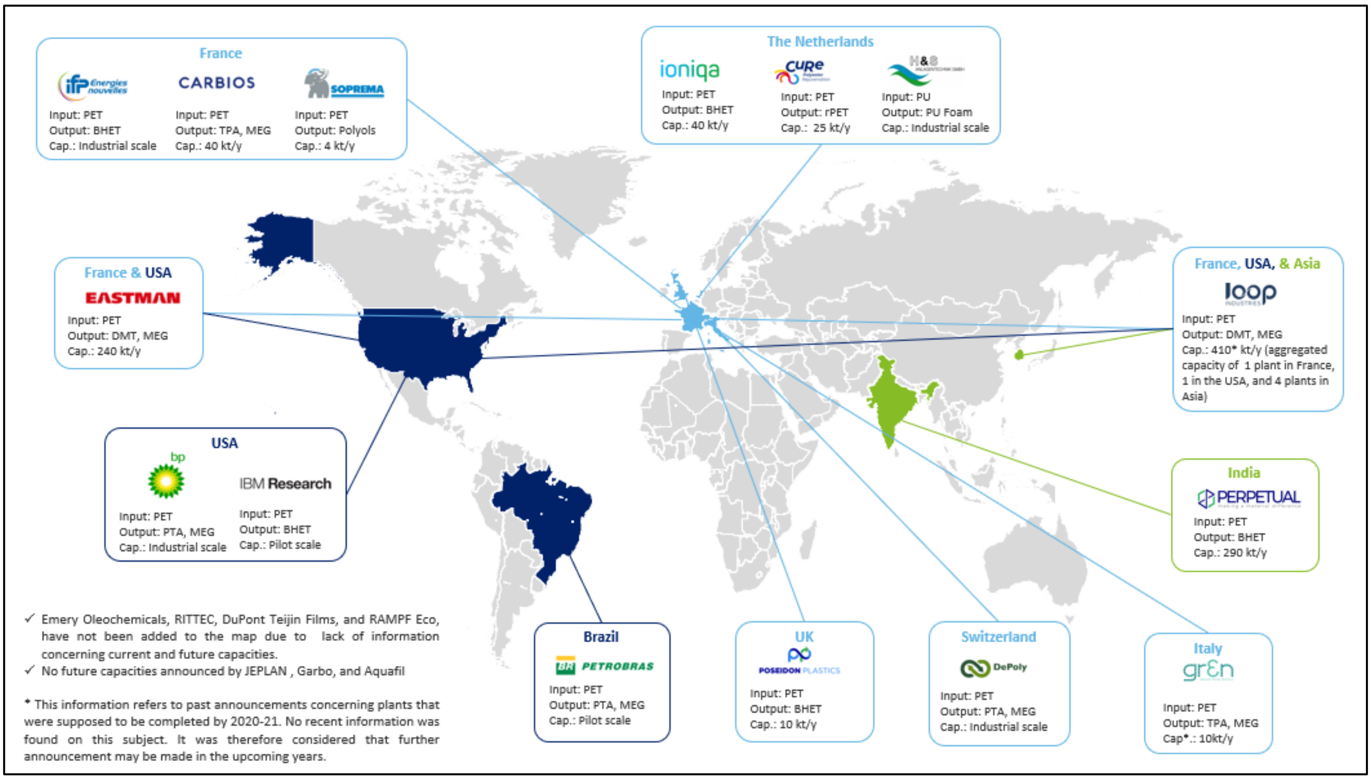


Figure 8 : Additional capacities of chemical depolymerization processes announced by the technology developers by 2025 (RECORD, 2022)

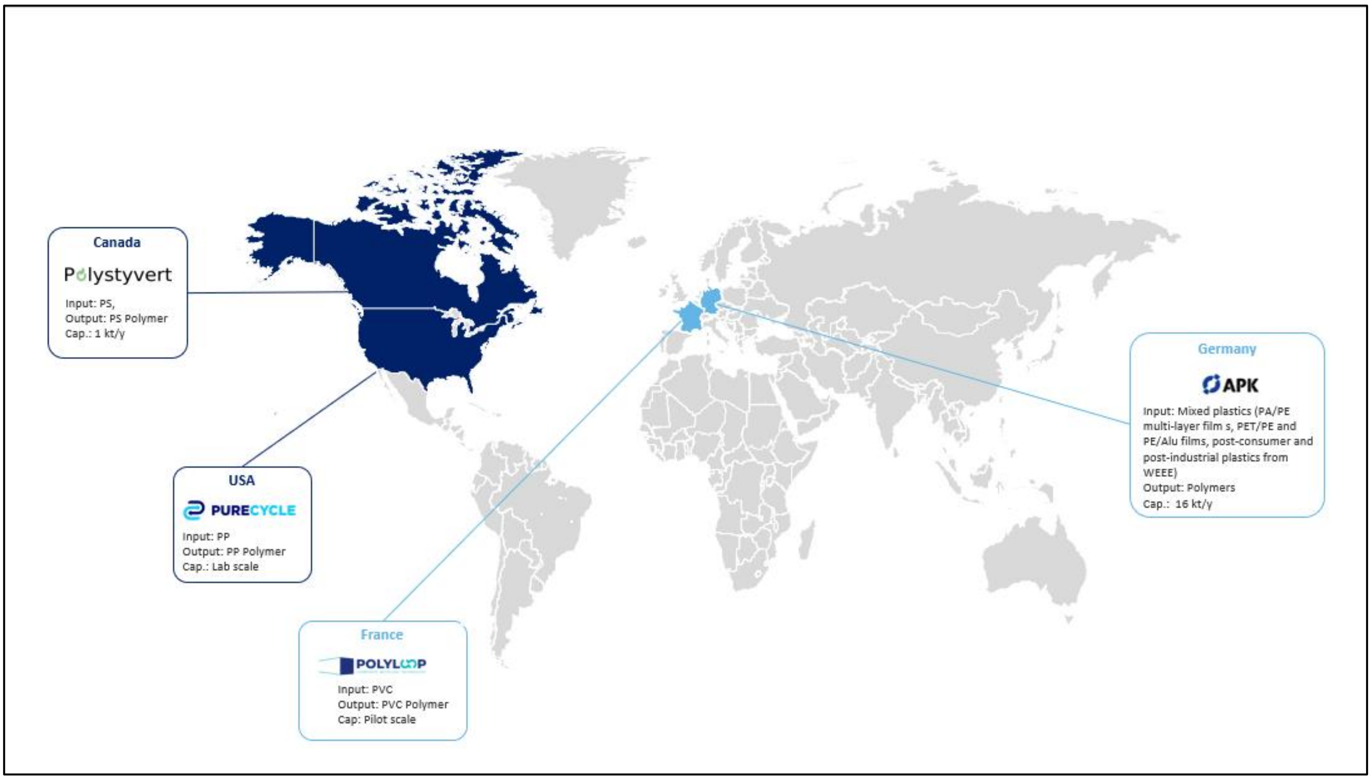


Figure 9 : Capacities of dissolution technologies in 2021 (RECORD, 2022)

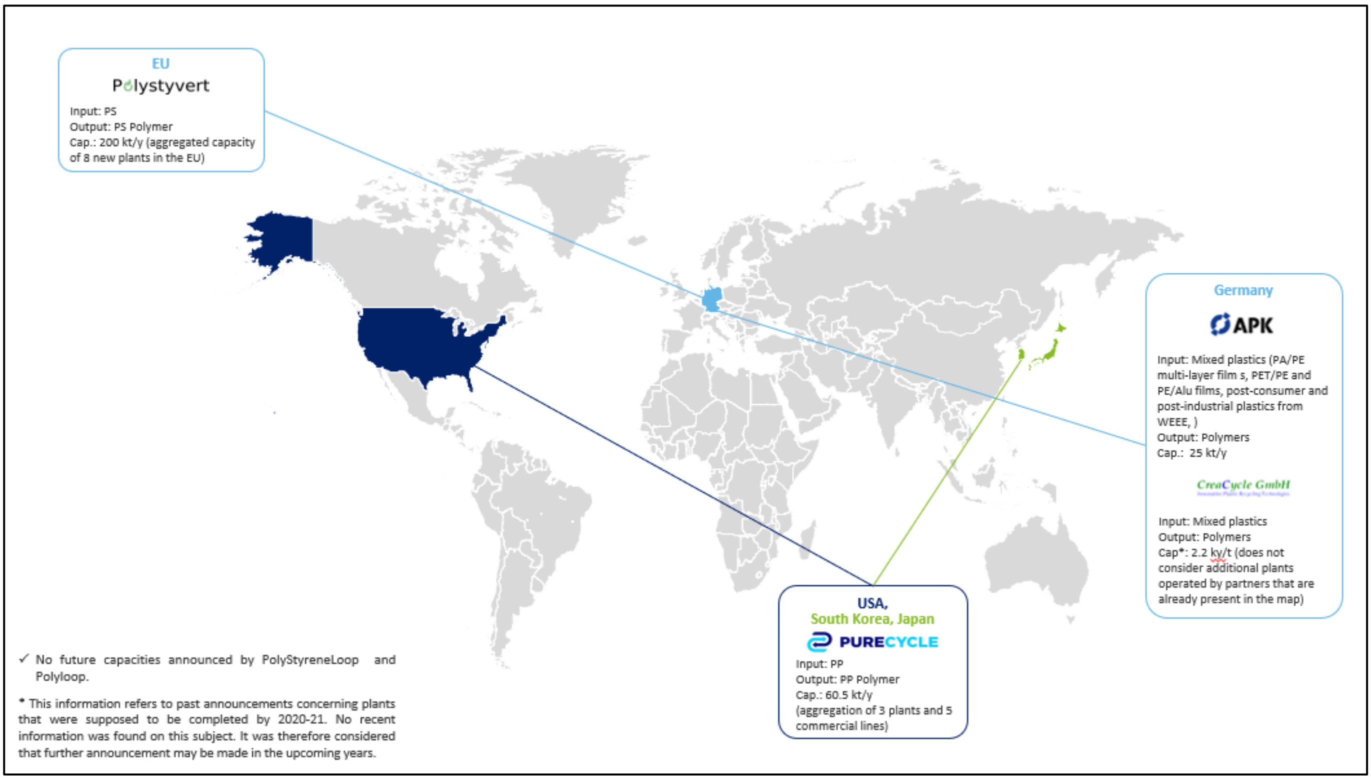


Figure 10 : Additional capacities of dissolution processes announced by the technology developers by 2025 (RECORD, 2022)

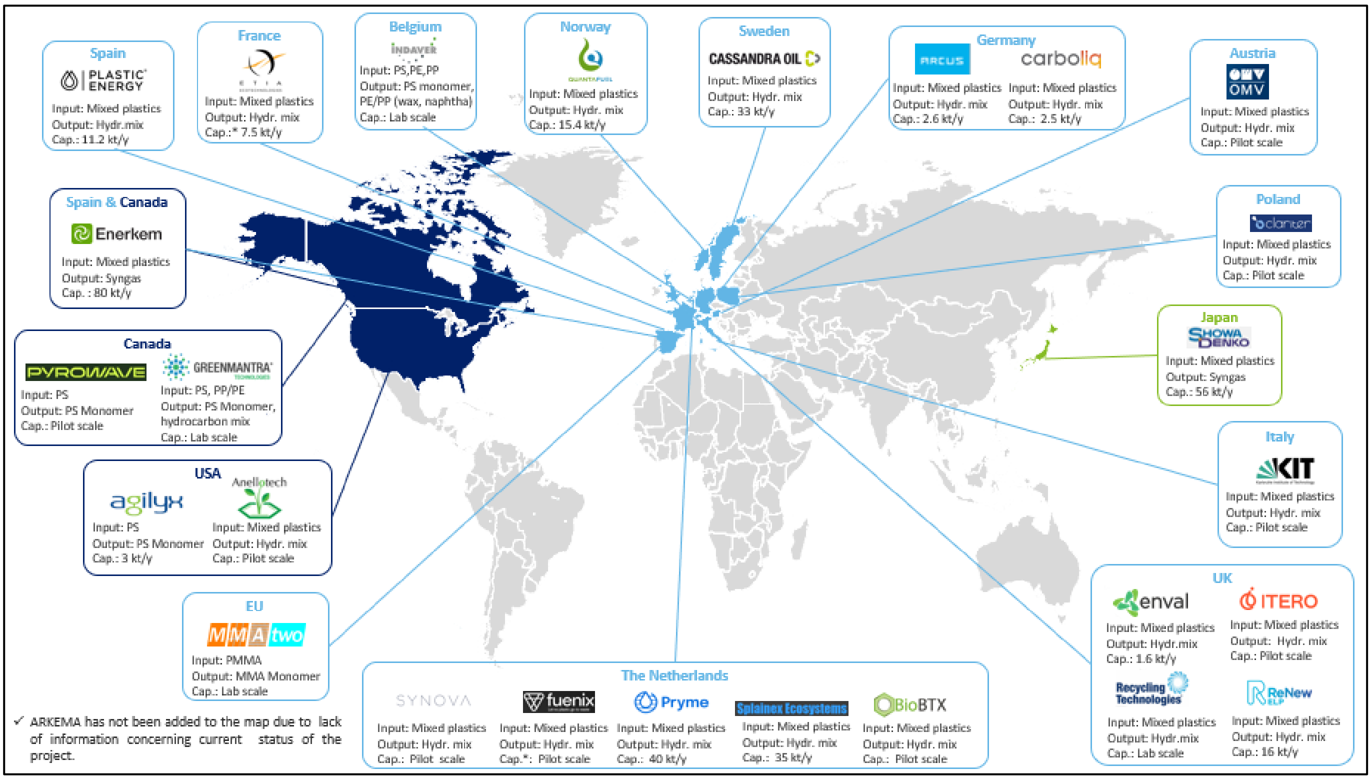


Figure 11 : Capacities of thermal treatment technologies in 2021 (RECORD, 2022)

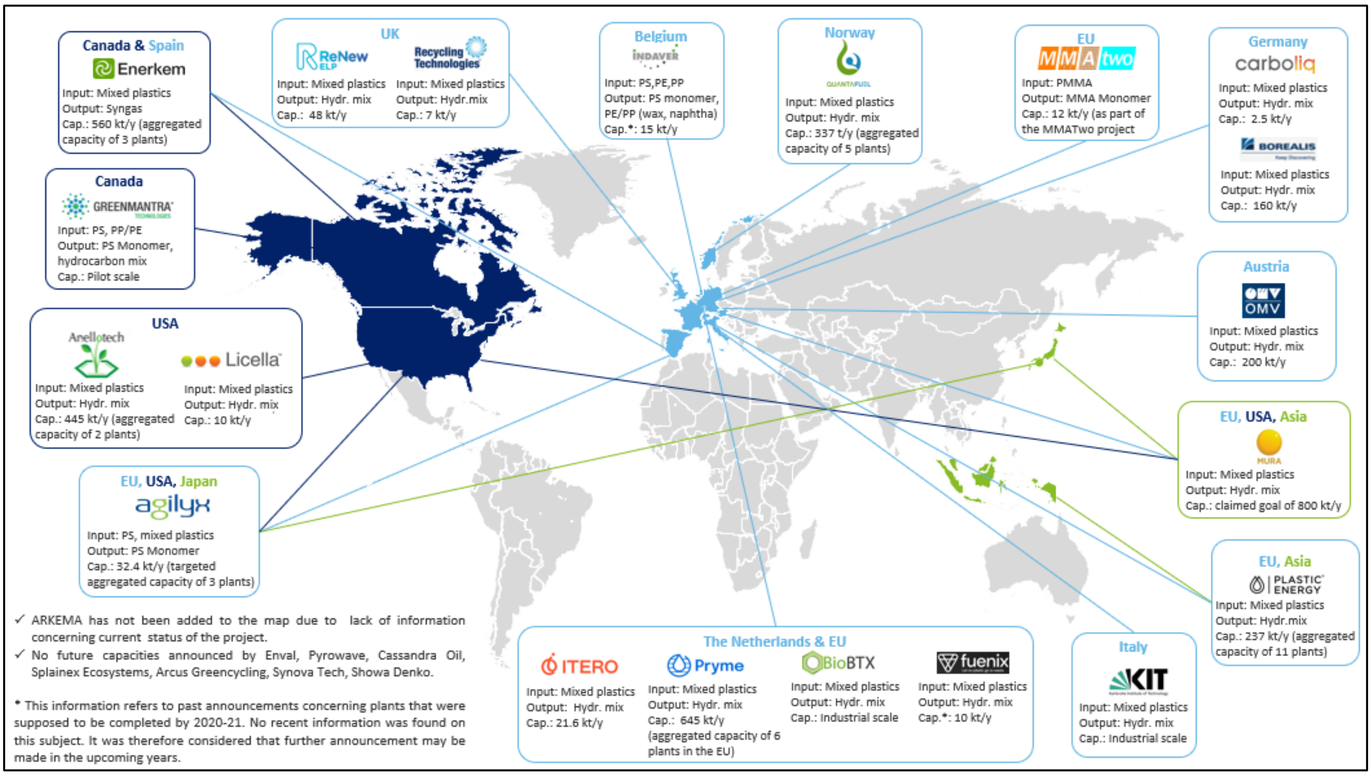
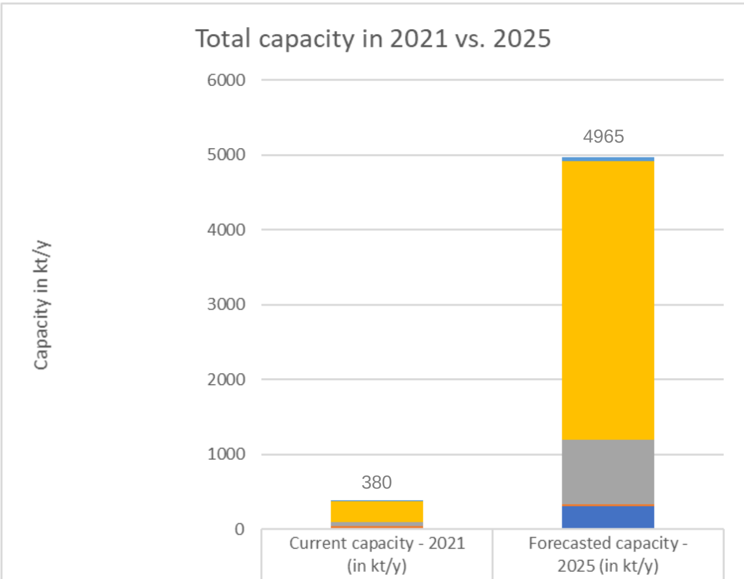


Figure 12 : Additional capacities of thermal treatment processes announced by the technology developers by 2025 (RECORD, 2022)

The total current and estimated future output capacities (2021 vs. 2025) of the studied technology developers (as of January 2022) are presented below.



	Current capacity - 2021 (in kt/y)	Forecasted capacity - 2025 (in kt/y)
Thermal Treatment PS	5	50
Thermal Treatment Mixed Plastics	280	3720
Solvolysis PET	55	860
Solvolysis PA	20	20
Dissolution	20	315

Figure 13: Total capacities in 2021 vs. 2025 (RECORD, 2022)

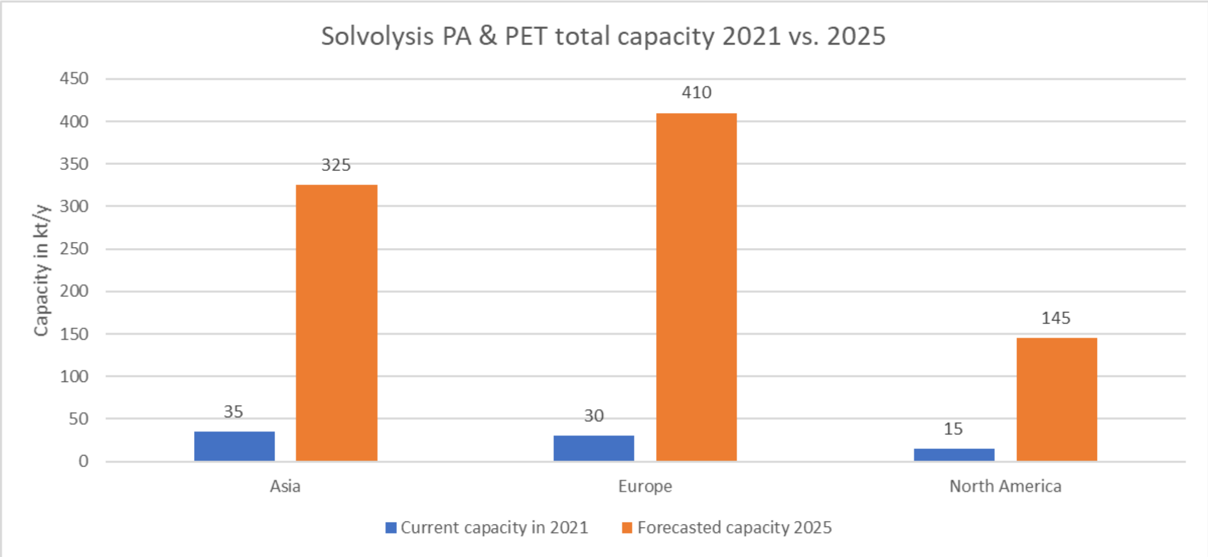


Figure 14: Solvolysis PET and PA capacities in 2021 vs. 2025 (RECORD, 2022)

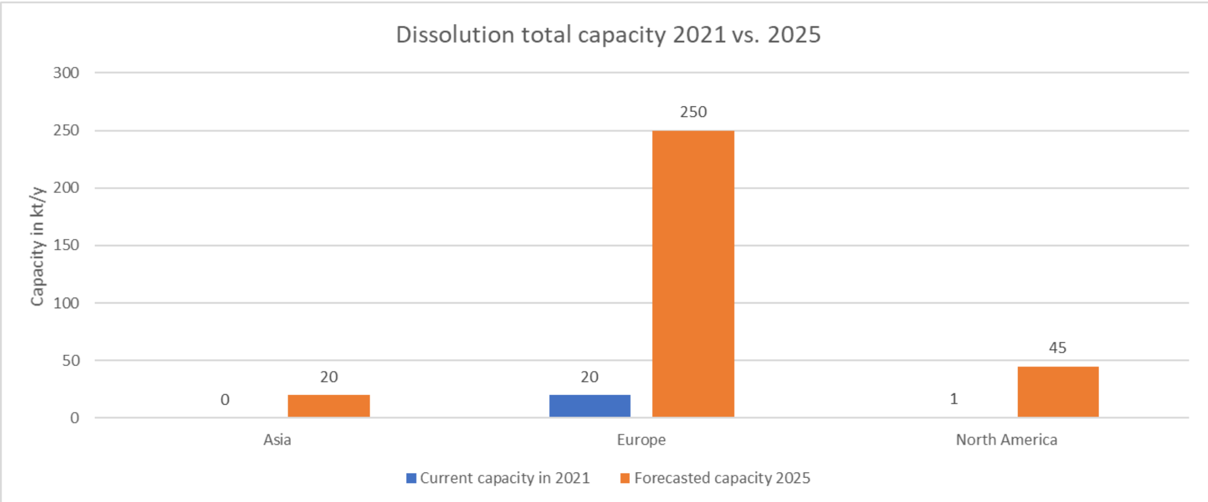


Figure 15: Dissolution capacities in 2021 vs. 2025 (RECORD, 2022)

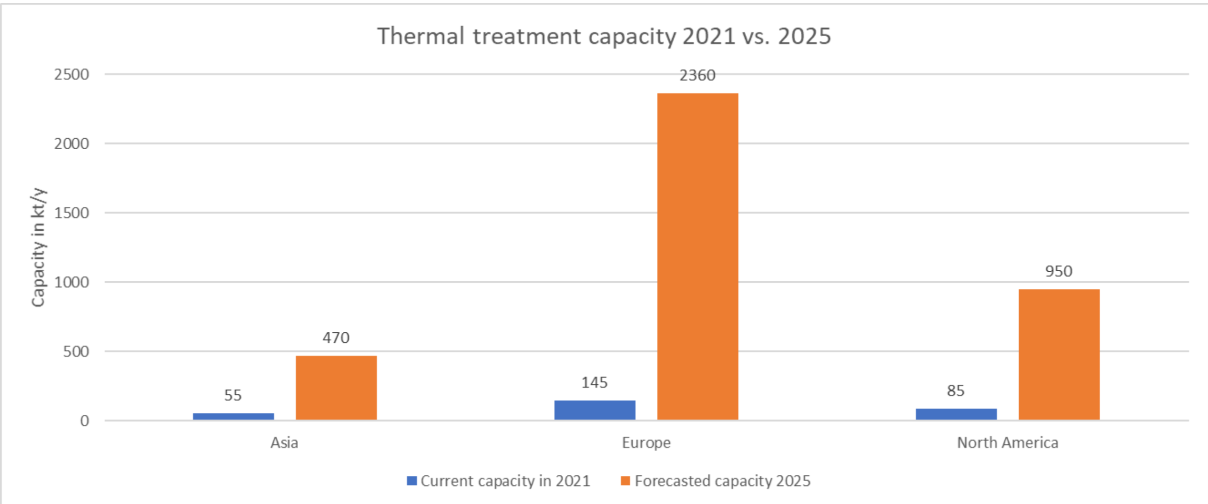


Figure 16: Thermal Treatment PS, PMMA, Mixed Plastics capacities in 2021 vs. 2025 (RECORD, 2022)

X. Focus on regulations and certifications

This section focuses on the definition of the mass balance approach as well as on the following regulatory aspects in Europe, the United States and Japan:

- Main regulatory and fiscal situations applicable to recycling plants
- Opportunity to use recycled resins for food-contact applications after approval by competent authorities
- Acceptability of the implementation of a mass balance approach
- Departure from the status of waste
- Qualification of a recycled state

Please note that within the following section the generic term “chemical and physico-chemical recycling” was used whenever it was not clear if the regulation discussed also applied to dissolution technologies.

1) Introduction to the mass balance approach

As manufacturers take their first steps towards producing bio-based drop-in chemicals or chemically recycled materials, there will often be the need to use existing facilities, which currently process petroleum derived/fossil materials, somewhere in the supply chain. Since there is generally a significant gap between the capacity of existing industrial assets and the initial volumes of bio-based materials/recycled material, batch conversion of 100% bio-based/chemically recycled materials is technically and economically challenging, if possible, at all in some situations. This will lead to the “dilution” of the recycled (or bio-based) material with fossil material.

The term “Mass-balance” refers to a type of chain of custody model. Chain of custody models are methods used to transfer, follow, and control information about materials that are entering and those that are leaving a system. The main types of chain of custody models used are: Identity preservation, Segregation, Mass balance, Controlled blending, and Book & claim (26, 27). The ISEAL Alliance states that “In the mass balance model the volume of certified product entering the operation is controlled and an equivalent volume of product leaving the operations can be sold as certified. The physical mixing of certified and non-certified product is allowed, but not required (i.e., does not define the model to have physical blending) at any stage in the production process provided that the quantities are controlled in documentation”[236].

The mass balance approach can be used in the absence of a physical traceability system whenever certain products/materials with defined characteristics are mixed with other materials that do not possess those same features (26). Using an auditable bookkeeping system, the mass balance approach determines how the products/materials of interest are allocated within the output that is produced (27). While already used in sectors such as furniture or textiles, the application of the mass balance approach to the plastic recycling industry is still new and, therefore, under investigation. Several organizations (including Plastics Europe – 2020, and the Ellen MacArthur Foundation – 2019) have already published position papers and recommendations on the use of the mass balance approach in the plastics industry. The following paragraphs focus on the most recent report that was found on this topic. The document was published by the ADEME in 2021 under the title “Approche « Mass balance » et recyclage chimique des plastiques” (Mass balance approach and chemical recycling of plastics).

It is relevant to specify that the ADEME makes a clear distinction between two types of mass balance.

- *Rolling average*: Materials with specific characteristics are mixed with other materials. The quantity of a given input material is not constant within the products produced, however, content can be allocated in the form of an average.

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[236] ISEAL_Chain_of_Custody_Models_Guidance_September_2016.pdf (isealalliance.org)

- *Credit method*: Materials with specific characteristics are mixed with other materials. The content of a given material is allocated freely to the different products produced (independently from the actual physical characteristics of those final products).

The report published by the ADEME focuses mainly on the application of the mass balance approach to pyrolysis and vapocracking. As discussed on the report, the quantity of pyrolysis oils that are produced today are not sufficient for them to be the only material entering a vapocracker. Pyrolysis oils derived from recycled plastics constitute therefore a very limited portion of a vapocracker's input when compared with conventional naphtha. Hence, plastic producers are driven towards the use of the mass balance approach.

While the ISO certification 22095:2020 (Chain of custody — General terminology and models) provides some general guidelines on mass balance, there is yet no internationally recognized standard specifying which conditions are to be respected to use this approach. In the absence of such norm, private certification schemes have been created, to certify a product developed under a mass balance approach (e.g., ISCC, RED Cert GmbH, UL, etc.). In this context, one of the main issues point out by the ADEME is the fact that each of individual certification system establishes its own mass balance set of requirements. The analysis of such systems has identified three topics that may become a subject of discussion if an official ISO norm will be created (26):

1) "The understanding of the input/output balances of steam crackers and the possible issues of coherence between the technical data and, in particular, the concrete methods of calculating the conversion factors".
2) "Regulatory texts, especially the new European rules on calculating recycling rates".
3) "The points of view expressed by various stakeholders on the implementation of a mass balance model".

All these subjects are discussed in detail within the ADEME's report. Overall, this document provides a complete overview of the multiple challenges associated with the use of the mass balance approach when using pyrolysis oils. Upcoming regulations and standards on mass balance will inevitably have a direct impact on chemical recyclers. Further updates on this subject are expected in the years to come.

2) Regulation in the United States

Note: regulation in the Unites States sometimes uses the term "advanced recycling" to refer to chemical recycling technologies. Within these paragraphs, the two terms have been used interchangeably.

a. Main regulatory and fiscal situations applicable to recycling plants

In the United states, plants are subjected to environmental regulations on air, water, and land use. Indeed, the United States Environmental Protection Agency (EPA) counts several laws that every waste management facility must comply with. The main regulation is the Resource Conservation and Recovery Act (RCRA), aiming at managing the hazards of waste disposal[237]; conserving energy and natural resources by recycling and recovery; reducing or eliminating waste; and cleaning up waste that which may have spilled, leaked, or been improperly disposed of. Recycling facilities usually falls under the category of solid waste management facilities. As of January 2022, there are no federal laws that specifically refer to chemical recycling. In 2021, the EPA issued an Advanced Notice of Proposed Rulemaking to regulate pyrolysis and gasification on USA territory. Indeed, the EPA has been working on the collection of informative material on pyrolysis and gasification to establish whether there is the need to enhance the regulation of these technologies. The questionnaire aims to collect data such as construction date, startup date, air emissions, pollution control equipment and project design. The results of this assessment will determine if and how the EPA will decide to enhance regulation on

[237] https://www.epa.gov/regulatory-information-topic/regulatory-and-guidance-information-topic-waste

chemical[238]. One possible scenario is to make pyrolysis and gasification facilities subject to article 129 of Clean Air Act (this act is currently regulating waste incineration units). On a state-level, approximately 14 states (Louisiana, Arkansas, Florida, Wisconsin, Georgia, Iowa, Tennessee, Texas, Illinois, Ohio, Pennsylvania, Virginia, Oklahoma, and Arizona) have already exempted advanced (chemical) recycling facilities from general solid waste and recycling laws[239].

Some states are defining more granularly recycling plants regulations (these states are represented on the Figure 17 below). Indeed, in the last years, a dozen of American states has passed bills to expand recycling infrastructure and support chemical recycling facilities. Among these states, Oklahoma's SB 448[240], passed on April 19th, 2021, defines regulatory aspects with which a chemical recycling plant must comply:

"Advanced plastic recycling facility" means a manufacturing facility that receives, stores, and converts post-use polymers and recovered feedstocks it receives using advanced recycling[241]. An advanced recycling facility shall be subject to applicable Department of Environmental Quality regulations for air, water, waste, and land use. Advanced recycling facilities shall not be considered disposal sites, solid waste management systems, transfer stations as defined in this section or incineration. Advanced recycling facilities shall be subject to inspections by the Department to ensure compliance with applicable laws and regulations. If an advanced recycling facility does not comply with the requirements of this definition it shall not be considered an advanced recycling facility and is subject to all applicable solid waste laws and regulations as determined by the Department"

Arizona has passed a similar bill (SB 1156[242]) in March 2021, subjecting recycling facilities to the same regulations. It has additionally created a recycling fund:

"A recycling fund is established to be administered by the director. The fund consists of monies appropriated by the legislature, gifts, grants, donations, and monies derived from the landfill disposal fees in section 49-836. Monies derived from landfill disposal fees are subject to legislative appropriation. Monies in the fund are exempt from lapsing under section 35-190. On notice from the director, the state treasurer shall invest and divest monies in the fund as provided by section 35-313, and monies earned from investment shall be credited to the fund. B. Monies from the recycling fund shall be used for the following purposes:

1. Grants to or contracts with political subdivisions, nonprofit organizations or private enterprise for research, demonstration projects, NEW TECHNOLOGIES, market development and source reduction studies and implementation of the recommendations or reports prepared pursuant to this article.
2. Public information, public education and technical assistance programs concerning litter control, recycling, and source reduction.
3. The collection and administration of monies in the fund.
4. The administration of this article.
5. The administration of the Arizona commerce authority's recycled market development program.

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[238] https://www.reuters.com/business/environment/us-epa-weighs-regulation-chemical-recycling-2021-09-22/

[239] https://www.americanchemistry.com/chemistry-in-america/news-trends/press-release/2021/louisiana-becomes-14th-state-to-support-reduction-of-plastic-waste-through-advanced-recycling

[240] http://webserver1.lsb.state.ok.us/cf_pdf/2021-22%20FLOOR%20AMENDMENTS/Senate/SB448%20(3-09-21)%20(TAYLOR)%20FS%20FA1.PDF

[241] According to the bill, ""Advanced plastic recycling" means a manufacturing process for the conversion of post-use polymers and recovered feedstocks into basic hydrocarbon raw materials, feedstocks, chemicals, liquid Req. No. 1970 Page 2 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 fuels and other products like waxes and lubricants through processes that include pyrolysis, gasification, depolymerization, catalytic cracking, reforming, hydrogenation, solvolysis and other similar technologies. The recycled products produced at advanced recycling facilities include, but are not limited to, monomers, oligomers, plastics, plastics and chemical feedstocks, basic and unfinished chemicals, crude oil, naphtha, liquid transportation fuels, waxes, lubricants, coatings and other basic hydrocarbons."

[242] https://legiscan.com/AZ/text/SB1156/id/2331769/Arizona-2021-SB1156-Engrossed.html

At the end of each fiscal year, any funds not spent by the authority for this purpose shall be returned to the fund. "

Other states are lightening the regulations to which chemical plants are subjected. For instance, in Ohio, the HB166 regulation, passed in July 2019, is excluding pyrolysis and gasification facilities from solid waste facility regulations. Indeed, it is stating that *"Disposal" does not include the process of converting post-use polymers and recoverable feedstocks using gasification or pyrolysis.*"
Indeed, in these states, pyrolysis and gasification facilities are reclassified as manufacturing facilities and thus subjected to the state's air, water, and waste regulations applicable to manufacturing facilities, which are usually are weaker than solid waste facility regulations.

Similarly, Louisiana has passed its SB97[243] bill in June 2021 that excludes advanced recycling facilities from the categories “resource recovery and management facility" and "Solid waste disposal facility": “Advanced recycling shall not be considered solid waste disposal, processing, incineration, combustion, or storage.”

In other states, certain types of manufacturing or alternative fuel production facilities may qualify for current or future renewable energy credits[244] [245].

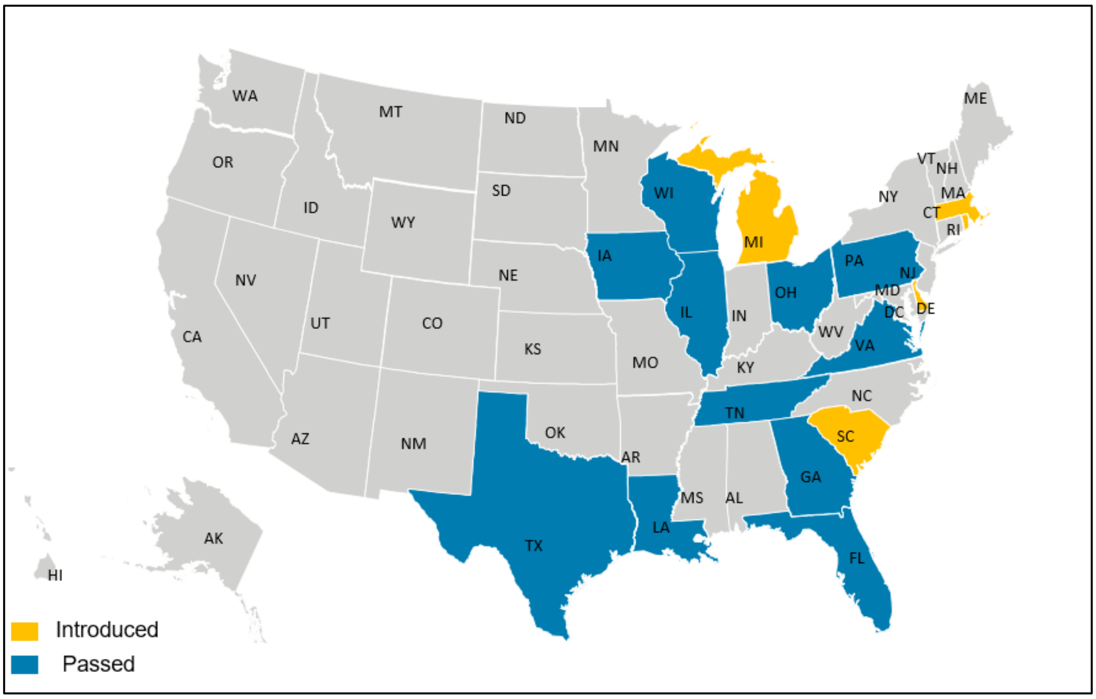

Figure 17: States exempting pyrolysis and gasification facilities from being regulated as solid waste facilities (update of Gaia map110)

[243] https://legiscan.com/LA/text/SB97/id/2421666/Louisiana-2021-SB97-Chaptered.pdf
[244] According to the Environmental Protection Agency (EPA), “A renewable energy certificate, or REC, is a market-based instrument that represents the property rights to the environmental, social and other non-power attributes of renewable electricity generation. RECs are issued when one megawatt-hour (MWh) of electricity is generated and delivered to the electricity grid from a renewable energy resource”. Source: Renewable Energy Certificates (RECs) | Green Power Partnership | US EPA
[245] https://www.no-burn.org/wp-content/uploads/US-ACC-State-Legislation-Alert_updated-July-2020.pdf.pdf

On the other hand, Maryland has tried to pass its HB 21[246] bill in January 2021 that forbids the building of a chemical recycling facility in the State. The ban however died in committee. The definition of chemical facilities in this bill is a facility "that converts plastic to fuel or feedstock through those […] chemical conversion processes" (which are: pyrolysis, hydro pyrolysis, methanolysis, gasification, enzymatic breakdown, or a similar process). It has to be noted that, the state of Maryland has also redefined the term "recycling" to exclude "pyrolysis, hydro pyrolysis, methanolysis, gasification, enzymatic breakdown, or a similar process"[247].
As for fiscal situations, the United States does not discriminate chemical recycling plants from other recycling plants.

b. Opportunity to use recycled resins for food-contact applications after approval by competent authorities

When used for food-contact applications, recycling materials must comply with the requirements of Chapter 21 of the Code of Federal Regulations, which is reserved for rules of the Food and Drug Administration (FDA).
Indeed, the FDA has set requirements on recycled plastics such as maximum acceptable level(s) of residual contaminants in the recycled material that are represented in the table below:

Recycled Polymer	Density, g/cm^3	Maximum residual contaminants to maintain an estimated daily intake of consumer inferior to 1,5 microgram/person
PET	1.4	220 µg/kg
Polystyrene	1.05	300 µg/kg
PVC	1.58	200 µg/kg
Polyolefins	0.965	320 µg/kg

Table 21 : acceptable level of residual contaminant by polymer type[248]

In the case of the use of a non-food container as a feedstock for the recycled resin, to be used in a food-contact application, this resin should respect current adjuvants and contaminants levels set by the FDA The recycled resin should also comply with FDA's regulations regarding barriers to stop contaminants migration into food. The recycler should thus conduct additional migration test.
Recycled plastics that are approved by the FDA receive a Letter of No Objection specifying that the material has been deemed as suitable for food-contact applications[249].
FDA issued a favorable opinion on the suitability of chemical recycling processes for producing post-consumer recycled plastic to be used in the manufacturing of food-contact articles for several

[246] https://trackbill.com/bill/maryland-house-bill-21-environment-recycling-prohibition-on-the-chemical-conversion-of-plastic/1957979/
[247] Bill HB21: https://trackbill.com/bill/maryland-house-bill-21-environment-recycling-prohibition-on-the-chemical-conversion-of-plastic/1957979/
[248] https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-use-recycled-plastics-food-packaging-chemistry-considerations
[249] https://resource-recycling.com/plastics/wp-content/uploads/sites/4/2019/10/PNC-2372.FNL_signed-1.pdf

companies, which are listed below. Only PET and PEN (Poly(oxy-1,2-ethanediyloxycarbonyl-2,6-naphthalenediylcarbonyl)) resin have been approved for now[250].

Company	Polymer	Recycling type
Hoechst Celanese	PET	Chemical - Regenerated dimethyl terephthalate from depolymerized PET bottles
Eastman Chemical Co.	PET	Chemical - Regenerated ethylene glycol and dimethyl terephthalate from depolymerized PET bottles
Far Eastern New Century Corporation APG Polytech LLC Corpus Christi Polymers, LLC	PET	Chemical - PET oligomers from depolymerized PET bottles
DuPont Co.	PET	Chemical - Regenerated ethylene glycol and dimethyl terephthalate from depolymerized post-consumer PET.
Hoechst Celanese	PET	Chemical (glycolysis)
Wellman, Inc.	PET	Chemical (glycolysis)
Innovations in PET Pty Ltd.	PET	Chemical (glycolysis)
Eastman Chemical Co.	PEN	Chemical - Regenerated dimethylnapthalene dicarboxylate and ethylene glycol from depolymerized PCR poly(oxy-1,2 - ethanediyloxycarbonyl - 2,6-naphthalenediylcarbonyl (PEN) resins using a methanolysis process.
Eastman Chemical Co.	PET	Chemical (glycolysis)
Eastman Chemical Co.	PET	Chemical (glycolysis/methanolysis)
JEPLAN, INC	PET	Chemical (glycolysis)
NanYa Plastics Corp.	PET	Chemical (glycolysis)
Teijin Limited	PET	Chemical (methanolysis)
Mitsubishi	PET	Chemical (methanolysis)
Futura Polymers	PET	Chemical (glycolysis)
Roychem	PET	Chemical (glycolysis)
Eastman Chemical Co.	PET	Chemical (glycolysis)
Selenis Canada, Inc.	PET	Chemical (glycolysis)
DAK Americas LLC	PET	Chemical (glycolysis)
Indorama Ventures	PET	Chemical (glycolysis)
M&G Polímeros México	PET	Chemical (glycolysis)
Loop Industries Inc.	PET	Chemical (process not specified)
OCTAL SAOC FZC	PET	Chemical (process not specified)

Table 22 : Recycled materials non objected by the FDA for food-contact applications

[250]https://www.cfsanappsexternal.fda.gov/scripts/fdcc/index.cfm?set=RecycledPlastics&sort=Recycle_Number&order=DESC&startrow=1&type=column&search=Recycling%20Process%C2%A4VARCHAR%C2%A4chemical

As for the use of recycled content in cosmetics applications, there is no legal regulations in the USA for now, as complementary safety assessments of products are not mandatory and only considered as a best practice[251].

c. Acceptability of the implementation of a mass balance approach

Several states in the US are nowadays considering implementing recycled contents requirements. California was the first state to constrain the integration of recycled plastics in beverage bottles through its bill AB-793, which passed on August 2020. The bill sets a recycled plastic target of 50% postconsumer recycled plastic per year by 2030 and defines these targets on the percentage of recycled plastic content on the total plastic bottles sold in the state[252].

Washington's bill SB 5022, passed on April 2021, has a similar definition of the recycled content to be integrated into bottles, in the aim of reaching a 50% postconsumer recycled content plastic by weight by 2031:

"A producer of a beverage in a plastic beverage container must meet the following annual minimum postconsumer recycled content percentage **on average for the total quantity of plastic beverage containers, by weight**, that are sold, offered for sale, or distributed in or into Washington by the producer"[253]

The state has introduced an additional bill in January 2021, SB 5219[254], to implement targets on plastic packaging as well. These targets have been defined on the same indicator, which is the minimum postconsumer recycled content on average for the total amount of plastic packaging sold, offered for sale, or distributed.

Oregon's HB 2065, which was introduced in February 2021, is more explicit in its definition of the recycled content to be taken into account in reaching these targets. It clearly states that the recycled content is measured compared to a packaging total weight. The mass balance approach seems thus non accepted:

""Recycled content" means the portion of a package's total weight that is composed of recycled material, as determined by a material balance approach that calculates total recycled material in the package as a percentage of the total weight of the package[255]."

In conclusion, several states are requiring a certain amount of recycled plastic content to be integrated into products sold, offered for sale, or distributed. There is however no mention if a mass balance approach would be accepted.

d. Departure from the status of waste

In order to reclassify the pyrolysis and gasification facilities as manufacturing facilities, the 17 states evoked in the first part of this chapter (see X.2)a above) have reclassified post-consumer plastic. Indeed, their status has been reclassified into "non-solid waste" (in Massachusetts[256] for instance in an introduced bill), "recovered materials" (in Virginia[257] in an introduced bill) or "raw materials for manufacturing"[258].

In Illinois, the very definition of "waste" was modified in the bill HB2941, passed on May 16, 2021, to exclude post-use polymers or non-recycled feedstocks processed through pyrolysis or gasification[259].

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251 http://www.foodlaw.rdg.ac.uk/pdf/2020-FDF-Recycled-Plastics-Guidance.pdf

252 https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200AB793

253 http://lawfilesext.leg.wa.gov/biennium/2021-22/Pdf/Bills/Senate%20Passed%20Legislature/5022-S2.PL.pdf?q=20210625023553

254 http://lawfilesext.leg.wa.gov/biennium/2021-22/Pdf/Bills/Senate%20Bills/5219.pdf?q=20210625021636

255 https://www.njleg.state.nj.us/2020/Bills/S3000/2515_I1.HTM

256 https://legiscan.com/MA/text/H829/2019

257 http://lis.virginia.gov/cgi-bin/legp604.exe?201+sum+SB591

258 http://www.legis.ga.gov/legislation/en-US/Display/20172018/HB/785

259 http://www.ilga.gov/legislation/BillStatus.asp?DocNum=2491&GAID=15&DocTypeID=HB&LegID=118521&SessionID=108&GA=101&SpecSess=0#actions

The same phenomenon occurred in Wisconsin[260] and Pennsylvania[261] (the bill has been introduced), where "post-use plastics" were excluded from the solid waste or municipal waste category if processed in pyrolysis or gasification facilities.
For instance, the state of Oklahoma in its SB448 bill, passed on April 19th, 2021, redefines post-consumer plastics as follows:
"Post-use polymer shall not be considered solid waste as defined in this section, unless the post-use polymer is improperly managed, abandoned or disposed of"[262].

No specific information has been found on the departure from the status of waste.

e. Qualification of a recycled state

<u>Qualification of production tools and qualification of products</u>

The association of plastic recyclers (APR), an international trade association, has implemented a post-consumer (PCR) resin certification program to certify PCR pellet or flake.
The certification guarantees that the product certified complies with APR's definition of PCR, aligning with the ISO 14021:2016 definition: "*Postconsumer Recycled Content means material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product which has been used for its intended use or can no longer be used for its intended purpose. This includes return of material from the distribution chain*"[263].
The certification ensures, via a material balance analysis, that the recycled content claims are accurate and evaluate the source of the recycled material to determine the final percentage (by weight) of PCR in the product[264].
This certification does not seem to require producing PCR in the United-States, as some companies listed on their website are located in Canada, Malaysia, or Mexico.

<u>Acknowledgement of pyrolysis oil as a recycled material when used to produce new polymers</u>

The EPA (Environmental Protection Agency) is currently exploring the definition of recycling and consulting on whether to include certain streams. This definition is used to afterwards calculate the national recycling rates.
The consultation covers five aspects: Sources of Recyclable Material, Material Streams, Material Management Pathways, Material Destination and Other Considerations. In the material management category, the agency wonders if pyrolysis should be included and if so, what products should it include (purified polymers, chemicals, fuels…)[265]. 108 comments were made from recycling industry stakeholders and opinions are diverging.
Indeed, the American Chemistry Council (ACC) stated that "advanced recycling processes that produce feedstock for new plastic, chemical products, waxes, and lubricants should count as 'recycling,' but feedstocks used for fuels should be classified 'advanced recovery.'"[266]
As for Brightmark (a global waste solutions company), pyrolysis processes should be defined as recycling: "All products should be considered as recycling in recycling rate calculations including fuels, fuel blend stocks and waxes"[267].
Gaia, an alliance of groups, NGOs, and individuals, has emitted a strong opinion of not including any chemical recycling technology in the definition of a recycled product:

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[260] http://docs.legis.wisconsin.gov/2017/proposals/reg/asm/bill/ab789
[261] https://legiscan.com/PA/bill/HB1808/2019
[262] http://webserver1.lsb.state.ok.us/cf_pdf/2021-22%20FLOOR%20AMENDMENTS/Senate/SB448%20(3-09-21)%20(TAYLOR)%20FS%20FA1.PDF
[263] ISO 14021:2016 Section 7.8.1.1
[264] https://plasticsrecycling.org/images/PCR_Certification/APR-Endorsed-PCR-Certifier-Application.pdf
[265] https://www.epa.gov/americarecycles/national-recycling-goal-recycling-rate-measurement-comment-period#comments
[266] https://www.regulations.gov/comment/EPA-HQ-OLEM-2020-0443-0101
[267] https://www.regulations.gov/comment/EPA-HQ-OLEM-2020-0443-0133

"Among the material management pathways which could potentially be considered as recycling in recycling rate calculations, EPA lists various forms of incineration, including pyrolysis, solvolysis, depolymerization, gasification, and combustion with energy recovery; all of which not only fall short of tackling the waste crisis at the source but also have negative environmental, climate, and financial impacts. Burning things is not recycling them at all, regardless of what technology is used and whether it generates energy or a byproduct. EPA must in no way count these methods toward national recycling goals"[268].
No final decision has been made public yet, but the limit date for submitting comments has been reached on March 8, 2021.
It has to be noted that, the state of Maryland has redefined the term "recycling" to exclude "pyrolysis, hydro pyrolysis, methanolysis, gasification, enzymatic breakdown, or a similar process"[269]

3) Regulation in the European Union

Note: The term "chemical depolymerization" within European regulation refers to technologies that break down plastics into monomers and other starting substances. It is however not specified which specific types of chemical recycling technologies this term refers to[270].

The following sections briefly discuss some of the regulations and standards in the field of recycling that are most relevant for the purpose of this report. Many more directives that have not been mentioned exist in relation to subjects such as plastics, recycling, waste management, and materials' production processes.

a. Main regulatory and fiscal situations applicable to recycling plants

In the European Union, recycling plants are subjected to laws and taxations that traditionally apply to the general category of producers/manufacturers as well as those of waste management companies. Waste management legislation includes directives related to the classification of waste, to trans-boundary transfers of waste, and to transitions from waste to product status. Relevant regulations include:

- the Waste Framework Directive 2008/98/EC
- the European List of Waste (Commission Decisions: 2000/532/EC, 2014/955/EU)
- the Waste Shipment Regulation (EC) (No. 1013/2006)
- the POP Regulation (EC) (No. 850/2004)
- the Seveso III Directive (2012/18/EU)

The Waste Framework Directive 2008/98/EC is one of the most relevant regulations for recyclers. This law defines recycling as "*any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes*". It is relevant to specify that the EU's definition excludes any type of waste processing that is used for the purpose of energy recovery, plastic-to-fuel applications, and backfilling[271] (28). Although chemical and physico-chemical recycling seems in some cases to fall under the legal definition of "recycling" on a European level (excluding plastic-to-fuel applications), no regulations nor amendments specific to these technologies have been published.

The latest update on the subject dates 2021, when the European Chemicals Agency published a study focused on the investigation of the chemical and physico-chemical recycling of plastic waste. Within the report, the agency recognizes the need for further clarity on chemical and physico-chemical recycling's

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268 https://www.regulations.gov/comment/EPA-HQ-OLEM-2020-0443-0142
269 Bill HB21: https://trackbill.com/bill/maryland-house-bill-21-environment-recycling-prohibition-on-the-chemical-conversion-of-plastic/1957979/
270 https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:32008R0282&from=EN
271 EU definition: "'backfilling' means any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping." (28)

terminology and for the harmonization of EU directives on plastics' recycling. Several actors operating in the sector (such as Chemical Recycling Europe) have indeed been arguing that the delay in the adjustment of regulations constitutes a hindrance for technology developers. Yet, according to the ECHA, generalizations on chemical and physico-chemical recycling should be avoided. New regulatory measures should be developed on a case-to-case basis depending on the technology in question. As an example, regulation should consider that chemolysis[272] seems to be a more circular solution than pyrolysis and gasification. Chemolysis produces in fact virgin monomers with no evidence on the presence of by-products, while pyrolysis and gasification produce by-products and non-reusable residues (making it an open-loop process).
Some of the stakeholders of the industry (e.g., NGOs and organizations such as Rethink Plastic and Plastic Recyclers Europe), advocate that chemical recycling processes are a form of recovery rather than actual recycling. The Joint Research Center (JRC) is still investigating whether all these processes technologies should be included or excluded from the current definition of recycling.

Zero Waste Europe advanced the proposal to categorize them as following:

- **Thermal recovery**: plastic to fuel solutions.
- **Material recovery**: polymer to molecule solutions (pyrolysis and gasification).
- **Chemical recycling**: polymer to monomer/oligomer solutions (depolymerization, solvolysis, chemolysis)[273].

Zero Waste Europe also suggested that, following the phase of technology categorization, the European Waste Hierarchy should be reviewed. According to their recommendations, mechanical recycling and dissolution should be preferred over depolymerization, which should likewise be favored to pyrolysis and gasification. In their opinion, pyrolysis and gasification are to be considered as recovery due to their low material recovery rates, high energy requirements, high CO_2 emissions, and consequent lower circularity. These technologies should therefore be ranked lower than recycling.

According to the ECHA report, being also classified as manufacturers/producers, chemical recyclers also have to comply with the following regulations:

- Regulation 1907/2006 on the Registration, Evaluation, Authorization and Restriction of Chemicals (REACH).
- The Regulation on classification, labelling and packaging (CLP Regulation).
- The consolidated version of the Regulation (EU) No 2019/1021 on persistent organic pollutants (POPs Regulation).

Although legislations that are specific to chemical and physico-chemical recycling are still being drafted on a European level, some technology developers[274] have already been selling their output in compliance with REACH (29).

Chemical Recycling Europe (CRE) promotes the vision by which chemical and physico-chemical recycling could significantly contribute to the achievement of the carbon-neutrality targets set by the EU Green Deal (2019) and to the attainment of the ambitious recycling rates set through the Packaging and Packaging Waste Directive (Directive 94/62/EC - objective to recycle 50% of plastic packaging by weight by 2025, and 55% by 2030). Hence, the organization strongly supports the idea that regulation should be harmonized among the Member States, and that the Waste Framework Directive and the REACH regulation should be aligned (30). They additionally share the perspective of Zero Waste Europe that recycling should be better promoted as an alternative to waste shipment to non-EU countries, that plastic

[272] The ECHA refers to chemolysis as a synonym of solvolysis/chemical depolymerization. It is defined as a process that treats plastic waste using solvents and reagents (or catalysts) to depolymerize the polymer into low molecular weight chemicals and oligomers.
[273] There is no definition of chemolysis, depolymerization and solvolysis in ZWE document.
[274] Information published by CRE. The source does not specify which technology developers it refers to.

products should be designed by reference to the EU Waste Hierarchy, that Extended Producer Responsibility (EPR) should be "*expanded to other groups beyond packaging and WEEE*"[275] (31).

While sharing a common perspective on several topics, Chemical Recycling Europe and Zero Waste Europe have contrasting views on a variety of other subjects. In particular, Zero Waste Europe believes that new regulations should be created to prevent chemical recycling from hindering the development of more circular solutions in the waste hierarchy (prevention, minimization, reuse). To do so, they suggest restricting plastic inputs for chemical recycling to contaminated and degraded plastics, to prevent plastics from separate collection to be chemically recycled, and to ensure that the outputs of these technologies will be limited to plastic-to-plastic applications (32). In July 2020, Rethink Plastic (Zero Waste Europe among the members) published a report suggesting seven steps to effectively legislate chemical recycling. The document recommended the following actions (33):

1. Define the term "chemical recycling" within the Waste Framework Directive so that it will formally exclude all types of plastic-to-fuel applications.
2. Define the legal status of chemical recycling, clarifying its position on the Waste Hierarchy.
3. Prevent chemical recycling from becoming a solution for single-use plastics or plastics that are collected to be mechanically recycled by limiting input to degraded and contaminated plastics.
4. Assess the environmental and health impact of chemical recycling on an industrial level.
5. Determine a methodology to exhaustively calculate both direct and indirect emissions of chemical recycling technologies.
6. Develop a standard that will be used to determine the amount of recycled content of materials obtained via chemical recycling.
7. Ensure that EU funds will only be attributed to develop processes with a lower environmental impact than the production of virgin feedstocks.

Chemical Recycling Europe strongly disagrees with some of these viewpoints. The organization advocates that chemical recycling is by definition a circular solution. Its input should therefore not be restricted to degraded and contaminated plastics but should include all plastics for which mechanical recycling is too complex or not economically viable. Furthermore, they suggest that plastics from separate collection should be eligible for chemical recycling to valorize all waste that is not suitable for mechanical recycling (thus preventing it from being incinerated), and that plastic-to-fuel solutions should not be restrained as they present a better alternative than the extraction of new primary materials (31).

It seems however that none of the stakeholders weigh chemical recycling against energy recovery. A more precise regulation seems to be expected.

From a financial perspective, rules that apply to recyclers are the same as traditional manufacturers. This includes environmental taxes that are either set by the European Union or by different Member States. Energy, transport, pollution, and resources are the aspects which are most frequently subject to environmental taxation. No specific environmental taxes were found for chemical recyclers (34). It should additionally be highlighted that, as of today, chemical recyclers do not seem to receive incentives through Extended Producer Responsibility (EPR) schemes as their technology is still under development.

b. Opportunity to use recycled resins for food-contact applications after approval by competent authorities

In the European Union, recycled plastics that are to be used for food-contact applications must comply with the requirements set by Regulation No 282/2008. This regulation is currently under review. A new draft of regulation 282/2008 has been circulated by EU in December 2021 for consultation[276]. EU is

[275] As of today, all EU Member States are required by law to have EPR schemes in place for the WEEE, Batteries, ELV, and packaging sectors. Certain States have put in place additional EPR schemes for tyres, waste oil, paper and card, construction and demolition waste, etc.

[276] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12013-Food-safety-recycled-plastic-in-food-packaging-updated-rules-_en

aiming at publishing the new version of Regulation 282/2008 by summer 2022. Inclusion of chemical and physico-chemical recycling in the future new draft is still unclear. This could delay the development of chemical and physico-chemical recycling technologies. However, Article 1 of the regulation points out that this law only applies to mechanical recycling processes. Forms of chemical recycling which lead to the depolymerization of plastics into monomers and other starting substances (referred to as chemical depolymerization), are to be excluded from the scope of this legislation. Monomers and oligomers resulting from chemical depolymerization are instead subject to the same criteria as monomers manufactured by chemical synthesis, which are set by Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food (35). The latest information available concerning the adaptation of Regulation No 282/2008 to plastics other than mechanically recycled PET was found in a document released by the British Plastics Association (BPA) in April 2020. As stated in the report "*steps for establishing evaluation criteria where these do not currently exist would be drawn up and an Annex setting out material specific rules would be included. This is expected to be discussed and further developed during 2020 and 2021*" (35). So far, no further updates have been found on this topic and no commercialized outputs have yet received the food grade approval. Based on the available information, it seems that chemical and thermal depolymerization will be more likely than dissolution (referred to by Eunomia as solvent purification) to obtain the food grade for their outputs (16).

In accordance with Article 13 of Regulation No 282/2008, mechanical recycling technology developers are to submit their request for approval to the European Food Safety Authority (EFSA) in compliance with the respective EFSA Guidelines (latest version published in March 2021)[277]. As of today, such guidelines have not been adapted to chemical and physico-chemical recycling. According to Chemical Recycling Europe, based on the rationale of Regulation No 282/2008 for which substances obtained from chemical depolymerization are to be considered as those obtained via chemical synthesis, the authorization of the EFSA should not be deemed necessary to obtain their food-grade approval. Policies for pyrolysis and depolymerization recognition are still being discussed by DG SANTE (or DG Health and Food Safety) and are yet to receive official authorization. An exception exists for hydrocarbon oils obtained from pyrolysis, which have been approved to be used in food-grade packaging[278] (29).

<u>Note on substances of concern based on the ECHA report</u>: Substances of concern (such as plasticizers, flame retardants, and stabilizers) can be found in plastics used for applications such as EEE, the automotive industry, construction waste, etc. These components are listed and subject to restrictions within the REACH legislation[279], under the Stockholm Convention (POPs), or in EU sectorial or regional regulations. Their use is highly regulated due to the high threat they constitute for the environment and to human health. While already challenging to manage, handling these substances can become even more complex due to the lack of traceability along the supply chain. Poor historical data on plastic composition is a major challenge for the recycling industry. Chemical and physico-chemical recycling technologies are often claimed as a solution for the recycling of plastics containing these components. Yet, a recent investigation by the ECHA concluded that more research has to be conducted to determine whether chemical and physico-chemical recycling technologies are a suitable option to treat plastics featuring substances of concern. On this topic, the agency highlighted the importance of improving screening and sorting technologies, as well as the role of digitalization to improve substances' traceability[280].

c. Acceptability of the implementation of a mass balance approach

As of today, no legislation nor harmonizing standard regulating the mass balance approach has been approved on a European level. Despite the lack of regulation, mass balance is one of the most debated subjects in the field of chemical recycling. In 2020, the Ellen MacArthur Foundation (EMF) published a

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[277] https://efsa.onlinelibrary.wiley.com/doi/epdf/10.2903/sp.efsa.2021.EN-6512

[278] This information was published by CRE. The source of the information does not specify which regulation it refers to, nor which authority authorized the approval.

[279] Within the REACH regulations, substances of concern include those listed as substances of very high concern and within Annex XVII.

[280] https://echa.europa.eu/documents/10162/1459379/chem_recycling_final_report_en.pdf/887c4182-8327-e197-0bc4-17a5d608de6e?t=1636701265520

white paper by the title “Enabling a circular economy for chemicals with the mass balance approach”. Following an extensive introduction on the principles of mass balance and its applicability to the chemical sector, the EMF discusses how the formal validation of this approach could become a key enabler for reducing plastic pollution and increasing recycled content in manufactured goods. It is argued that this system can be beneficial for both mechanical and chemical recycling. Yet, the Foundation supports the principle by which establishing appropriate standards is vital to protect consumers. According to their point of view, relevant standards used to regulate mass balance should: be international, be recognized as a contribution to the achievement of recycling targets, ensure transparency on societal and environmental benefits, be applicable both on a corporate or on a finished product level, and consider that multiple different feedstock sources might be used to manufacture the same product (36). Similarly, to the EMF, PlasticsEurope published a position paper supporting the mass balance approach. Although focused on renewable rather than recycled feedstocks, the organization also puts a strong emphasis on the necessity to create regulating standards (37).

While organizations such as the EMF and PlasticsEurope are presenting the mass balance approach as an enabler for circular economy and advocate for the harmonization of reference standards, other stakeholders appoint it as a potential greenwashing tool. Rethink Plastic published a position paper[281] on this subject. The organization supported the idea by which, in order to prevent greenwashing activities and protect consumers from misleading marketing claims, the regulation applied should be very strict when the mass balance approach is used in the context of calculating recycled content. Moreover, setting a rigorous legislation is deemed as necessary to prevent the chemical recycling industry from hindering incentives to increase the recyclability of plastics and from discouraging efforts to increase the recycled content in plastic products. To this end, the organization proposes the following recommendations (38):

1. Aim for the highest possible amount of recycled content and segregate recycled feedstock from virgin feedstock in the supply chain.
2. Use ‘batch level’ mass balance to determine recycled content when segregation is not feasible, which enables you to know the proportion of recycled material fed into the process and estimate actual recycled content in final products placed on the market.
3. Do not allow for the trading of recycled content as part of a credit system, both between sites and countries, including other sites belonging to the same company.
4. Evenly allocate the recycled content to output products where mass balance is used instead of allocating it arbitrarily (unless the actual recycled content of each output can be verified).
5. Ensure strong physical and chemical traceability of recycled content, thus ensuring that there is a proven chemical route between the input feedstock and the final product; and that input material can only replace its own share of the final product.
6. Avoid converting recycled content into theoretical ‘currencies’ such as calorific value or carbon, which would further facilitate a certification scheme for recycled content.
7. When determining recycled content, only include post-consumer waste and not pre-consumer waste.
8. Set strict eligibility criteria for plastic waste used for ‘chemical recycling’ to avoid competition with mechanical recycling feedstock.
9. Account for the full life cycle of products in the chain of custody model, taking consideration to material and carbon losses.
10. Ensure full transparency towards consumers by avoiding false claims and excluding additives from counting towards recycled content targets.

Numerous discussions are still ongoing on the mass balance approach and its use in the chemical recycling sector.

[281] https://ecostandard.org/wp-content/uploads/2021/02/2021_zwe_joint-paper_recycling_content_mass_balance_approach.pdf#:~:text=The%20%E2%80%98mass%20balance%20approach%E2%80%99%20is%20one%20such%20set,while%20harming%20the%20credibility%20of%20the%20recycling%20industry.%C2%A0%C2%A0

d. Departure from the status of waste

The Waste Framework Directive 2008/98/EC sets the basic criteria to determine under which conditions waste regains the status of product or acquires the title of secondary raw material. Article 6 – "End-of-waste status" (EoW) of this European law specifies that, for materials to cease to be waste, the following requirements must be met (28):

- The substance or object is to be used for specific purposes (e.g., no fuel nor energy applications, etc.).
- A market or demand exists for such a substance or object.
- The substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products; and
- The use of the substance or object will not lead to overall adverse environmental or human health impacts.

Since the publishing of the Directive in November 2008, the European Commission has been working on the adaptation of this regulation to specific waste streams. This work, which has been carried out with the collaboration of the Joint Research Centre Institute for Prospective Technological Studies (JRC-IPTS), aims at setting Union-wide end-of-waste criteria that are specific to certain types of waste (39). On one hand, the IPTS drafts waste-specific technical proposals containing all the information that is necessary to ensure compliance with Article 6 of the Directive. On the other hand, the Commission uses these technical proposals to implement the existing regulation. The latest available official document discussing the end-of-waste (EoW) criteria for waste plastic for conversion was published in 2014 by the JRC. This technical proposal explicitly excluded chemical recycling from its scope. The reasons behind the decision of not including chemical recycling[282] in the study were (39):

1. The refined output of feedstock recycling was considered to be out of scope as no barrier was found in the process of recognizing it as a product.
2. Mechanical and chemical recycling technologies were claimed to be too different for their output to be evaluated using the same EoW criteria.
3. The lack of clear distinctions between plastic-to-plastic and plastic-to-fuel outputs raised concerns that the adaptation of EoW criteria could incentivize non-recycling uses. Such outcome would have conflicted with regulations promoting the recycling of plastic waste.
4. Feedstock recycling still had a marginal role, accounting for only 50kt of materials treated yearly in the EU compared with over 5Mt for mechanical recycling.

Since the "End-of-waste criteria for waste plastic for conversion: Technical proposal" was published in 2014, no amendments have been officially released by the European Commission on chemical and physico-chemical recycling. Even when the Waste Framework Directive was last modified in 2018 (Directive 2018/851), no implementations were made regarding this subject (40).
The adaptation of the EoW regulation to chemical and physico-chemical recycling is therefore assumed to either be on hold (not progressing) or still under discussion.

e. Qualification of a recycled state

<u>Qualification of production tools and qualification of products</u>
The main reference standard used on a European level for the evaluation of recycled plastics is the EN 15343:2007 - Plastics - Recycled Plastics - Plastics recycling traceability and assessment of conformity and recycled content[283]. This standard provides the basic directives to calculate the amount of recycled content within a product and establishes reference procedures for the appropriate traceability of mechanically recycled plastics. Additional standards exist that are applicable to the recycling of specific type of plastics, examples include:

[282] The 2014 publication from the JRC that his paragraph refers to uses the terms « feedstock » and « chemical » recycling interchangeably.
[283] https://shop.bsigroup.com/ProductDetail/?pid=000000000030097507

- EN 15342:2008 Plastics. Recycled plastics. Characterization of polystyrene (PS) recyclates
- EN 15344:2021 Plastics. Recycled plastics. Characterization of polyethylene (PE) recyclates
- EN 15345:2008 Plastics. Recycled plastics. Characterization of polypropylene (PP) recyclates
- EN 15346:2015 Plastics. Recycled plastics. Characterization of poly(vinyl chloride) (PVC) recyclates
- EN 15348:2015 Plastics. Recycled plastics. Characterization of poly(ethylene terephthalate) (PET) recyclates

All these standards were created in compliance with the CEN/TR 15353:2007 Guidelines for the development of standards for recycled plastics. As of today, no standards have been found which are explicitly applicable or created with the purpose of evaluating chemical and physico-chemical recycling processes.

Multiple certifications exist on a European level to evaluate production tools and to qualify recycled materials/products.

In August 2020, the European Commission presented the Recycled Plastics Traceability Certification on its Circular Economy Stakeholders Platform. This certification is part of the RecyClass initiative (one initiative launched amongst others)[284], which aims at increasing the recyclability of plastic packaging by harmonizing the methods for recyclability and recycled content evaluation across the EU. The Certification Audit Scheme developed by RecyClass is used to evaluate and calculate the recycled content found in plastics. Traceability and Chain of Custody[285] are the core principles on which the Scheme is based. These two concepts ensure monitoring and verification at each step of the supply chain (including pre- and post-consumer phases), while also ensuring compliance with the ISO 22095 and the EN 15343:2007 standard (41). Section 5 of the Audit Scheme – Production Process includes information concerning the inclusion of a mass balance calculation method as part of the auditing process. Further details on the calculation are however not publicly available (41). Given that this certification was created as part of an initiative from the European Commission, it is assumed that it is valid mainly on a regional (European) level. Moreover, it is not specified whether chemical recyclers are eligible to obtain this type of certification.
In France, LNE (laboratoire national de métrologie et d'essais) and IPC (Centre Technique Industriel de la Plasturgie et des Composites) published a certification scheme on recycled content in January 2022[286]. Polymers produced from chemical and physico-chemical recycling seem eligible to this kind of certification.

The Recycled Plastics Traceability Certification was created as a complementary initiative to the already existing EuCertPlast. The EuCertPlast certification[287] was launched by the European Commission as part of the Eco-innovation program (2009-2012). It is mainly used to trace plastics across the value chain and assess the quality of the recyclates that are integrated into end-products. This verification is based on the EN 15343:2007 standard and is claimed to help recyclers meet REACH and food-grade application requirements (42). Plastic recyclers wishing to be certified by EuCertPlast must forward an online request for their plant to be evaluated by an accredited auditor and undergo third party checks that ensure impartiality. Recyclers that successfully complete the application process receive a one-year valid certificate, which can be used as proof that their facility operates in compliance with the best available practices and respecting the environment. Based on the available data (e.g., EuCertPlast online database[288]) it seems that, so far, no chemical recycler has been accredited the certification, this information has however not been officially confirmed. Given that this certification was created as part of an initiative from the European Commission, it is assumed that it is valid mainly on a regional (European) level.

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[284] https://recyclass.eu/recyclass/
[285] The term "Traceability and Chain of Custody" refers to the fact that the certified product should be trackable across the whole value chain, from the origin of the waste to the material.
[286] https://www.lne.fr/fr/actualites/matieres-plastiques-recyclees-lancement-nouvelle-certification
[287] https://www.eucertplast.eu/about
[288] https://www.eucertplast.eu/certified-recyclers

Supplementary REDcert² scheme principles for the chemical industry (or REDcert²)[289] is also a relevant standard valid on a European level. REDcert GmbH was originally created in 2010 by German actors operating in the field of agricultural and biofuel economy. The organization was funded with the goal of supporting the implementation of Sustainability Ordinances by encouraging the use of certified sustainable biofuels and liquid biomass. Given the increasing reliance of the chemical industry on biomass as an alternative to primary fossil resources, the organization later decided to create an additional certification that is applicable to the chemical sector. That is why, in 2018, the "Supplementary REDcert² scheme principles for the chemical industry" (or REDcert² - certification of sustainable material flows in the chemical industry) was launched in compliance with EU Directive on Renewable Energy. This initiative consisted in the integration of the TÜVSÜD's CMS 71 standard[290] into the already existing REDcert² certification (43). At first, the REDcert² scheme was reserved to companies integrating both sustainable biomass and recycled fossil-based materials into new products. However, since 2019, chemical companies can also receive a REDcert² certification of sustainable material flows in the chemical industry for integrating sustainable (recycled) fossil waste materials within their products even when no biomass content is added to them. This decision was made to better support decarbonization and circular economy objectives (43). The REDcert² scheme relies on the certification of the mass balance approach for recycling. Actors that successfully meet the requirements to obtain this certificate can then use it on their products as an advertising tool[291]. This certification is valid on German territory and on a European level[292]. BASF was the first actor belonging to the chemical sector to receive the REDcert² for the allocation of biomass to its products[293]. In 2019, REDcert published a press release supporting the applicability of REDcert² to chemical and physico-chemical recycling (no additional definition provided)[294]. The REDCert² logo can be sticked to the certified products. The following product-related claims on the mass balance approach are allowed: "*Fossil resources saving product*", or "*Fossil resources saving product by using recycled materials in the value chain*", or "*This product supports / comes with / leads to / entails a x% substitution of fossil with recycled materials in the value chain*" [295]. No further details were found about other certified chemical and physico-chemical recycling technologies.

No additional information was found concerning the certifications of chemically recycled products.

<u>Acknowledgement of pyrolysis oil as a recycled material when used to produce new polymers</u>

As mentioned in the previous paragraph, the European Waste Framework Directive establishes that, in order for a technology to be considered as recycling, its output has to be used for plastic-to-plastic applications. It is acknowledged that, in some cases, the output of chemical recycling technologies is suitable for both plastic and fuel applications. The end-of-life applications of these materials will therefore determine whether or not they can be attributed the status of "recyclate". This is the case for pyrolysis oil. Pyrolysis oil could only be recognized as recycled if it is used as an input in the manufacturing of new polymers. If used for plastic-to-fuel applications, this same material could not be acknowledged as a recycled output.

However, this raises the question of material traceability to ensure that the company, which purchases the recycled material (e.g., pyrolysis oil) and claims it will be used for plastic production, will actually process the material for such purposes (and not for fuel applications).

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289 https://www.redcert.org/en/redcert-systems/chemical-industry.html
290 https://www.tuvsud.com/de-de/-/media/de/industry-service/pdf/broschueren-und-flyer/is/energie/zertifizierungsstandard-erneuerbare-rohstoffe-tuvsud-is-ut.pdf?la=de-de
291 https://www.redcert.org/en/redcert-systems/chemical-industry.html
292 https://www.redcert.org/en/about-us.html
293 https://www.basf.com/global/en/who-we-are/sustainability/whats-new/sustainability-news/2019/BASF-REDcert2-standard.html
294 https://www.redcert.org/images/REDcert_press_release.pdf
295 https://www.redcert.org/images/REDcert_Guidelines_of_using_the_logo_and_claims_V10.pdf

f. European green taxonomy

In June 2020, the European Union published the Taxonomy Regulation (2020/852) within the Official Journal of the European Union. The EU taxonomy is a classification system establishing a clear guidance for the identification of sustainable economic activities. This system works by setting a list of technical criteria. Economic activities that comply which such criteria can officially recognized as sustainable. This new system is meant to help direct financial investments towards green activities. Areas of focus involve sectors that have the highest environmental impacts in the EU (such as energy, manufacturing, transportation, construction, etc.). Sustainable economic activities must respect the four following conditions (44):

1. Make a substantial contribution to at least one of the six environmental objectives
    - Objective 1: Climate change mitigation.
    - Objective 2: Climate change adaptation.
    - Objective 3: Sustainable use and protection of water and marine sources.
    - Objective 4: Transition to a circular economy.
    - Objective 5: Pollution prevention and control.
    - Objective 6: The protection and restoration of biodiversity and ecosystems
2. Do no significant harm to any of the other environmental objectives.
3. Comply with minimum social safeguards.
4. Comply with the technical screening criteria.

The Regulation, which entered into force in July 2020, will help the EU reach the objectives set by the European Green New Deal and will support the achievement of 2030 climate and energy targets[296].

In June 2021, one year after the initial publication of the Taxonomy Regulation, a first delegated act (setting the criteria for activities to meet environmental objectives 1 and 2) was formally adopted by the Commission for scrutiny by the co-legislators. The act, which came into force at the beginning of 2022, focuses on defining sustainable activities that contribute to climate change adaptation and mitigation objectives. No additional delegated acts have been published since. However, a second act (setting the criteria for activities to meet environmental objectives 3, 4, 5, and 6) is expected for mid-2022, entering into force in 2023.

The first delegated act contains information that will directly impact plastics manufacturers and recyclers. The document contains in fact compliance criteria for the manufacturing of plastics in primary form (including plastics manufactured using mechanical recycling, chemical recycling[297], as well as entirely or partially derived from renewable feedstock[298]). Specific requirements can be found within section 3.17 of Annex I of the first delegated act. Annex I focuses on objective 1 – Climate change mitigation, of the taxonomy criteria. Based on this document, "manufacturing of plastics in primary form is to be considered a sustainable activity if it can prove its contribution to climate change mitigation though these technical screening criteria"[299]:

a) "The plastic in primary form is fully manufactured by mechanical recycling of plastic waste".
b) "Where mechanical recycling is not technically feasible or economically viable, the plastic in primary form is fully manufactured by chemical recycling of plastic waste and the life-cycle GHG emissions of the manufactured plastic (excluding any calculated credits from the production of fuels) are lower than the life-cycle GHG emissions of the equivalent plastic in primary form manufactured from fossil fuel feedstock. Lifecycle GHG emissions are calculated using

[296] https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en
[297] Please note that, although mechanical and chemical recycling are discussed within the Taxonomy legislation, the European Commission does not include a definition of these terms within the regulation nor in its first delegated act.
[298] "Renewable feedstock refers to biomass, industrial bio-waste or municipal bio-waste".
[299] https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=PI_COM:C(2021)2800&from=EN

Recommendation 2013/179/EU or, alternatively, using ISO 14067:2018 or ISO 14064-1:2018. Quantified life-cycle GHG emissions are verified by an independent third party."

c) "Derived wholly or partially from renewable feedstock and its life-cycle GHG emissions are lower than the life-cycle GHG emissions of the equivalent plastics in primary form manufactured from fossil fuel feedstock. Lifecycle GHG emissions are calculated using Recommendation 2013/179/EU or, alternatively, using ISO 14067:2018 or ISO 14064-1:2018. Quantified life-cycle GHG emissions are verified by an independent third party."

Annex II, which focuses on objective 2 - Climate change adaptation, also contains clauses for the manufacturing of plastics in primary form. However, no reference was found to recycling activities within this section.

Criteria for meeting the remaining four environmental objectives of the EU Taxonomy are yet to be published. In August 2021, a draft report was published by the by the Technical Working Group (TWG) of the Platform on Sustainable Finance[300]. The document was published with the aim of collecting feedback on proposed preliminary recommendations on technical screening criteria for:

- Objective 3 - Sustainable use of water and marine sources,
- Objective 4 - Circular economy,
- Objective 5 - Pollution prevention,
- Objective 6 - Healthy ecosystems and biodiversity.

Within the annex, the report additionally puts forward the idea by which an activity should be considered sustainable if it involves design for recycling for food/beverage packaging. The document mentions that food/beverage packaging product manufacturing (including primary, secondary, and tertiary food/beverage packaging[301]) activities can be considered sustainable if at least 85% of total packaging (by weight) respects the following criteria[302]:

- "Fully manufactured by mechanical or chemical recycling of post-consumer material, with claims on recycled content made using a batch level mass balance[303] method. For chemical recycling technologies the material conversion rate should be at least the rate of existing mechanical recycling technologies for that material."
- Derived from renewable feedstock, which is material that is composed of biomass from a living source and that can be continually replenished, or from a source which is continually replenished by nature. When claims of renewability are made for virgin materials, evidence is provided to show that those materials shall come from sources that are replenished at a rate equal to or greater than the rate of depletion."
- "A combination of the options above."[304]

The paper additionally suggests that all claims on recycled and/or renewable content should be validated using international certification systems (e.g., ISCC PLUS certified packaging).

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[300] The Platform on Sustainable Finance is a permanent expert group created by the European Commission to support the implementation of the new Taxonomy regulation.

[301] *Primary packaging*: packaging in direct contact with the product that is being sold. *Secondary packaging*: packaging used to keep a certain number of products together. *Tertiary packaging*: bulk/transport packaging used to group a large number of products.

[302] https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/210803-sustainable-finance-platform-report-technical-screening-criteria-taxonomy-annex_en.pdf

[303] The term « batch level mass balance » is not defined within the report. The ISEAL Alliance refers to batch-level mass balance also as 'percentage blending' or 'batch blending'. They define it as a type of mass-balance that "ensures the end-product contains at least a proportion of certified product". "This model maintains segregation until the final point of blending or mixing for a specific batch of a product. Mixing with non-certified product is controlled and recorded, so the proportion of certified content in each final product is known.". From: https://www.isealalliance.org/sites/default/files/resource/2017-11/ISEAL_Chain_of_Custody_Models_Guidance_September_2016.pdf

[304] No further details available.

While this report represents the latest publication found on taxonomy implications on recycling activities, it should be noted that the document does not have policy implications and is not an official EU Commission document.

4) Regulation in Japan

According to the Basic Law for Establishing the Recycling-based Society, the following order of priority was specified for the processing of recyclable resources in 2000: (1) generation control, (2) reuse, (3) recycling, (4) thermal recovery, and (5) appropriate disposal.[305]

This is complemented by the amendment to the Waste Disposal Law on May 2005 which states that "first, emission of waste plastic should be reduced, after which recycling should be promoted; any remaining waste plastic should not go to landfill as it is suitable for use in thermal recovery".[306]

The Law for Promotion of Sorted Collection and Recycling of Containers and Packaging (known as the Containers and Packaging Recycling Law) was put in force in April 2000 and was amended in 2006. It aims to promote recycling and reduce the amount of container and packaging waste produced by households. Businesses, consumers, and municipalities are required to contribute to reducing emissions and recycling waste. Under the amendment in 2006, the emission reductions are promoted as well as high quality sorted collections, the PET bottle category was modified to include containers such as noodle broth bottles.

The Containers and Packaging Recycling Law recognizes the following recycling processes:

- Material (mechanical) recycling
- Chemical (feedstock) recycling (which includes monomerization, liquefaction, use as a blast furnace reducing agent, coke even chemical feedstock recycling, conversion to chemical feedstock by gasification)
- Energy recovery (thermal recycling) (liquefaction, gasification)

Refuse Derived Fuels[307] (RDF) and other forms of energy recovery were also included with some limitations in the amendment in 2006.[308]

a. Main regulatory and fiscal situations applicable to recycling plants

Please note there is a lack of available information on this topic.

Based on the article 15-8 of the Waste management and Public Cleansing Law in 1970, **"**In each fiscal year, a center shall prepare an operational plan and a budgetary statement of income and expenditure and submit them to the Minister of the Environment in accordance with the Ordinance of the Ministry of the Environment. To revise its operational plan, the center shall prepare a revised operational plan and a revised income and expenditure budget and submit them to the Minister of the Environment. After the end of each fiscal year, a center shall prepare an operation report and a year-end income and expenditure report and submit them to the Minister of the Environment in accordance with the Ordinance of the Ministry of the Environment."[309]

A "Waste Treatment Facility Development Plan" (FY 2018–22) which aims at establishing waste treatment facilities that include measures to prevent global warming and promote energy production was also approved by the Japanese cabinet in June 2016.[310]

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305 http://www.env.go.jp/recycle/low-e.html
306 https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf
307 Refuse Derived Fuels (RDF): solid fuel made from burnable waste, plastic waste, etc.
308 https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf
309 https://www.env.go.jp/en/recycle/basel_conv/files/Waste_Management_and_Public_Cleansing.pdf
310 https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf

b. Opportunity to use recycled resins for food-contact applications after approval by competent authorities

The food grade regulatory framework for recycled plastics in food packaging is based on the Food Sanitation Act of 1947, the positive list system for food packaging materials developed by the Ministry of Health, Labor and Welfare (MHLW) and the voluntary standards to ensure the baseline for safety of food-contact materials from industrial hygienic associations (e.g., Japan Hygienic Olefin and Styrene Plastics Association - JHOSPA).
Some guidelines for use of recycled plastics in food contact articles were published by MHLW in May 2012 and specified that:

- post-consumer plastic should be from the food contact use in principle and be collected separately
- this plastic could be recycled via chemical, physical reprocessing or via a new technology (no further detail was provided)
- the recycled plastics have to be verified for safety including validation for material and barrier as well as material and/or migration testing for example.[311]

Simultaneously, the Food Safety Commission of Japan (FSCJ), established as a part of Japan's Cabinet Office in July 2003, has implemented science-based risk assessment of food and risk communication about the results of the assessments. This is independent from risk management organizations (Ministry of Agriculture, Forestry and Fisheries (MAFF), Ministry of Health, Labor and Welfare (MHLW), Ministry of Environment (MOE), Consumer Affairs Agency (CAA)).[312]

Some recycled materials have already been approved for food-contact applications such as the following examples:

- Teijin Ltd. technology developed a process which used ethylene glycol and methanol to break PET down into DMT. After improvement, the technology allowed to break PET bottles down from DMT to PTA. The main goal was the production of textiles and films. Teijin started operation of a facility in 2003. The Japanese Food Safety Commission considered the resin produced was suitable for use in food containers in 2004. With the approval of the Ministry of Health, Labor and Welfare, the B-to-B production started in April but was withdrawn by Teijin Fibre due to a shortage in raw materials (i.e., significant increase in the export of waste PET bottles).[313]
- The chemically recycled PET from JEPLAN BRING Technology™ will be used by Kao Corporation for their cosmetic bottle containers starting in June 2021. The high-quality r-PET has received the certification by the Food Safety Commission of Japan, which is part of the Cabinet Office, for use in food containers.[314]

c. Acceptability of the implementation of a mass balance approach

Please note there is a lack of available information on this topic.

In June 2021, BASF and Mitsui Chemicals announced the launch of a study to promote chemical recycling in Japan. Via its ChemCycling™ project, BASF will convert post-consumer plastic waste into pyrolysis oil thanks to their technology partners. This oil will serve as a feedstock for the production recycled materials via a mass balance approach. In Europe, products developed under this approach are already available in the market. Through their collaboration, BASF and Mitsui Chemicals will assess collaborative business models and options for the commercialization of chemical recycling in Japan.

Several measures have been developed by the Japanese government, notably its "Green Growth Strategy Through Achieving Carbon Neutrality" in December 2020 to reach sustainability goals by 2050. In this context, chemical recycling could be an option. Through their collaboration, BASF and Mitsui

311 https://www.worldpackaging.org/Uploads/SaveTheFood/Japan.pdf
312 https://www.fsc.go.jp/english/what_we_do.html
313 https://www.pwmi.or.jp/ei/plastic_recycling_2019.pdf
314 https://www.kao.com/global/en/news/sustainability/2021/20210602-001/

Chemicals will promote the development of chemical recycling in Japan and the efficient use of recycled materials and would like to accelerate the discussions on this topic with ministries, agencies, and industry groups.[315]

d. Departure from the status of waste

Please note there is a lack of available information on this topic.

Below is presented the definition of “waste”:
Based on the Article 2 from the Waste management and Public Cleansing Law in 1970, “the “waste” refers to refuse, bulky refuse, ashes, sludge, excreta, waste oil, waste acid and alkali, carcasses and other filthy and unnecessary matter, which are in solid or liquid state (excluding radioactive waste and waste polluted by radioactivity)” and “"municipal solid waste" refers to waste other than industrial waste”.[316]

Based on the Act on the Promotion of Sorted Collection and Recycling of Containers and Packaging (Act No. 102 of June 16, 1995), “the term “waste containers and packaging” as used in this Act shall mean containers and packaging which have become municipal solid waste (meaning municipal solid waste prescribed in Article 2, paragraph 2 of the Waste Management and Public Cleaning Act (Act No. 137 of 1970; hereinafter referred to as the “Waste Management Act”); the same shall apply hereafter).”[317]

e. Qualification of a recycled state

Please note there is a lack of available information on this topic.

Qualification of production tools and qualification of products
Based on the definition from the 3R (Reduce, Reuse, Recycle) initiative launch in 2000, “Recycle" refers to material recycling and "recyclable resources" should be used as raw materials to develop new products.[318] This definition is in line with the Act on the Promotion of Effective Utilization of Resources in 1991, which states: “the term "Recycling" as used in this Act shall mean to change the condition of the whole or part of such Used Products, etc. that are useful, so as to make them available as Recyclable Resources or Reusable Parts” and “the term "Recyclable Resources" as used in this Act shall mean such Used Products, etc. or By-products that are useful and are available or can be made available as raw materials.”[319]

Toray Group developed recycled PET/ABS and PC/ABS alloy compounds made from plastic waste (process not detailed, probably reformulation and compounding). The group applied for the ISO 14021 and EU EN15343 recycled plastics verification, and US EPEAT standards under the IEEE 1680 and UL 110, for the post-consumer recycled PET/ABS and PC/ABS alloy compounds. Inspections and on-site inspections of Toray's factories and its recycled-materials suppliers were conducted by TÜV Rheinland Japan, Shenzhen, and Taiwan to ensure that the product complies with the standards in terms of percentage of recycled materials and limits on hazardous substances. Toray Group products were granted the TÜV Rheinland New Test Mark: Recycled Materials in December 2015.[320]

However, no further information was found on the certification of chemically recycled materials.

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[315] basf_mitsui_chemicals_chemcycling.html
[316] WASTE MANAGEMENT AND PUBLIC CLEANSING LAW (env.go.jp)
[317] <5461726F31332D97658AED95EF9195838A83548343834E838B964081698970> (meti.go.jp)
[318] waste_management_recycling_japan.pdf (eu-japan.eu) ; METI Ministry of Economy, Trade and Industry
[319] <5461726F31332D8E918CB9974C8CF89798977091A390699640816989708CEA> (meti.go.jp)
[320] Staying On the Move: Toray Group Receives TÜV Rheinland's First Post-consumer Recycled Materials Verification | id | TÜV Rheinland (tuv.com)

Based on our understanding, the material produced via pyrolysis/gasification is almost always used for energy applications in Japan (mentioned on the JCPRA website). In general, the potential use of the generated oil for plastic production is not mentioned. Only Nippon Steel indicated that the produced oil can be used as raw material for the manufacturing of plastics.[321]

Acknowledgement of pyrolysis oil as a recycled material when used to produce new polymers

Please note there is a lack of available information on this topic

5) Regulations in Europe, the USA and Japan - Key learnings

	Europe	USA	Japan
Main regulatory and fiscal situations applicable to recycling plants	• Recycling plants are subjected to laws and taxations that traditionally apply to the general category of producers/manufacturers • Legislations on chemical and physico-chemical recycling are still being drafted on a European level • Numerous discussions ongoing on chemical and physico-chemical recycling (definition and applicability)	• EPA counts several laws that every waste management facility must comply with (including the Resource Conservation and Recovery Act (RCRA)). • Dozens of American states have passed bills to support chemical recycling facilities	• Facilities are subjected to the Waste management and Public Cleansing Law and Waste Treatment Facility Development Plan • *Lack of information*
Opportunity to use recycled resins for food-contact applications	• Monomers and oligomers resulting from chemical depolymerization are subject to the same criteria as monomers manufactured by chemical synthesis, which are set by Regulation (EU) No 10/2011 on plastic materials and articles intended to come into contact with food • EFSA approval needed • Some hydrocarbon oils obtained from pyrolysis have been approved to be used in food-grade packaging	• Recycling materials must comply with the requirements of Chapter 21 of the Code of Federal Regulations, which is reserved for rules of the FDA • Chemically recycled PET and PEN approved by FDA	• Chemically recycled PET already approved by the Japanese Food Safety Commission and the Ministry of Health, Labor and Welfare
Acceptability of the implementation of a mass balance approach	• No legal framework • Numerous discussions are ongoing on this topic • This approach is not accepted by the current regulation in France.	• Mass balance approach not mentioned in the legislation, it seems not to be accepted	• *Lack of information*

321 https://www.nipponsteel.com/en/csr/env/circulation/waste.html

Departure from the status of waste	• Definition from the Waste Framework Directive 2008/98/EC • The adaptation of the EoW regulation to chemical and physico-chemical recycling is assumed to either be on hold (not progressing) or still under discussion	• Post-consumer plastics reclassified in 17 states to consider the pyrolysis and gasification facilities as manufacturing facilities • Definitions of post-consumer waste may differ from one state to another	• Definition of waste from Waste management and Public Cleansing Law • Lack of information on the departure from the status of waste
Qualification of production tools and qualification of products	• Multiple certifications exist at a EU level to verify the production of tools and qualification products (Recycled Plastics Traceability Certification, EuCertPlast, REDcert, LNE / IPC, …).	• Post-consumer (PCR) resin certification (includes the mass balance approach)	• TÜV Rheinland Japan certification
Acknowledgement of pyrolysis oil as a recycled material when used to produce new polymers	• No official statement identified on this specific topic • Based on the definitions, it seems that pyrolysis oil could be considered as a recycled material only if it used for new polymers production (not for fuel applications)	• The EPA is currently exploring the definition of recycling – no final decision has been made public • Numerous discussions ongoing on the acknowledgment of pyrolysis oils as recycled material when used to produce new polymers.	• *Lack of information*

Table 23 : Comparative table of the regulations in Europe, the USA and Japan (RECORD, 2022)

6) Global Standards and Certifications

Aside from regional initiatives, global standards exist which can be used to certify recycling operations and outputs. The following paragraphs present some relevant standards that are applicable to recycled materials.

a. ISCC PLUS [322] [323]

The International Sustainability & Carbon Certification (ISCC) system has created the ISCC PLUS certification. This type of standard can be used to certify bio (e.g., cotton, corn, etc.), bio-circular (e.g., forestry residues, tall oil, etc.), and circular economy materials (e.g., mixed plastic waste, end-of-life tires, etc.) and is applicable to all markets which are not regulated by the EU renewable energy or by fuel quality directive (for which a different certification named is ISCC EU used) (45). The ISCC PLUS can certify feedstock either through the mass balance approach or through physical segregation. In the first case, the standard ensures that the mass balance accounting respects a series of pre-established requirements. The second case consists of a chain of custody option (43). This standard is well aligned with relevant initiatives including: the Ellen McArthur's White Paper on the mass balance approach, Plastics Europe industry view paper on the mass balance approach, the American Chemistry Council principles for mass balance, and Cefics' position paper on chemical recycling. It additionally has validity

[322] https://www.iscc-system.org/about/circular-economy/
[323] https://www.iscc-system.org/wp-content/uploads/2021/06/ISCC-for-Industrial-Applications_June.pdf

on a global level (45). To certify the mass balance approach, the ISCC PLUS analyses the inputs, outputs, and losses of certified feedstock that occur during the process. Several organizations use this certification, some examples are presented below:

- Since 2019 this certificate is being used by SABIC to certify its circular polymers (PE and PP) produced with the Plastic Energy's TACOIL (pyrolysis oil)[324].
  Eastman's glycolysis processing site is also ISCC PLUS certified, and so is its processing site for methanolysis which is expected to become operational by 2022[325].
- The same certification has been accredited to RECENSO's chemical recycling technology Carboliq (catalytic pyrolysis)[326] and to INEOS Olefins and Polymers USA (technology used/technology partner not specified)[327].

The following claims on a product developed via a mass balance approach and ISCC PLUS certified can be done: "*An equivalent amount of ISCC compliant material has been sourced*", or "*product from certified sources on a mass balance basis*", or again "*committing to.*"). However, it is forbidden for these claims to refer to the physical characteristics of the product.

b. RSB[328]

The RSB Global Advanced Products Certification is a worldwide certificate released by the Roundtable on Sustainable Biomaterials (RSB). The RSB is a member organization formed by multiple stakeholders who share the objective of achieving the UN's Sustainable Development Goals. The RSB Global Advanced Products Certification can be used to certify non-energy products within the chemicals and polymers industry. These products can fall within Category I - Bio-based products; Category II - Recycled content products; Category III - Bio-based or recycled fossil carbon mixed with fossil carbon products (this last category refers to the utilization of the mass balance approach)[329]. RSB openly supports chemical recycling (technology not specified) as a circular way to overcome the barriers of mechanical recycling[330]. Yet, to be certified, at least 25% of the virgin fossil feedstock over a 3 months-period needed to produce the certified product batch must be replaced by alternative feedstock[331]. After having been certified, recyclers can use the RSB certification logo on their products, stating that "*This RSB compliant product leads to a x% substitution of fossil resources through waste recycling in the production system*" or again that "*Over its production lifecycle, this material provides x% greenhouse gas savings compared to a fossil fuel equivalent*" [332].
Several organizations use this certification, some examples are presented below:

- In December 2020, Plastic Energy received the RSB certification for their facility in Sevilla (processing plastic waste into pyrolysis oil via non-catalytic pyrolysis)[333].
- Lactel's Montauban plant for the production of UHT milk bottles also received the RSB certification in April 2021. The bottles are produced in partnership with INEOS and integrating its circular polyethylene (HDPE) obtained from post-consumer recycled material. According to available information, a trial production of 140,000 milk bottles was conducted. These bottles proved to be compliant with food safety regulations and fully recyclable[334].

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[324] https://www.iscc-system.org/cracking-the-problem-of-waste-plastics/
[325] https://www.iscc-system.org/wp-content/uploads/2020/06/Enabling-world-scale-advanced-circular-recycling-of-plastics-with-ISCC-PLUS.pdf
[326] https://www.openpr.com/news/2268254/sustainability-certificate-for-chemical-recycling
[327] https://www.cosmeticsandtoiletries.com/networking/news/company/INEOS-Receive-ISCC-PLUS-Certification-for-Advanced-Plastic-Recycling-574259841.html
[328] https://rsb.org/about/
[329] https://rsb.org/wp-content/uploads/2020/08/RSB-Guide-to-Certification-for-Advanced-Products.pdf
[330] https://rsb.org/wp-content/uploads/2020/07/Chemicals-and-Polymers-Report-WEB2.pdf
[331] https://rsb.org/wp-content/uploads/2018/12/18-12-11_RSB-STD-02-001-v2.0-RSB-Standard-for-Advanced-Products.pdf
[332] https://rsb.org/wp-content/uploads/2020/08/RSB-Guide-to-Certification-for-Advanced-Products.pdf
[333] https://plasticenergy.com/rsb_certification_sevilla/
[334] https://rsb.org/2021/06/01/ineos-and-lactel-partner-to-produce-the-worlds-first-hdpe-milk-bottles-from-advanced-recycling/

c. UL LCC

Through its UL 2809 - Environmental Claim Validation Procedure (ECVP) for Recycled Content certification, UL LCC certifies products based on the amount of recycled content in it. Recycled materials may include post-consumer and post-industrial recycled content, closed loop recycled content, and total recycled content[335]. The UL LCC has incorporated a mass balance approach which can be applied to both mechanical and chemical recycling[336]. By receiving this certification, companies can prove their environmental claims and protect themselves against greenwashing allegations. Being a global safety leader, UL LCC can certify companies worldwide[337]. In 2021, BASF received a UL certification for their chemically recycled Ultramid Cycled polymers (ChemCycling's non-catalytic pyrolysis output)[338]. No further details were found about other certified chemical recycling technologies.

d. Recycled Claim Standard (RCS)[339] and Global Recycled Standard (GRS)[340]

The Recycled Claim Standard and the Global Recycled Standard were created by Textile Exchange[341] with the goal of increasing the amount of recycled materials used in products. Although initially meant to be used within the textile industry, the scope of these global standards has been widened to actors operating outside of this sector (no further information available specifying relevant sectors). The RCS is used for products that contain at least 5% certified recycled material free from any pollutant. The GRS is used to certify recycled content within products that contain a minimum of 20% of recycled material[342]. The GRS additionally includes a set of social and environmental requirements and chemical restrictions. [343]. To be certified through either standard, recycled materials must meet pre-established requirements across the whole supply chain. Yet, no further information has been found concerning the applicability of these standards to certify chemical recycling outputs. No examples of chemical technology developers that have obtained this certificate have been identified.

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[335] https://www.ul.com/services/recycled-content-validation
[336] https://www.ul.com/news/mass-balance-new-approach-calculating-recycled-content
[337] https://www.ul.com/services/recycled-content-validation
[338] https://chemengonline.com/basf-advances-chemical-recycling-portfolio-with-new-ul-validation/?printmode=1
[339] https://textileexchange.org/wp-content/uploads/2017/06/Recycled-Claim-Standard-v2.0.pdf
[340]https://cdn.scsglobalservices.com/files/program_documents/Global%20Recycled%20Standard%20-%20FINAL.pdf
[341] Global non-profit multi-stakeholder organisation (brands, retailers, suppliers, etc.) supporting the transition towards a more sustainable textile industry: https://textileexchange.org/.
[342] https://textileexchange.org/standards/development-hub/grs-rcs-revision/
[343] http://www.cuc-china.net/uploadfile/infoPic/20131015114849409.pdf

XI. Synthesis of experts' opinion

1) Experts' point of view

a. What are the main opportunities and constraints to chemical and physico-chemical recycling technologies and to their scaling up?

Introduction (based on the literature review)
The bibliography review highlighted the different opportunities and discrepancies between the different chemical and physico-chemical recycling technologies.
Indeed, all **solvolysis technologies** are usually designed to handle mono-material waste streams, which necessary requires pretreatment steps to be implemented. The need for such pre-treatment steps is heightened by the fact that these processes demonstrate a relatively low tolerance for contaminants, which are thus to be removed beforehand. The nature of these steps highly depends on the feedstock, whose composition is key. Underestimating the importance of pre-sorting could be detrimental to the scaling-up of the technology. Nevertheless, **technology developers rarely elaborate on this subject and often claim that their technology does not necessitate any pre-sorting or pre-treatment step**. These technologies produce monomers or chemical intermediaries that would have to be reintegrated in an existing polymerization chain and would thus require adapting conventional production processes to ensure that the waste is effectively recycled into a new polymer. Downstream steps are thus necessary to ensure the repolymerization of the material to its initial chemical form. However, **there are a lack of information and uncertainties about the nature and extent of such steps in the literature**. The maturity level of solvolysis technologies is evaluated at the **development phase**, with some very specific methanolysis developers at a higher TRL (around 8 in the best cases).
On the contrary, **thermal treatment technologies** can usually handle multi-material waste streams, as long as they don't contain non-processable materials, such as PVC, PET or PU. Limited levels of contamination (with PVC, PET, etc.) could be tolerated depending on the considered technology developer process. These technologies are usually applied on polyolefins mix or specific polymers such as PS or PMMA. Pre-treatment steps would also be required in order to remove these components, but the feedstock concentration requirements would however be less stringent than solvolysis. Controversy, multiple downstream steps seem to be required to produce a recycled polymer from these technologies. Information about the nature and extent of these steps are however scarce in the literature. Issues arise in the case of pyrolysis oil, which has to be mixed with virgin oil. Indeed, the low level of available feedstock compared to the virgin amount of materials implies that the recycled material would be a small portion of the recycled material, with traceability issues. This would not be as problematic for other technologies, as the outcome does not need to be mixed with virgin material and thus can be differentiated in distinct polymerization lines. It would seem that, in PS or PMMA's cases, thermal processes going back to the monomer would need similar pretreatment and posttreatment steps as in solvolysis' case. The maturity level of thermal treatment technologies is higher compared to other chemical and physico-chemical recycling technologies, as the majority of the technologies studied have a TRL ranging from 5 to 8, with some having industrial capacities.
Similarly, **dissolution** is practically **suited to all types of thermoplastics**, even if it is mainly applied to PS, PVC, and polyolefins. This process can **treat mono-material contaminated streams**, and sometimes mixed plastics. Pre-sorting or pre-treatment are however often necessary, even if there is little information disclosed by developers or by literature on the subject. This chemical process has the advantage of almost not altering the chemical structure of the recovered polymer and targets either the polymer of choice or the impurities. It can thus be used as pre-treatment to dissolve impurities contained in a specific feedstock. The maturity level of dissolution technologies is evaluated at the **development phase**, with an average TRL of 5.

Volumes of available feedstocks
POINTS OF AGREEMENT BETWEEN EXPERTS
Experts agree on the fact that a major challenge for chemical recyclers is to access **feedstock with sufficient volume**. Indeed, the feedstock targeted might be scarce and/or diffuse. The ease of accessing the feedstock will highly depend on the resin and on the requirements. Accessing a feedstock of specialty polymers in sufficient quantity might be challenging due to the geographical dissemination

of this resource. Yet the demand for such feedstock in the different industries will be less important than for commodity polymers.
Accessing enough commodity polymers feedstock is difficult due to different factors such as purity levels or concentration in the polymer of interest.

Box 1: Specific examples raised by some experts on the quantity of feedstock available

In **specialty performance polymers' case**, **lower volumes are produced** than for commodity polymers. As a consequence, this means that:
- Collecting these materials at their end-of-life can be challenging.
- This aspect requires recycling processes to be more efficient while treating lower volumes. It may therefore be necessary to put an intermediate plant which will additionally sort sorting refusals containing specialty plastics.
- In order to increase waste volumes, there could be long-distance transport to reach the recycling plant.

Indeed, **feedstock volumes** is an issue as chemical recyclers are looking for a specific type of waste, meeting criteria such **as concentration in the targeted polymers**.

Feedstock type

POINTS OF AGREEMENT BETWEEN EXPERTS

Chemical and physico-chemical recycling technologies give more or less promising results depending on the feedstock that they treat. Indeed, most of the experts agree on the fact that**, to target a specific application, a suitable match between a specific process and a specific polymer is more likely to give adequate results.** Thus, depending on the polymers at hand, the chemical and physico-chemical recycling technology should be adapted.

Hence, knowing the exact composition of the feedstock is essential to evaluate what type of technology could be used, as no technology can treat all types of input. Additionally, some products cannot be mechanically recycled, such as multi-layered products, or printed and colored packaging, which means **there is a need for chemical and physico-chemical recycling technologies to be tolerant towards these products**. The case is similar for non-carbonaceous polymers for which depolymerization might result technically less challenging than incineration.

Box 2: Specific examples shared by some experts on feedstock type

The following examples have been tackled by some experts:
- A stream of **PET** would give better results through a **depolymerization** reaction,
- A **PS** stream would be suited for **dissolution**. A more **contaminated** stream of PS could be treated through **high temperature** - catalytic or not – pyrolysis,
- A **polyolefin mix** will be better treated by **liquefaction** or **gasification**,
- **PE/PP flexible multilayer packaging**, which cannot currently be mechanically recycled, is a good feedstock for **pyrolysis** followed by **steam cracking**. Some experts agree on the fact that pyrolysis would however represent a small volume when compared to the steam cracker total capacity in Europe. Having such a low amount of recycled content in products could represent an issue when trying to sell the recycled material.

Thus, having a **homogeneous feedstock** is key in being able to feed a technology and meet the desired application characteristics. Yet, its **purity** might also be an issue as to the intended output quality.

Purity of the feedstock

POINTS OF AGREEMENT BETWEEN EXPERTS

A main well-known constraint of the chemical and physico-chemical recycling technologies lies in the purity of the feedstock. Indeed, most experts agree that **the prerequisite condition for a successful recycling process is the access to a feedstock with sufficient volumes and quality**. The recycler will then be influenced by the latter. Thus, the building of an entire value chain is key.

Indeed, depending on the feedstock contamination level, it can be recycled either via **mechanical recycling technologies** or through **chemical processes**. Contaminated plastics would have to be very well sorted and washed for the feedstock to be eligible for mechanical recycling. Not implementing these throughout steps would raise concerns on the quality of the recyclates that would be produced. They however come with non-negligeable environmental impacts.

There are moreover consequent risks to be taken into account when recycling a contaminated stream. Firstly, the **economic viability is key.** A process that is efficient at pilot or demonstration scale might not be efficient at industrial scale. From an economic point of view, it might not make sense to process mixed and contaminated plastic waste if multiple costly purification steps are required.

Then, **the desired output has to be taken into account.** The type of output the recycler is aiming for should be adapted to the feedstock it can access, and the potential impurities incorporated in it.

Finally, treating contaminated plastics could lead to **corrosion of the equipment**, especially when halogenated compounds are present within the feedstock. Subsequently, either halogenated compounds should be removed before entering the recycling process or the unit should have been purposely built for treating waste containing these additives. The presence of halogenated compounds only represents an issue when the operating temperature is not high enough. In this case, options to treat contaminated waste are either gasification or incineration.

Box 3: Specific examples shared by some experts on feedstock purity

The following examples on purity requirements by technology type have been tackled by some experts:

- Thermal treatment conversion processes are suitable to handle plastics, even if they are **mixed with other materials**, such as biomass for instance. However high levels of PVC in a feedstock dedicated to gasification would require minimizing chlorine at less than 10%,
- Dissolution, if applied to a PS feedstock, would typically require a **minimum of 90-95%** of PS in the feedstock,
- Depolymerization, when used on PET feedstock, would require **a minimum of 85% of PET**, except for enzymatic depolymerization. Indeed, enzymes are more selective than chemical catalysts. Even when treating mixed materials, they demonstrate a high selectivity and target a specific polymer. According to an expert, **enzymatic depolymerization could process about 80% of PET and 20% of impurities**. This would be an advantage when recycling textiles, for instance, as enzymes will be able to target PET despite the presence of multiple other materials, such as cotton or metal. However, this technology still requires prior removal of contaminating substances, due to CAPEX considerations, and to ensure that the recycled polymers will meet the technical requirements,
- **Enzymatic processes** can be highly selective in terms of feedstock composition. In the case of PET, these processes need a preparation step to turn PET from the crystallized to the amorphous form, as enzymes react to amorphous PET. This would not be required for solvolysis processes that do not involve the use of enzymes,
- Technologies such as plasma-based gasifiers can be used to treat **refractory waste**.

Moreover, it should be considered that buyers of specialty polymers use these materials because their **properties are superior to those of other plastics**. In the case of PMMA, buyers are looking for transparency and optical quality. In some cases, such high purity is not achievable through recycling processes or requires high energy consumption. These factors could represent a hindrance for chemical and physico-chemical recycling.

Thus, depending on the **level of impurities the feedstock contains**, in depth pre-processing might be needed to ensure it meets the technology requirements.

Pre-treatment and preparation of the feedstock

POINTS OF AGREEMENT BETWEEN EXPERTS

Numerous start-ups claim that their process does not require feedstock preparation (or limited pre-treatment). However, the experts agreed on the fact that **feedstock has to be prepared and impurities have to be removed**, for economic and quality reasons. The alternative would be to undergo a series of purification steps after the chemical reaction, which is likely to be more costly and may have a higher impact from an LCA perspective.

Once again, the pre-treatment steps highly depend on the chemical and physico-chemical recycling technology chosen.

The first pre-treatment step usually needed consists in **pre-sorting**. Indeed, as mentioned previously, depolymerization and purification processes require a high concentration of the targeted polymer. Consequently, upstream value chain players are entailed to **previously sort feedstocks by resin.**

Afterwards, chemical and physico-chemical recycling technologies would require the **removal of contraindicated contaminants**. The selection of the appropriate preparation steps highly depends on the initial composition of the waste and the recycling technology to be used afterwards. This implies that **better feedstock characterization is needed** to determine which components could be a burden to the selected recycling technology.

Preparation steps may involve **size reduction** (such as crushing), sometimes **washing**, **cleaning**, and low temperature treatment or adsorption to remove halides[344] from the feedstock.

When evaluating the need for feedstock preparation steps, **geography** should also be considered. Some countries have already been putting in place programs for improving plastics' collection, enhanced sorting or the separation of bags for the collection of hard to recycle waste. This aspect has an impact on feedstock's quality.

Several players in the waste management and mechanical recycling industries already own **sorting equipment**. Many chemical and physico-chemical recycling technology developers have either invested in their own sorting equipment or have already created partnerships with companies that do. The most appropriate actor to carry out these steps depends on the type of preparation required and the desired target products. In general, from a logistics and regulatory perspective, it is **often preferable to conduct feedstock preparation phases on the waste site.** Some chemical recyclers who use dissolution or solvolysis, usually carry out additional sorting and pre-treatment of waste on their own site to make sure the feedstock meets their specific requirements.

Box 4: Specific examples shared by some experts on feedstock contaminants removal

The following examples on feedstock contaminants removal have been tackled by some experts:

- **Solvolysis** has the advantage of allowing for specific separation of a targeted polymer, as long as the contaminants are not impacted the same way as the polymer. In theory they could thus be removed.
- As for **pyrolysis**, removal or separation of contaminants is necessary when these compounds would lead to an undesired output composition. For instance, the presence of aromatics in the feedstock could lead to high level of aromatics in the output, which is unwanted in a cracker feedstock. Even if higher feedstock flexibility could be allowed in the case the process used is catalytic or high temperature pyrolysis, pre-treatment of feedstock is systematically necessary to remove contaminants such as Cl, Br, etc.
- To an expert's mind, **dissolution** could also be considered as a pre-treatment for both mechanical and chemical and physico-chemical recycling and could be used to make the waste more suited for a specific recycling technology.

[344] Chemical compound consisting of a bond between a halogen atom and a less electronic atom (of the general formula X = F, Cl, Br or I)

Thus, the different pre-treatment applied to the feedstock will consequently affect the **output and its quality**.

Outputs

POINTS OF AGREEMENT BETWEEN EXPERTS

The **pre-treatment steps and the level of residual contaminants** are key factors in the yield and quality of the output obtained. Indeed, the output can usually be produced in different grades: the monomer grade and the chemical grade. The **presence of impurities in the output could affect the molecular weight** and the **properties of the polymer** and consequently highly impact the final application.

The outputs produced are also dependent on the **operating conditions** (e.g., temperature, use of a catalyst).

Box 5: Specific examples shared by some experts on the output produced

According to an expert, more forgiving pyrolysis technologies, which are not producing steam cracking feedstock, are a **preferable solution** than solely focusing on naphtha production. Indeed, they entail less restrictions on the initial feedstock composition, as the main issues could be solved either via a catalytic step or through pyrolysis and specific separation conditions. Thus, the output produced would be more homogenous and less sensitive to impurities and contaminants. This product **could afterwards be mixed with the steam crackers' output**. These technologies would avoid too stringent specifications on the feedstock (which are necessary in order to produce a cracker's feed). Indeed, these specifications usually are similar to those of mechanical recycling, which should be preferred to pyrolysis in an environmental point of view.

An expert believes that efficiency and yields of pyrolysis oils processed into a cracker are completely different from those of naphtha. A key parameter to avoid variability is **the homogeneity of the waste** feedstock as upgrading of the final product is more troublesome. A cracker could theoretically contain from 1 to 10% of pyrolysis oil. This would require the use of a mass balance approach.

An example mentioned regarding operating conditions was the maximization of the **production of monomers**, in the case of pyrolysis using **high temperature**. The addition of a catalyst to a high temperature pyrolysis process will generally produce a high concentration of aromatics mixed with olefins. Hence, the higher the operating temperature is, **the more the product will resemble the steam cracker output.**
Similarly, in enzymatic depolymerization, factors such as **temperature range, solubility and concentration effect or the presence of organic and metal inhibitors**, could have an impact on enzymes' activity and thus on the final yield of the reaction.

Output conversion

POINTS OF AGREEMENT BETWEEN EXPERTS

Outputs of chemical and physico-chemical recycling processes might need **further processing**, depending on the requirements for the final product. Indeed, impurities can represent an issue for downstream applications, especially if a high-quality material is required. Yet, it seems the easiest way to deal with impurities would be to remove them during upstream steps. Otherwise, downstream steps can include separation of gases, distillation, selective aromatics removal by distillation or adsorption in pyrolysis' case. In many cases, existing facilities could be adapted so that they could carry out downstream steps.

To avoid these steps, there **may be a need adjust operating conditions**, either via the use of a catalyst that would steer the output composition towards the targeted products, or by applying specific temperature and pressure conditions.

Another aspect to consider before converting the output is its **chemical composition**.

Box 6: Specific examples shared by some experts on the output conversion

Adjusting the operating conditions in pyrolysis' case could mean using high temperature that would maximize the production of monomers. These techniques could avoid going through a steam cracker, as **the composition of the final oil would be similar to a cracker's output.**

In the case of pyrolysis, the oil produced needs to undergo several transformation steps before reinterring a virgin value chain. Indeed, to an expert's opinion, the **output of standard pyrolysis is not suited as steam cracker feedstock**. Any substances other than carbon and hydrogen can be detrimental to the equipment or the output through corrosion, unexpected reactions, and catalyst poisoning. As an example, unsaturated compounds are not allowed in crackers and, on the other hand, having a pyrolysis oil containing a wide range of hydrocarbons is not optimal. Hence, there is a need to ensure that the **chemical composition of oils**, including chains length, **matches the steam cracker requirements**. Usually, these requirements include high content in olefins, which means an initial feedstock rich in polyolefins and the previous removal of chlorine and bromine. A way to improve the quality of the pyrolysis oil would be through a series of intermediate refining steps.

Operating risks

POINTS OF AGREEMENT BETWEEN EXPERTS

Handling hydrocarbons involves a series of risks. Developers have to be cautious enough to take all possible risks into account and adopt preventive measures.

Indeed, the variability of the feedstock mentioned earlier leads consequently to variability in operations. The more the plastic is contaminated, the more **sanitary risks** are involved in its treatment. This risk would be affected by whether the pretreatment of waste is carried out on the recycling site or not. Moreover, unwanted materials in the feedstock (e.g., undesired polymer, glass, metal, or stone) would lead to the disruption of the process, which would have to be **continuously adapted** if the feedstock composition changes from batch to batch. This might be a source of inefficiency in operations.

Another major risk of thermal treatments lies in the **volume of the produced gas and the storage of flammable materials**. Safety precautions should be taken to avoid any incident.

Treatment of wastewater and disposal of by-products to avoid soil contamination should be implemented to avoid any **pollution of the surrounding environment**. The developers should also be prepared to manage unforeseen emissions from hazardous gases and liquids.

The way all of these risks are managed depends on the materials and the technology used. Hazard and Operability Studies (HAZOPs) are required throughout different steps of the value chain.

Box 7: Specific points raised by some experts on operating risks

One expert believed that there is **often a fear of chemical and physico-chemical recycling processes being polluting or toxic from a consumer perspective**. However, it should be reminded that these plants are regulated under the same industrial directives as other processes (the Industrial Emissions Directive) and thus mitigation measures have to be implemented to comply with the regulation.

The presence of **odors and aromatics in pyrolysis oils** could also represent a risk in the utilization of this oil. The composition of the oil has to be monitored closely and steered towards an acceptable composition.

Technology readiness level

POINTS OF AGREEMENT BETWEEN EXPERTS

Most of the experts agree on the limitations of the TRL indicator. Indeed, a **specific TRL should not be generalized to a family of technologies**, as there are significant differences from one technology developer to another. The TRL should be assessed for each technology. Moreover, the **TRL should not necessarily be linked to capacity**. For solvolysis processes, the capacity required to achieve commercial scale will be much lower than that for gasification. Finally, it would be **more appropriate to consider the maturity of the technology**, which includes TRL, but also the size and number of units operated by a technology developer.

The experts evaluate the TRL of the different technologies, as represented on Figure 22 below. These figures are given as an **indication**. They have been **estimated by some experts** and thus **are not necessarily totally aligned with other studies**. For informative and comparability purposes, they have been compared with Closed Loop's Partners' indications. The ranges indicated below depend on each technology.

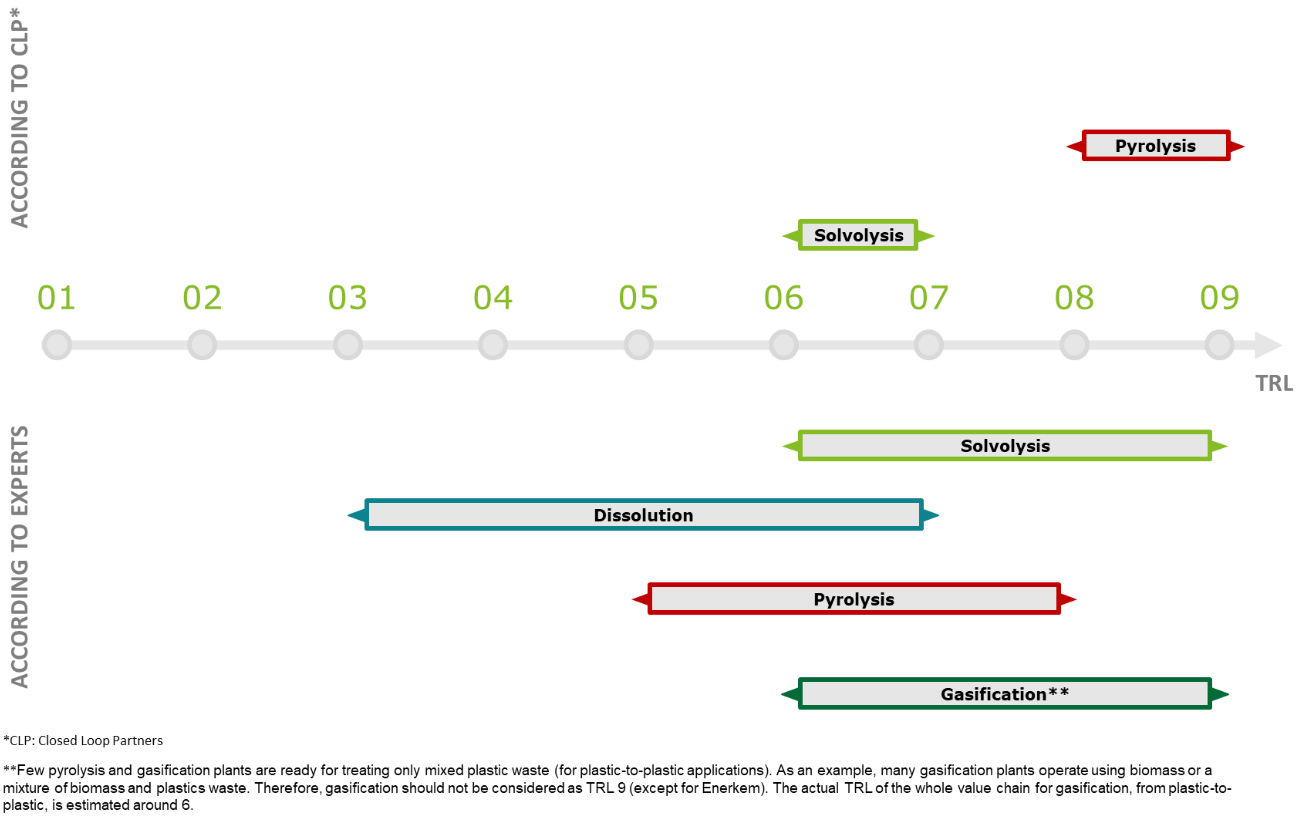


Figure 18: Evaluation of chemical and physico-chemical recycling technologies' TRL by some experts (RECORD, 2022)

The experts also evaluate the TRL of the chemical and physico-chemical recycling of different polymers, as represented on Figure 19.

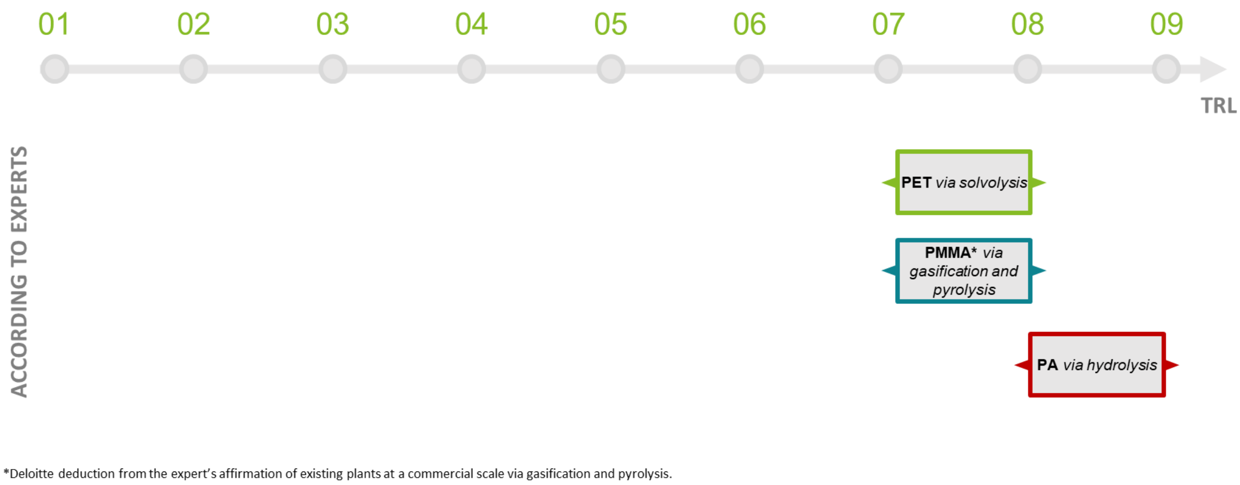


Figure 19: Evaluation of the chemical and physico-chemical recycling technologies' TRL depending on the treated polymer by some experts (RECORD, 2022)

Box 8: Specific examples raised by some experts on technology development by polymer

The following examples on the chemical recycling of specific polymers have been tackled by some experts:

- There are currently numerous **PET** chemical recycling technologies operated at a **demonstration scale**. Examples include Carbios, Loop Industries, Ioniqa. JEPLAN, Eastman and Polygenta Technologies are at commercial scale.
- Commercial scale plants for the recycling of **PMMA** via gasification and pyrolysis already exist.
- Aquafil already has a **PA** commercial plant and has been selling its recycled products for a few years.

Perspectives of evolution

POINTS OF AGREEMENT BETWEEN EXPERTS

The experts anticipated the evolution of chemical and physico-chemical recycling technologies to be fueled or, at the opposite, constrained by different factors such as regulations, eco-design trends, collection models improvements and sorting or recycling progress.

Indeed, on the **regulatory** side, future legislations on plastics will impact the composition of waste and its available volumes. This trend can already be observed nowadays. Indeed, due to China ban on waste imports, some of the waste that used to be exported now remains in the EU.
It is also likely that **sorting and mechanical recycling technologies will improve** in the future. This progress is expected to impact the volumes of available waste for chemical recyclers.

Moreover, **eco-design efforts** are currently being made to facilitate recycling of plastic products put on the market. The strong push from the packaging industry (flexible and rigid) to go towards PE, PP, and PET, will increase the share of these materials found in waste. The industry is already evolving to ensure better sorting and recycling of materials put on the market. Thus, it is increasingly **moving away from multi-layered multi-material packaging**. Having access to better quality feedstocks will not only favor mechanical recyclers, but it will also be an advantage for chemical recyclers. The economic viability of their processes will indeed be improved by reducing the need for additional sorting and purification.

Additionally, to this temporal variability, experts find it very likely that a geographical variability will emerge. Indeed, due to the **geographical variability** of the feedstock mentioned earlier, it can be expected that, in the future, **aggregation models** depending on existing collection infrastructure, which also depends on location, will be developed.

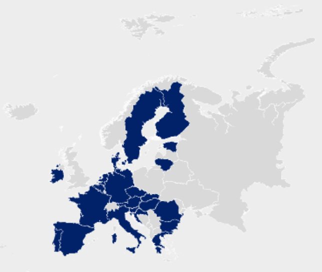
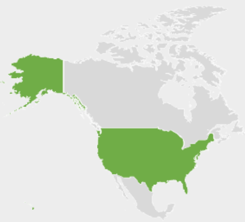
b. What is the current and future regulatory context in the USA, EU, and Japan?

Introduction (based on the literature review)
It can be observed that the regulatory framework on chemical and physico-chemical recycling differs between the considered geographical areas. Indeed, in the USA, as of January 2022, there are **no federal laws** that specifically refer to chemical and physico-chemical recycling and **bills are passed on a state-level,** either to promote or hinder chemical recycling technologies. As for food-grade applications, the FDA has already issued a non-objection on the **suitability of chemical recycling processes for producing post-consumer recycled plastic** to be used in the manufacturing of food-contact articles for several companies. Several states in the US are also considering implementing recycled contents requirements. There is however **no mention if a mass balance approach would be accepted**. Some states have also requalified the waste status, using terminologies such as "non-solid waste", "recovered materials" or "raw materials for manufacturing".

In the European Union, although chemical and physico-chemical recycling seems in some cases to fall under the legal definition of "recycling" on a European level (excluding plastic-to-fuel applications), no regulations nor amendments specific to these technologies have been published yet. Waste management legislation includes directives related to the **classification of waste, to trans-boundary transfers of waste, and to transitions from waste to product status**. Moreover, **food-contact regulation only applies to mechanical recycling** technologies and there are uncertainties about whether or not chemical and physico-chemical recycling technologies' outputs could be certified as food-grade materials. Moreover, **no legislation nor harmonized standard regulating the mass balance** approach has yet been approved on a European level.

As for Japanese regulations, there are a lack of information and **uncertainties on the topics' studied and regulations on the subject of mass balance**, chemical and physico-chemical recycling facilities, the qualification of a "recycled state", the end of waste status. It has to be noted that several chemically recycled products have already been approved for food-contact applications (chemically recycled PET from JEPLAN technology for example).

New legislations and amendments of current regulations expected
POINTS OF AGREEMENT BETWEEN EXPERTS
In the regions of interest, **regulations are not yet operational on the subject of chemical and physico-chemical recycling**. Indeed, they have usually been developed for mechanical recycling and are **not yet up to date on chemical and physico-chemical recycling technologies.** There are also discrepancies between the different regions.
Thus, a clear regulatory framework is needed, with harmonized definitions (if possible). Indeed, strong regulations and financial incentives for chemical and physico-chemical recycling routes will be necessary to support the industry. It has to be noted that the lack of clear regulations presents a significant risk for technology developers.

Box 9: Specific examples for the EU	*Box 10: Specific examples for the USA*	*Box 11: Specific examples for Japan*
		
Within the EU, legislation on chemical and physico-chemical recycling is likely to consist of an **adaptation of existing regulations** rather than on the development of new rules. Regulations and Directives that might be subject to	As for the USA, fourteen states have passed a legislation defining advanced (chemical) recycling technologies as manufacturing technologies. They are therefore not	In Japan, household waste sorting is much more advanced than in the EU and the USA. Already 20 years ago, consumers were required to operate a thorough pre-sorting of their waste. In this condition, it is much easier to develop recycling

modification are represented on Figure 20 below. Regarding the REACH regulation, the experts believe that mechanical recycling products are exempted from this legislation. The exemption was made at a time when this type of recycling was dominating. As for chemical and physico-chemical recycling, the **REACH regulation only exempts the recycled monomers that comply with very strict criteria**. These criteria require for the virgin material to be already REACH registered, for the recycling operation to have been done in Europe (or at least the paperwork to have been drafted in the EU), and for a high-quality output product (the toxicity level has to be proven as identical to the virgin one). It has to be noted that certain chemical intermediaries (such as BHET) are currently not REACH registered. According to experts, some **adjustments should be made to the REACH legislation application for chemical and physico-chemical recycling**, especially due to the high costs associated with the registration process. Moreover, having a product that is REACH registered does not guarantee it has passed the end of waste regulation requirements. A **connection should therefore be made between the End-of-Waste and the REACH regulations**. Moreover, Zero Waste Europe is building a case for making a distinction between chemical recycling and recovery from a regulatory perspective. For instance, pre-treatment processes should not be considered as recycling but as recovery.	regulated as waste disposal. As a consequence, this regulation excludes the feedstock used for these processes from the definition of solid waste. Two states (Maryland and Oregon) have taken the opposite path by proposing a **ban on chemical recycling**, which was however defeated. The American Chemistry Council has advanced a proposal to **define terms** such as advanced recycling processes, products, feedstocks, or mass balance, on a federal rather than on a state level, as part of the "5 Actions for Sustainable Change"[345]. **The lack of definitions currently makes the industry vulnerable**. As an example, the Environmental Protection Agency has put forward an advanced notice of proposed rulemaking to perhaps classify the chemical recycling technologies as solid waste incineration under the Clean Air Act[346].	technologies. This shows that **easy implementations could be done from a legislative point of view**. As an example, colored PET bottles could be prohibited to facilitate recycling given that the product's color only has a marketing value but has no value for consumers.

[345] *5 actions for sustainable change,* American Chemistry Council, Action #2
[346] [U.S. EPA weighs regulation of chemical recycling | Reuters]

Figure 20: European regulations and directives expected to be reviewed according to some experts (RECORD, 2022)

<u>Mass balance approach</u>

POINTS OF AGREEMENT BETWEEN EXPERTS

The experts all share certain perspectives, notably the fact that **the lack of regulation on mass balance represents an issue** for big brands' credibility and for the value their products delivered to customers. Whenever there is a disconnection between the input and the output of the process (for instance pyrolysis oil obtained on one site but turned into products at a different site), traceability becomes a challenge. To their minds, **improved physical traceability methods would be preferable to a mass balance approach**. As there are no such methodologies currently, the use of mass balance is debatable. However, if mass balance is necessary to develop chemical recycling, then its **application has to be regulated** and **made understandable for customers**. Moreover, the implementation of a mass balance approach should only be considered as a **transition phase**, given this is the main available solution today.

The experts also agree on the fact that the mass balance approach **can be misleading and confuse consumers** when it comes to communication claims. Clear communication is needed to avoid creating disappointment among customers regarding the recycled content of the material they purchase.

<u>Box 12</u>: Specific examples raised by some experts on mass balance

Caution should be applied when **treating output of pyrolysis processes**. Indeed, in such processes, approximately 70% of the output is liquid. Of the liquid portion, 70% will consist in a naphtha-like material which, when fed into a stream cracker, achieves a yield of approximately 35% of ethylene and 17% propylene. As a result, the process only truly recycles one quarter (by weight) of the original plastic waste into plastic. Hence, it is clear that **mass balance approach could open the door to confusion,** as companies could claim that significant recycled materials are integrated in the value chain and a high premium price could be considered for the end-product.

Finally, accepting to transfer mass balance certificates from the EU to countries outside of the EU would go against the efforts made to create a circular economy. **Circular economy should be localized**, exporting products would mean taking materials to another country which perhaps has not made the same efforts to achieve circularity.

It also has to be noted that the use of mass balance approach may not be necessary for the chemical recycling of all polymers. Indeed, for some specialty polymers, small commercial chemical recycling facilities already exist and produce recycled products. In this context, the mass balance approach is not needed.

It has to be noted that the share of "recycled" material should be allocated to all end-products and not only to the production of new polymers. This approach is more appropriate, although less favorable for technology providers.

DISAGREEMENTS BETWEEN EXPERTS ON THE TOPIC OF MASS BALANCE

The experts express divergent views on the subject. The different arguments are presented on Table 24 below.

Arguments in favor of a mass balance approach	Arguments against a mass balance approach
• One expert believes that the use of a mass balance approach is new for chemical recycling but can be replicated on the basis of what has **already been applied across various other industries** (such as cocoa, sugar, etc.). As an example, a customer purchasing its energy from renewable sources will inevitably consume a portion of electrons from non-renewable sources that is present in the grid. Many American manufacturers are already using the ISCC standard to certify their products (e.g., ice-cream tubs, cups, etc.). • In order to ensure that the chemical recycling industry will grow, there is a need to be slightly **more flexible on the use of the mass balance approach** and focus on the benefits they can generate. Indeed, credits transfer is acceptable within an integrated company. • An expert believes that **regulation** on mass balance has to be **flexible** to boost the development of chemical recycling technologies.	• Other experts consider that accepting mass balance to support certain technologies would **create a disadvantage for other new technologies** that could be more promising but that would also require additional investments. • The use of mass balance in the chemical recycling industry **may not be compared with its use into other sectors**. When it comes to renewable energy, the electrons cannot be stored. Therefore, the number of electrons generated from renewable sources has to be measured at the moment it enters the system or, in other words, before it gets lost in the energy flow. That is why mass balance becomes an appropriate measurement tool for this sector. Plastic does not have the same characteristics and it cannot be compared to energy. • Mass balance has proven **not to work well for certain industries** (such as palm oil for instance). • Some experts insist on the need for a regulation **limiting mass balance applications**.

Table 24: Arguments in favor or against mass balance approach (RECORD, 2022)

Food grade applications

POINTS OF AGREEMENT BETWEEN EXPERTS

As previously mentioned, legislation varies in the different regions, specific examples are presented on the different geographies in *Box 13* below. The regulation in the USA is more open than in the EU towards new chemical and physico-chemical recycling technologies. Indeed, in Europe, for resins to be approved for food-contact applications, there is a need **to prove that materials do not contain any toxins**. This process can be time consuming. In the USA, there is a need for the FDA to better understand what chemical and physico-chemical recycling is.

Box 13: Specific examples raised by some experts on food grade applications

In the USA, PureCycle recently announced they will be **bringing to market food grade r-PP**. In Europe, it is very complex to obtain an approval from EFSA to allow the use of chemically recycled resin in food applications. One participant provided the example of its organization having identified **specific feedstocks** that could be used for dissolution and would allow to produce high quality recyclates. These materials have been passing compatibility tests for food-grade materials.

An expert believes that **dissolution could also be considered as a pre-treatment** for both mechanical and chemical recycling and could be used to make the waste more suited for a specific recycling technology. Therefore, the **output of dissolution would not be considered as a food-grade material** given it will require further treatment and purification.

Legacy substances

POINTS OF AGREEMENT BETWEEN EXPERTS

Legacy substances are additives put on purpose in the virgin material for it to feature some specific properties. There are different types of legacy substances such as flame retardants, plasticizers, lubricants, pigments, etc.

Legacy substances can be **contained within products with long lifecycles**. Changing regulations imply that substances that were authorized in products 10 years ago might be prohibited today. When products containing these substances reach their end-of-life, lack of traceability could make it challenging to identify the exact composition of this waste, which **additives were used** during the manufacturing of the product and when it was put on the market. Yet, from the moment these substances are prohibited on the market, mechanical recycling is no longer an option as this technology cannot remove them. Chemical and physico-chemical recycling technologies can be useful in this situation. The little amount of research conducted on the topic shows there is a lack of clarity on how to deal with these substances both from a technological and a regulatory perspective. From a business perspective, legacy substances affect chemical recyclers in three different ways:

- Firstly, the recyclers are affected in the **selection of feedstocks.** Indeed, the legacy substances could both stimulate or hinder the chemical and physico-chemical recycling market.
- Then, regardless of the process, there is also a concern of **where the legacy substances end up in the outputs produced**.
- Else, chemical and physico-chemical recycling processes would also have to be **able to treat legacy substances.** Indeed, challenges encountered on legacy substances depend on the processes that is being used.

Finally, the **legacy substances could hinder the catalysts' activity.** It is thus important to better understand these substances in order to be able to switch to a non-catalytic process when necessary.

Box 14: Specific examples raised by some experts on legacy substances

The legacy substances could stimulate the chemical and physico-chemical recycling market, especially in **selecting the feedstock**. As an example, **EPS waste containing HBCD** is currently sent to incineration and is subject to a gate-fee. **Selective dissolution** of EPS containing HBCD could therefore benefit from an economic value due to the presence of a gate-fee.

An expert believes that, in the case of a **pyrolysis** process, if legacy substances, such as mercury, were to be concentrated within the solid residue burnt for energy recovery, the recycling plant would no longer be carrying out only recycling, it could be considered as an incineration plant as well. It is therefore key to trace how these substances move across the value chain.

According to an expert, for pyrolysis and steam cracking, legacy substances do not really represent an issue as pyrolysis oils undergo purification. When it comes to selective dissolution, it is much harder to **ensure that all substances have been properly handled.**

DISAGREEMENTS BETWEEN EXPERTS ON THE TOPIC OF LEGACY SUBSTANCES

Two experts disagree on the ability of high temperature processes to get rid of all legacy substances.

Departure from the status of waste

Points of agreement between experts

Experts agree on the fact that current regulation is unclear about the end of waste status and this could represent a threat for chemical and physico-chemical recycling technologies.

The steps of the depolymerization process designated in Europe by the status of waste are represented on Figure 21: Status of waste in the chemical recycling value chain and expert's suggestions below.

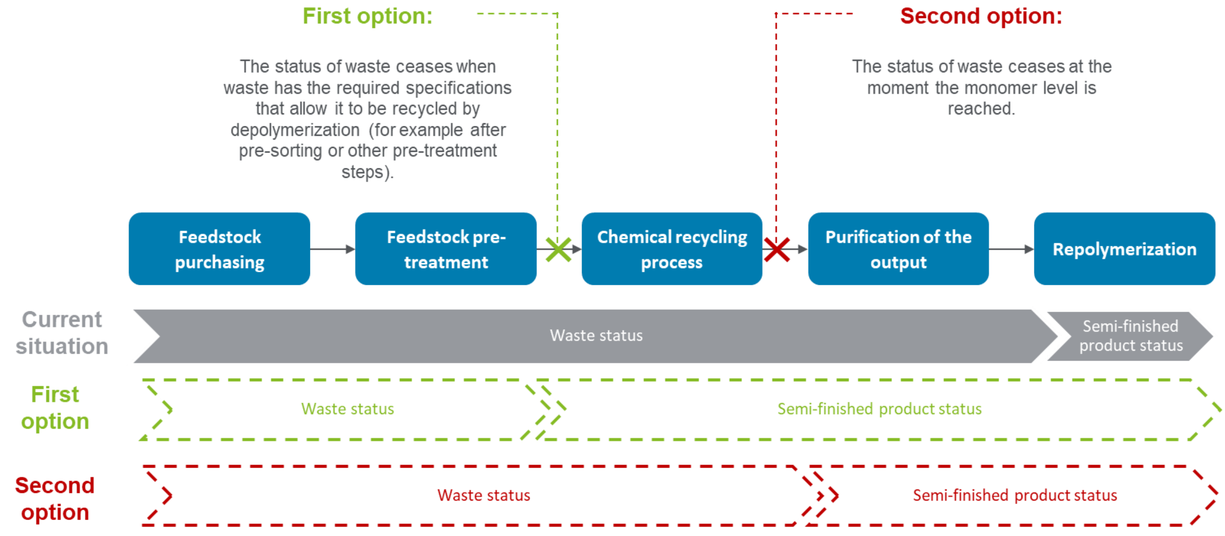


Figure 21: Status of waste in the chemical recycling value chain and expert's suggestions (RECORD, 2022)

<u>Box 15</u>: Specific examples raised by some experts on the departure from the waste status

An expert's suggestions on **new regulation development** to determine with more clarity at which step of the value chain the status of waste ceases is also represented on Figure 21 above.

Another expert considers that the lack of clarity on this subject is **not only generated by the lack of regulation but also from the fact that regulation in the EU is not harmonized across all European countries** and that Member States have the room to pass their own waste regulation.

Qualification of a "recycled state"

Points of agreement between experts

This qualification should differ between post-consumer and post-industrial waste. Most experts agree on the fact that the focus of plastic recycling should be on **post-consumer waste**, and the term "recycled" should only be dedicated to materials that have completed a full cycle within the economy, that is to say post-consumer materials.

During products manufacturing, the waste which is produced at the beginning or at the end of the extrusion step can be used again in the process. Similarly, some companies already shred their post-production waste, such as spare parts, reintegrate the material in their process and then claim that these products have been recycled. In this case, **production waste cannot be qualified as recycling given it is normal practice to either valorize, reprocess, or reuse it**. An additional distinction should be made between easy to recycle post-production or pre-consumption plastics and hard to recycle post-industrial waste, for instance multi-material packaging, which, due to its complexity, could be considered a post-consumption product (proposal from some experts).

For brand-owners, another challenge regarding the "recycled state" of materials is generated by the fact that **many companies wish to integrate recycled materials into their products.**

Moreover, there is a lack of clarity on whether the definition of "recycled" could apply to the output of chemical and physico-chemical recycling. Indeed, most regulations on the "recycling state" at the EU

level were developed for mechanical recycling. The Waste Framework Directive defines “recycling” as the reprocessing of organic material, **excluding energy recovery and fuel applications**. Thus, when it comes to thermochemical processes, **the part of the output that is to be used as fuel should not count as recycled material** but be deducted instead. When it comes to pyrolysis oil or syngas, this output still requires **further downstream steps**, **therefore the product is not considered as a recycled material**. As for gasification, there are already many developers using mixed streams of biomass and mixed plastic waste as feedstock. The syngas obtained from these processes can be transformed into ammonia and CO_2 or hydrocarbons including a naphtha fraction or ethanol and methanol (such as the technology developer Enerkem). When using gasification processes that use both plastics and biomass as input, **it would not necessarily be possible to calculate the exact recycled plastic content** given that it would get mixed with materials originated from biomass. Since regulations similar to the Single-Use Plastics Directive are expected to be enacted in the future for materials other than plastics, **separating the notion of recycled content from recycled plastic content** will become even more relevant.
For other processes, such as solvolysis, this issue does not arise as the end-of-waste criteria is met and because it is unlikely that fuel will be produced from it.

Box 16: Specific examples raised by some experts on the qualification of a recycled state

An expert believes that, in Europe, many mechanical recyclers are not aware of the existence of REACH regulations and requirements for recycled materials.[347] If **regulation is too complex** for chemical recyclers, who are sometimes small players, there is a good chance that these actors will not comply with it. Hence, chemical recyclers may decide to **focus on the recycling of post-production materials instead**, as they usually would not contain legacy substances. In this case, the challenge is that post-production or pre-consumption waste may not be accounted for as recycled content given it has not completed a full lifecycle. This point was not approved nor denied by other experts and represents solely one stakeholder’s point of view.

In the USA, post-consumer and post-industrial waste are differentiated in the same way as the EU.

An expert mentioned the example of the integration of PET recyclates by brands in their final product. Two main issues will arise:

- First of all, **available supplies** of r-PET will be **too limited** compared to demand.
- Then, it should be considered that **some recyclates’ applications are less circular** than others. As an example, transforming PET bottles into textiles reduces the quantity of materials that could be used for recycled bottles applications. Given that PET contained in textiles is more challenging to recover than that in bottles, this increases the risk that the material will not be recovered at its end-of-life.

Thermal depolymerization is recognized in different ways in the USA and in the EU. In the EU, when plastics are recycled, the component that goes to energy recovery would not be accounted for as recycled plastics, whereas in the USA, the definition of recycling includes both streams. Therefore, **when American products are imported into the EU, they create an unfair competition for European recyclers**.

[347] Information about REACH is available on the internet. At French level, recyclers are members of SRP (Syndicat national des Régénérateurs de matières Plastiques). On its website, information about REACH is available http://www.srp-recyclage-plastiques.org/images/pdf-documents/mars-2019/srp-mrp-reach-v-finale-2-05-2019.pdf

c. What are the strengths and weaknesses of the different environmental assessments and their comparisons?

Introduction (based on the literature review)
The bibliography review highlighted that the results of different assessments conducted by technology developers are **often communicated in favor of the chemical and physico-chemical recycling technologies**, that are allegedly **more environmentally friendly** than **virgin production** or other **end of life treatments, but less virtuous than mechanical recycling**. Yet, the different analysis conducted lack transparency on the methodology, hypothesis chosen, and datasets used. Often, only the result of the lifecycle assessments is made public.
Some LCA are also made in the literature but they often rely on technology developer's data, which are, once again, kept private. It is thus arduous to link the main environmental impacts with specific steps of the chemical and physico-chemical recycling process.
Currently different methodologies are used to evaluate the impact of chemical and physico-chemical recycling technologies and they can sometimes encompass negative emissions. Indeed, the **cut-off** approach is assessing the environmental impact from the feedstock (which means that the waste comes without any burden). On the contrary, the **substitution** methodology is applied to treat the double functionality of recycling (waste treatment and new material production). In this case, they consider that the recycling process (e.g., pyrolysis) allows waste to be diverted from incineration or landfilling and thus deduct these associated impacts from the environmental impacts of the recycled polymer (e.g., produced from pyrolysis oil).

Comparison of chemical and physico-chemical recycling technologies with end-of-life and production processes

POINTS OF AGREEMENT BETWEEN EXPERTS

From a methodological point of view, chemical and physico-chemical recycling processes, could be compared to either end of life processes, such as landfilling or incineration, or virgin production processes.
Given that recycling processes are multifunctional processes, the lifecycle analysis could be conducted through **a comparison using a double functional unit**. This means considering the waste treatment function and the material production function of a recycling process, and to then compare the results obtained to a system which would be an adjunction of an end-of-life process and a virgin material production process. This would mean extending the framework of the system considering both functions.
The other option is to **focus solely on one of the two functions** (either waste treatment or material production).

DIVERGENT VIEWS ON THE COMPARISON WITH END-OF-LIFE OR PRODUCTION PROCESSES

The experts had divergent views on this subject, which are presented on Table 25 below.

	Comparison with production processes	Comparison with end-of-life processes	Comparison with both options
Arguments in favor	• Recycling processes lead to the **production of new polymers**.	• The volume of plastics destined to chemical and physico-chemical recycling is limited, which means **there will be a need to cannibalize other waste streams,** such as waste currently sent to energy recovery.	• One expert considers that the objective of the transition to circular models is to **enhance the value of recycling operations** compared to the use of virgin polymer, to **appreciate a change** of end-of-life treatments, and, overall, to acknowledge the environmental impact of the product that is being sold and put on the market. The dynamics of change and the effort put in transitioning from a linear to a circular economy must be valued. In this sense, **both approaches should be used** in the perspective of trying to achieve a circular economy. In fact, the combination of the two approaches is interesting because it **provides a complete overview** on the technology used by considering the double function of the process.
Arguments against	• No arguments were raised against this approach	• Landfilling and incineration are ideally **meant to disappear one day**, which means it is not relevant to compare their end-of-life performances with those of chemical and physico-chemical recycling technologies. • Some studies' methodology consider that pyrolysis allows waste to be diverted from incineration or landfilling and thus **deduct these associated impacts from the environmental impacts of recycled polymer** produced from pyrolysis oil. An expert disagrees with this approach as he/she considered there is a bias.	

Table 25: Arguments on the different assessment comparison (RECORD, 2022)

Comparison of chemical and physico-chemical recycling with mechanical recycling

Points of agreement between experts

Studies analyzing chemical and physico-chemical recycling technologies, especially pyrolysis, sometimes do not make such comparison saying that mechanical and chemical and physico-chemical recycling processes are complementary given they use different types of feedstock.

The experts agree that two main aspects should be considered when comparing environmental impacts of chemical and mechanical recycling.

Firstly, **the environmental impact of pre-treatment and post-treatment processes (including purification)** should be taken into account when evaluating recycling technologies. Pre-treatment and post-treatment processes are rarely accounted for within LCAs of chemical and physico-chemical recycling technologies, although most of the time they are necessary (e.g., turning pyrolysis oil back into polymers).

Then, comparing the LCA results of mechanical and chemical and physico-chemical recycling **is only relevant when the two processes produce the same outputs (with the same quality)**.

Box 17: Specific examples raised by some experts on the comparison with mechanical recycling

An expert pointed out the example of **bottles.** Indeed, they **have considerably shorter life cycles**. This implies that r-PET can undergo more than one recycling loop per year and thus determining the concentration of recycled material compared to virgin material in the waste would be more arduous.

Moreover, it **seems irrelevant to use the number of cycles as a moderating factor** as it is not necessarily interesting to calculate the number of recycling loops a material goes through. At the end-of-life of a recycled product, it will be most probably found in a waste stream amongst a majority of virgin plastics.

DIVERGENT VIEWS ON THE COMPARISON WITH MECHANICAL RECYCLING

The experts disagree on whether the comparison with mechanical recycling is relevant. The main arguments in favor and against are presented in Table 26 below.

Arguments in favor of comparison with mechanical recycling	Arguments against the comparison with mechanical recycling
• Making the comparison is relevant as long as the **quality of the output produced by different recycling technologies is the same**. LCA results are not a determining factor in the choice between recycled and virgin product. The relevant criterion lies in the **properties expected of the polymer**. Mechanical recycling often leads to the loss of properties and quality of polymers which results from mixing different grades of polymers. This aspect must be considered when evaluating the impact of different technologies. A **coefficient should be developed** to allow the comparison of these technologies. Today, Plastics Europe only qualifies one generic grade per polymer. However, ranking quality and properties will be increasingly important in the future. • When it comes to food-grade applications of recycled polymers, **chemical and physico-chemical recycling could become an alternative to mechanical recycling** (as only PET can currently be both mechanically recycled and used for food-grade applications).	• The **type of recycling** to be used is **directly determined** by the nature of the waste, the desired properties of the output, and the recyclates' application. Hence, the comparison between these two forms of recycling has limited relevance. • Regarding EEE or automotive applications, **mechanically recycled materials already perform efficiently**. Thus, it is not necessarily needed to compare mechanical and chemical recycling as the end-product applications will naturally drive the choice of the technology. These technologies are thus complementary and **virgin or chemically recycled material should not be used** when the mechanically recycled material is sufficient and meets the required specifications. • Depending on the market they operate in, mechanical recyclers will not have the same **economic viability.** Indeed, some markets are very accessible for mechanical recycling and others, particularly for food-applications, where it is extremely complicated to be able to address another polymer than PET if we only consider mechanical recycling. For all plastics that are easily accessible to mechanical recyclers, chemical and physico-chemical recycling will struggle to become economically competitive. The economics will thus naturally make the two technologies complementary. • There is no need to compare chemical and mechanical products because they **do not deal with the same feedstocks.** • Comparing a mechanical and a chemical and physico-chemical recycling unit would not be possible due to the **different size of the units** and the **geographical area** on which the feedstock must be collected. For a mechanical recycling unit, there is the need to locally source a specific amount of waste to justify the operations of the unit*. A chemical and physico-

	chemical recycling unit for the same polymer may require **much larger waste quantities as the capacity may be larger than that of mechanical recycling units**. In this sense, capacity factors have an impact on all logistic aspects (transport, energy consumed in transport, etc.). In general, higher volumes of feedstocks are to be sent to a chemical and physico-chemical recycling unit to recover the investment initially made. Additionally, there may come a time when **both processes will compete for the same resource in the collection area**, and it will be easier to fill a small unit (mechanical) than a large one (chemical). Moreover, scattered chemical and physico-chemical recycling units would raise logistic issues and questioning on the quality of the sorting done to divide waste between mechanical and chemical recycling centers. It can be risky to answer environmental questions now that chemical and physico-chemical recycling units are not yet fully mature. • The materials treated by the two processes will tend to diverge more and more. Indeed, mechanical recycling can involve **adding additives** when the product is passed in the extruder. By adding these materials to the mechanically recycled product, the **end-product becomes more complex**. Eventually, chemical and physico-chemical recycling of such products is more challenging.

Table 26: Arguments in favor and against the comparison with mechanical recycling (RECORD, 2022)

* Note: This argument is **not considered relevant by some experts** since **the usage of large units is not necessarily a pattern that will last in the long term** (for instance for pyrolysis processes). There is an ongoing logic of wanting to obtain **moderate size units** so that transports would have a lower impact and feedstock could be more accessible. This is the strategy used by Polyloop, which is approaching selective dissolution using small, distributed units.

Comparison of the different chemical and physico-chemical recycling technologies

POINTS OF AGREEMENT BETWEEN EXPERTS

It is challenging to compare chemical and physico-chemical recycling technologies with one another as there is **no polymer that can be recycled by all technologies**.

> *Box 18: Specific points raised by some experts on the comparison between technologies*
>
> Manufacturers are interested in creating a ranking based on the environmental impact of different processes that produce plastics, whether it is virgin, mechanically or chemically recycled. Such classification needs to be simple and clear, to be **understandable by people who know less about existing technologies**. It will not be possible to clarify the environmental impact of products' content if results are only accessible to specialists.

Comparison of chemically recycled material with virgin material

POINTS OF AGREEMENT BETWEEN EXPERTS

The relevance of this comparison highly depends on the **nature of the targeted polymer**. The comparison might be uneven for commodity polymers compared to specialty polymers. **Specific examples have been tackled by experts and listed in Box 19** below**.**

Again, the **end-product application should be considered**. Indeed, producing food-grade material through chemical and physico-chemical recycling could be environmentally impactful, due to the number of additional steps necessary to ensure its quality. It should thus be ensured that CO_2 emissions related to the production of a food-grade chemically recycled polymer are not higher than their virgin counterpart.

Box 19: Specific examples raised by some experts on the comparison with virgin polymers

In **specialty performance polymers' case**, there are **significant gains in terms of GHG emission reduction** for chemically recycled PMMA, PA6, and any technical or specialty performance polymer compared to their virgin counterpart. Some studies on PMMA have recorded a reduction of 70% GHG emissions of the produced chemically recycled monomer compared to the virgin monomer (without accounting for avoided emissions, based solely on the comparison of energy consumption and CO_2 emissions of recycling vs. virgin production). Indeed, virgin specialty polymers consume a lot of energy to be produced. For example, PA6 has an environmental footprint of at least 7 kg of CO_2/kg of polymer[348]. Most of these emissions are generated while adding nitrogen into the molecule during the production process. As a consequence, chemical and physico-chemical recycling processes have a limited environmental footprint compared to the production of the virgin material.
Another consideration to make about specialty polymers is **that lower volumes are produced** than for commodity polymers. This means that collecting these materials at their end-of-life can be challenging. In order to increase waste volumes, there could be long-distance transport to reach the recycling plant.
Finally, it should be considered that buyers of specialty polymers use these materials because their **properties are superior to those of other plastics**. In the case of PMMA, buyers are looking for transparency and optical quality. In some cases, such high purity is not achievable through recycling processes or requires high energy consumption. These factors could represent a hindrance for chemical and physico-chemical recycling.

The reasoning is different on **commodity polymers**. Indeed, when it comes to polyolefins, it can be challenging to show positive environmental results as energy consumption and CO_2 emissions remain low during manufacturing of virgin fossil-based resins. However, **GHG emissions are not the only environmental indicator that should be considered** in an environmental assessment. Even if GHG emissions indicators may detect a poor environmental performance, other sustainability indicators may still support the relevance of using a certain chemical and physico-chemical recycling process.

Some studies consider that **pyrolysis allows waste to be diverted from incineration or landfilling** and thus deduct these associated impacts from the environmental impacts of recycled polymer produced from pyrolysis oil. An expert disagrees with this approach as considered there is a **bias.**

Cut-off and substitution approaches

POINTS OF AGREEMENT BETWEEN EXPERTS

There are two main ways to assess the environmental impact of technologies: the "cut-off" approach and the "substitution" methodology. The **cut-off** approach is relying on the hypothesis that, from the moment a material becomes waste, it has no environmental impact attached to it. This means that, in this approach, waste intended for recycling is not attributed the benefits of the treatment channels that are avoided (such as incineration for instance). Collection, logistics, and other treatments' environmental impacts are allocated to the product using the secondary raw material. On the contrary, a **substitution** methodology is applied to treat the multifunctionality of recycling, which are waste treatment and new material production functions. This approach integrates emissions that have been avoided by preventing conventional end-of-life treatment processes, such as landfill or energy recovery.

DIVERGENT VIEWS ON THE METHODOLOGICAL APPROACHES

Experts disagree on the relevance of these methodologies. Their main arguments and concerns are presented in Table 27 below.

[348] Data from Plastics Europe

	Cut-off approach	Substitution approach
Arguments in favor	• Several experts argue that cut-off is a **better approach** than substitution because it allows to restart the count of emissions from the moment the product has reached its end of life.	• Some experts view substitution approaches as justifiable. Indeed, if a given amount of waste had not been chemically recycled, it would still have been **treated through other end-of-life processes**. • From a theoretical point of view, the ability of a recycling process to **produce an output that can be reused in plastics' manufacturing** has to be considered into the LCA equation. From this perspective, the substitution approach is methodologically required and can favor the sector's transition towards a more circular economy. • It is inaccurate to assume that all waste would be incinerated without energy recovery if it was not recycled. Some of it may be incinerated with energy recovery. This is why, **it would be relevant to compare the environmental impacts of recycling with that of incineration with energy recovery** to better represent the reality.
Arguments against	• No arguments were raised against the cut-off approach	Other experts disagree with this perspective and suggested there are three reasons for which substitution approaches should be discarded: • When it comes to the understanding and accounting for environmental impacts, **considering avoided emissions biases the system**. As an example, if different plastics of the same bale undergo different methods of recycling or incineration, how would CO_2 emissions be compatibilized and which ones should be deducted? • As **for future perspectives,** incineration and landfilling are not virtuous solutions and these end-of-life pathways should be limited. It is therefore not relevant to prove that a technology has environmental benefits if it is compared to inefficient and non-environmentally friendly incineration processes. • Additionally, this notion **leads to a delay in the implementation of better technologies** and can become a way finding justifications to maintain/implement solutions that are not the most efficient ones available. In fact, such perspective can lead to a misinterpretation of LCA results as new recycling technologies would be selected only because they are slightly better than incineration (whilst overall they might still perform less efficiently than other recycling solutions).

Table 27: Arguments on the different assessment methodologies raised by experts (RECORD, 2022)

Pre-treatment and purification impacts

POINTS OF AGREEMENT BETWEEN EXPERTS

Sorting is not the first step which has an impact on the total environmental performance of a recycling process yet is often deemed as such. Today, recycling challenges are linked to the **design of the initial product**. The design of the product may lead to higher complexity and additional challenges within the sorting and pre-treatment phases. As a consequence, the whole recycling process will end-up having a

higher overall environmental footprint. Hence, **recycling constraints should be brought up to the design phase.**
Using **different polymers in the same product** is not necessarily an obstacle to chemical and physico-chemical recycling and its environmental performance, as long as **they can be easily separated during sorting or pre-treatment phases** (e.g., separation of some polymers based on their density,…).
Considering current feedstocks, preparation steps are needed both for mechanical and chemical and physico-chemical recycling. These steps have to be considered as they have an environmental impact. Indeed, **pre-treatment steps and post-treatments steps are poorly defined in current LCAs**.

Box 20: Specific examples raised by some experts on pre-treatment and purification

An expert agrees that, in the automotive sector, a rear light made of PMMA, ABS, PC can be easily recycled. However, the recycling of a front light containing PP shells with 40% talc glued with polycarbonate, would be more challenging, and the product design should thus be revised.

One expert believes that, in some industries, such as the automotive one, the plastics that are collected today were put on the market fifteen years ago. The **new eco-design regulations that are put in place today will ease recycling processes** in twenty years' time.

Environmental performance assessment improvements

POINTS OF AGREEMENT BETWEEN EXPERTS

Multiple aspects must be considered to improve environmental assessments. These include the **availability of data**, the existence or absence of **common methodological rules**, the extent to which **differences in data robustness and process maturity** are to be considered, etc.
Regardless of the approach used to conduct a LCA, the methodology, hypotheses and references should **always be clearly stated in the study.**

On top of capacity and output purity, other factors that should be considered when evaluating recycling processes are the following:

- **Water consumption**: water consumption is a key indicator, especially when it comes to specialty polymers which consume a lot of water during production processes compared to recycling processes.
- **Energy consumption**: energy can be produced by burning oil, gas, plastic waste, heavy or light products of pyrolysis.
- **Geographical area**: global comparisons should not be made. Indeed, the energy mix may differ from one country to another. Moreover, processes can vary between regions.
  Presence of additives: it is important to ask the question of where all additives that were contained within plastics end up during the recycling process. As of today, this aspect is not sufficiently addressed in environmental analysis. In Asia, toxic additives are usually burnt together with plastics for the purpose of energy production.

Box 21: Specific examples raised by some experts on environmental performance assessments improvements

When it comes to the comparison of depolymerization units for PMMA, the following difficulties arise even when data is available:

- Different plants do not operate at the same **capacity** (varies from a few hundred tons to a few thousand tons).
- Different plants do not have the same level of **output purity**. Asian countries (India, China, Vietnam, etc.) accept products coming from depolymerization units which qualities are too low to be accepted in Europe.

Therefore, even when actual plant data is available, **comparison of LCAs should be done carefully**. There may be a need to make comparisons of products with the same purity level. For instance, 3 different grades could be defined for chemically recycled PMMA: purity below 95%, purity between 95% and 98% and purity above 99%. The review of existing LCA studies showed that the PMMA depolymerization units that performed worst in terms of product quality were better than virgin PMMA production in terms of CO_2 emissions/kg of monomers.

Other factors, such as **water consumption**, are relevant when conducting a LCA of PMMA. Indeed, PMMA is recycled via pyrolysis, which does not consume a lot of water. The geographical area is also important as there are three radically different processes to manufacture PMMA monomers. Not all of these processes have the same relevance everywhere. Indeed, different technologies for virgin fossil based PMMA production are used in Europe and in Japan. The data selected to make comparisons has to be applicable to the geographical area discussed. Therefore, making comparisons requires selecting the technology that is predominant in a given region as that is the one that would be substituted by recycling.

Moreover, environmental impacts of liquefaction processes are **based on the quantity of liquid produced during recycling.** In Asian countries for instance, the calculation does not take into account the amount of gas or solids produced (making the calculation inappropriate). This generates interest in having an available material balance.

According to an expert, the minimum criteria to be considered is for the technology to have a certain **TRL** (at least TRL=6-7) and a track record of output **volumes produced** (at least 100 tons of material produced and ideally 1000 tons of material produced). Making an environmental performance assessment additionally requires disclosing a **material balance** and an **energy balance of the process**. In Asian countries, it seems the calculation of yields is not methodical.

Additional methodological aspects

POINTS OF AGREEMENT BETWEEN EXPERTS

Quality comparison between the different technologies' outputs should be included in the methodologies, to most of the experts' minds. This comparison depends both on the **output produced** and the **end-application**. The produced output can either display the functional properties expected of a recycled material or do not meet the technical specifications for a given application - which would require adding virgin material to recycled materials to obtain an end-product with the proper specifications. In that case, a specific criterion should be developed to take this point into account.

Another way of evaluating recycling processes is whether they lead to **closed-loop or open-loop** recycling. Both approaches are perfectly legitimate and must be considered in relation to a reference, which would be the final application.

The experts also agree that processes should be compared taking into account the same output specifications (including purity).

Moreover, GHG emissions are mainly considered in LCAs. Other LCA indicators should also be studied such as resources scarcity, water use and sanitary risks. The energy mix could vary from one country to another, this should be taken into account. The efficiency of the processes should also be considered. The presence of additives should be further studied.

Eventually, there is a lack of available data and transparency. This is why, it may be relevant to disaggregate LCA inventories.

Several experts believe that the virgin fossil-based resin used for a specific application may be overqualified compared to the actual need. The use of a mechanically recycled resin may be sufficient, there may be no need to use a virgin grade resin or a chemically recycled resin.

Box 22: Specific examples raised by some experts on additional methodologies

Examples used to illustrate quality comparison include:

- In the **automotive industry**, recycled products that are to be used in certain parts of the vehicle (such as handles) must display specific characteristics. In this case, the focus of the industry is on the properties of the recycled polymer, little relevance is given to whether the plastic waste used to produce that recyclate was derived from an application of superior quality.
- Another example is provided by the **recycling of PET bottles**. PET bottles can either be recycled into other bottles or into textiles. Using r-PET from bottles for textile applications is simple, and the textile market has a demand that is twice that of the PET bottle market. From a technical, economic, and environmental perspective it would be better to turn bottles into textiles. However, the current legislation requires to integrate recycled plastic into bottles. This is why, we can observe a "bottle-to-bottle" approach is promoted on the market.

d. What are the main costs of the different recycling technologies?

Introduction (based on the literature review)
The bibliography review highlighted the vagueness around the economic data, considered sensitive by the chemical and physico-chemical recycling actors. **Very few technology developers have disclosed detailed information about the competitivity, price or cost of their final product**.
Public literature however underlines some contributing factors to the potential costs associated with these technologies, such as the need to invest in equipment made from noble metals, in order to resist corrosion, the potential additional costs linked with specific parts of the value chain (e.g., pre-processing, purification, or reprocessing of solvent) or the economic value associated with specialty polymers production.
However, **no figures are available on the final cost** of a recycled material. The only figures made public are investment in chemical and physico-chemical recycling plants, and highly varies depending on the location and technology targeted.

This is why, theoretical economic models have been developed, based on public information. Experts were invited to comment on these economic models presented in Appendix I. The models were afterwards enriched with their inputs. Some experts however expressed some concerns, as they consider these models as only theoretical and therefore potentially not representative of reality.

Discussions were focused on specific examples, corresponding to the economic models developed: hydrolysis of a PET, pyrolysis of polyolefins and PS dissolution.

Experts mostly highlight two parameters as being critical. The first one being the **feedstock**, due to its purchase price and its purity, which influences the yield. The second parameter lies in the **investments**. Indeed, they are considerable and must thus be optimized, accenting the need to have a **very pure feedstock** to reduce the size of equipment and reactors.

Feedstock costs
POINTS OF AGREEMENT BETWEEN EXPERTS
When considering feedstock costs, sometimes non-usable materials in the feedstock can still be economically valorized. Indeed, when sorting is conducted, at least two fluxes are generated. Hence, the question becomes whether the second flux generated is to be considered as **waste or as credit**.

Gate fees seem an **unrealistic assumption** for most of the feedstock meeting the requirements of chemical and physico-chemical recycling technologies. An exception to this lies in the case of PS containing flame retardants, dedicated to dissolution processes.

The **quality of the feedstock** used is moreover key in the process economics. Indeed, a contaminated feedstock will inevitably lead to additional costly pre-treatment steps.

<u>Box 23</u>: Specific examples raised by some experts on feedstock costs

Examples discussed by some experts:

- For **PET hydrolysis**, sorted cotton from textiles can be sold and produce an economic value for the technology developer.
  When considering the feedstock type, the textile industry accounts for two-thirds of the PET production. It is interesting to evaluate **PET from textile as a feedstock** because the main interest of depolymerization technologies is to recover PET when it is mixed with other products. If PET was already well-sorted and clean, then it would be eligible for mechanical recycling. When it comes to PET, this material would not necessarily be predominantly present in the residuals of household plastic waste. Bottles are sent to different sorting centers for mechanical recycling, so the chances of finding over 70% of PET within residuals are low. Therefore, the feedstock considered should perhaps be sorted PET plastic waste. Regarding the prices of such feedstock, the following estimates were shared by an expert:
  - Colorless PET bottles in 2017 had a price of about 300-400€ per ton[349].
  - PET bottles with mixed color had a price of about 100-300€ per ton[350] (containing 5%-20% humidity that would need to be dried).
  - Hot washed colorless PET flakes had a price of approximately 850€-900€ a ton in Europe (pre-covid), while colored ones had a price of around 650€ per ton[351].

  If this feedstock is further purified (for example, by removing remaining impurities or volatile organic compounds), then price levels would further raise to 1 100€ - 1 200€. At the same time, the price of virgin PET was around 1 000€ per ton. This means that in this scenario, recycled PET would be more valuable than virgin PET. Considering these values and the state of polymers during different phases, the best possible input for depolymerization to this expert's mind, would be dried hot washed colored PET flakes with a 650€ price per ton. In this case, 2% of input containing pigments and other impurities would still have to be discarded through additional sorting. This would then lead to some costs related to getting rid of this generated waste through incineration (in Scandinavian countries it costs about 60€ per ton, in Western Europe gate-fees can go up to 210€ per ton).

  The fact that low proportions of PET are contained in textiles (compared to packaging for example) combined with the presence of contaminants and unwanted materials in textile waste alter the mass yield of the process and thus its rentability. For this type of waste, options become to either only target the limited quantities of PET or to also economically valorize other materials:

  - <u>Option 1</u>: Targeting only the limited quantities of PET. Some technologies work with enzymes that only target PET and should therefore allow to treat PET contained in textiles. Input streams for hydrolysis should contain around 90% of PET, for which a gate-fee will probably not be applicable. At the same time, if the waste that is being treated consists of dirty clothing or rusty zippers, these impurities might affect the effectiveness of enzymes. Some technologies seem to operate using extremely stable enzymes which, combined with the fact their process operates at low temperatures, makes the technology very interesting. Their real advantage is the ability to treat mixed streams without a catalyst that reacts on everything but using a selective enzyme instead. One expert considers that, even in such a very selective process, the type of supply chains and the quality of the input remain important. Currently, it is still better to sort upstream than to treat these impurities in the reactor or during the purification steps. These aspects have an impact on the economic viability of the model.

[349] 2017 price, Google image search.
[350] ICIS reference, before Covid.
[351] Specific dates and data sources have not systematically been shared by experts

- Option 2: Economically valorize other materials. JEPLAN's technology can separate the cotton contained in waste from the PET to then resell both the recovered cotton and the recycled plastic[352].

- For **pyrolysis of polyolefins**, when considering feedstock costs, gate fees are only available for certain types of waste. Residual fractions from sorting facilities would probably not be compatible with pyrolysis reactors. That is mainly because the fractions would contain PVC. There are fractions of waste containing primarily polyolefins. However, these fractions would contain 5-20% of humidity and pyrolysis reactors are unlikely to work with water in it. Consequently, recyclers will have to shred it up, clean it, etc.
  Due to the mentioned feedstock requirements, the waste considered would probably have a **positively strong market value**. At the same time, claims on the technologies being able to process oxygen and nitrogen contained in waste would have to be verified. The lowest quality of polyolefins feedstock would already be marketed around at least 400-600€ a ton[353]. This makes the idea to have a pure hydrocarbon feedstock going into a reactor and with a gate-fee very unlikely.
  Oxygen and nitrogen are acceptable within the feedstock if the pyrolysis process is followed by a hydrogenation post-treatment. This would however have a cost associated with it which would have to be considered.
- In the case of **PS dissolution** there might be the opportunity to obtain a gate-fee depending on the type of waste (e.g., waste containing HBCDD which would be incinerated). Polystyreneloop's dissolution process is designed to remove contaminants (example of HBCDD[354]). This way, bromine found in waste can be recovered and used to make new bromine (which is expensive).

Operational conditions

POINTS OF AGREEMENT BETWEEN EXPERTS

Once assumptions on feedstock have been defined, understanding the economics of the different technologies requires determining how the input is prepared, and the costs associated to these operations. It is also likely that further upgrading will be necessary (e.g., hydrotreatment, etc.) to ensure the output will reach the required specifications. All of these specific steps make it very complicated to fully capture the economics of the processes.

Box 24: Specific examples raised by some experts on operating conditions

Examples used to illustrate quality comparison include:

- In the **PET Hydrolysis,** hydrolysis being a polycondensation reaction, the process is equilibrium limited. Hence, an excess of water is needed to shift the reaction and reach the final monomer product (which would otherwise remain a mixture).
  An expert also trusts that the **PTA produced would probably be purified by crystallization** due to its high melting point and low solubility in water. In a neutral environment the terephthalic acid is actually a salt. Being a salt, there will be a need to use another acid (usually acetic acid) or another technology to revert it to the acid form (the monomer is the acid form), which can come with additional costs.
  Precipitating PTA requires getting rid of all other solvents. The PTA is precipitated in the reaction medium (or just after). What is left afterwards is a mixture of ethylene glycol and water. Therefore, there is still a need to evaporate a large excess of water, get rid of residues, and extract the ethylene glycol.
  According to experts, **wastewater can be recycled and reused in the process**. Water boils at 100°C, while acetic acid (one of the first organic acids) boils well above that temperature. This means that evaporated water will not contain acids. There will be some water losses in the process, yet a majority of the water could be recycled in the process. The ability to recycle the acetic acid however depends on the characteristics of the recycling process used.

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[352] https://www.jeplan.co.jp/en/service/bring/
[353] Specific dates and data sources have not systematically been shared by experts
[354] https://polystyreneloop.eu/

- In pyrolysis, there is not much public data available on the subject of refining of pyrolysis oils according to experts. **The selection of the refining process depends on the quality of the pyrolysis oil and the type of steam cracker used** (as an example some crackers may be more suitable for light feedstocks, others for heavy ones).
  One expert asserts being skeptical about the ability of pyrolysis processes to reuse secondary outputs such chars to heat up the recycling process. These outputs are mainly waste products and thus can contain VOCs that could be released through the fumes. However, it seems that conventional fumes treatment (for instance dry process removal of fumes with sodium bicarbonate) could be installed at the exit of the plants. This would however require additional installation costs.
  Another expert believes that chars could have a value in certain industries.
  Gently heating up polymers leads to a heavy output (waxes, etc.). Shorter chains and naphtha require higher temperatures, which generates more gas. This gas could have a value by being purified and sold. Yet is can also be used to generate energy in the process. The chars obtained through this process will contain a lot of contaminants (metals, etc.). Moreover, when operating temperatures are high (such as for gasification), it is possible that Persistent Organic Pollutant (POP) waste will be produced.
  It is often likely that **further upgrading of pyrolysis oils will be necessary** (hydrotreatment, etc.) to ensure the output will have the required specifications to enter a steam cracker and thus produce olefins. These steps are highly dependent on the process and the feedstock chosen and are thus very complicated to generalize. According to an expert, it is also not possible to mix pyrolysis oil with virgin naphtha to remove the need for purification steps afterwards. This process is called dilution. Applying this technique would require ensuring that all contaminants do not affect the output yet, as of now, it is not possible to do so.
- As for **PS dissolution**, solvents have a high cost for many developers that decide not to use cheaper solvents due to their negative environmental impact (example Polystyreneloop and CreaSolv[355]). Moreover, energy costs associated with this process are usually high (due to the evaporation of the solvent).

<u>Depreciation costs</u>

POINTS OF AGREEMENT BETWEEN EXPERTS

There are high uncertainties on the investment costs according to some experts. These uncertainties are weighting on the costs and the sizing of the unit should thus be appropriate in regard to the feedstock at hand. The purer the feedstock will be the less investment in additional equipment will be needed.

<u>Box 25</u>: Specific examples raised by some experts on depreciation costs

The points below were discussed:
- Regarding **hydrolysis**, a chemical depolymerization plant for flexible PU was being built in the Netherlands for 55 million €. In Europe plants are built for **20 years**, depreciated in 10 years (equipment included). CAPEX would be significantly impacted by the fact that some of the pieces in these plants are completely new due to the **strong innovation change** leading chemical and physico-chemical recycling.
- Moreover, **start-up costs** and working capital would also influence the investment costs. These aspects refer to the extra costs that may be involved due to the construction of a first-of-a-kind plant and to the need to store materials, solvents, etc.

e. What are the perspectives of development of the different chemical and physico-chemical recycling technologies?

<u>Introduction (based on the literature review)</u>

The literature review highlighted the **variability between technology advancements** and plans for expansion from a developer to another.

[355] https://polystyreneloop.eu/faq/

Indeed, within the **solvolysis** category, planned capacities ranges from 4 kt to 100 kt, depending on the developer. The facilities are mostly planned for the coming years. The majority of the advanced developers are focusing on PET recycling.
Regarding **dissolution**, several technology developers claimed that they would have started operating their demonstration plant or commercial facilities in 2021/22. However, no further details have been found concerning the advancement of these operations so far. There is thus **a lack of clarity on whether these plants** will be operational. The majority of the advanced developers are focusing on PS recycling.
As for **thermal treatment** technologies, the same variability in announcements can be observed, as planned capacities range from 15 ktons per year to 350 ktons per year in a time horizon from 2021 to 2025. These developers are usually focusing on mixed plastic waste.
Thus, information publicly available usually focuses on the plants to be built and operated. However, very little is known about the **way to technically run these plants and their positioning in the value chain** of such actors.

Challenges and opportunities for scaling-up

POINTS OF AGREEMENT BETWEEN EXPERTS

First of all, it can be noted that the demand for recycled materials is very high (especially food-grade recycled polymers). **The demand for recyclates often does not match the supply available**.

The experts agree that building of the whole **value chain** is key when considering the scale-up of a technology. Deploying recycling at a commercial scale requires **access to meaningful volumes of waste with the appropriate feedstock specifications**. Further technical progress is required on the phases that come prior to chemical and physico-chemical recycling (design for recycling, collection, sorting, traceability of waste).
In this sense, it should be established beforehand whether the aim is to process mixed waste or to treat resins one-by-one. These technologies could reach commercial scale by 2030 as long as there is a **proper match between the technology and the feedstock.** This is why **feedstock needs to be selected based on the desired outputs**. Such approach implies reversing the value chain by determining the desired products, establishing the volumes of waste needed after sorting and cleaning, and, in some cases, adapting the technology to the available waste. Indeed, there will be the need to ensure that the right technologies are applied to the right quality feedstocks (high quality feedstocks to be treated via mechanical recycling and solvolysis, lower quality feedstocks to be treated via pyrolysis, the lowest quality feedstocks to be sent to gasification facilities).

In addition, the learning curve of operating such recycling technologies is important as time is needed to understand what the requirements are to reach acceptable yields, quality, and price.

Experts assume that, in all cases, the amount of chemicals produced via chemical and physico-chemical recycling will be a **very small part of the total demand of polymer chemicals**.

Moreover, there is a need to develop **better traceability systems**. There is currently a lack of monitoring during the transformation of waste into products. So far, the chemical and physico-chemical recycling industry has mainly considered non-physical traceability of waste, as the mass balance approach. For mechanical recycling, traceability standards are in place and oblige recyclers to disclose information from the origin of waste until its use under the form of recyclates. Efficient traceability systems should be used both for mechanical and chemical and physico-chemical recycling. For this purpose, these technologies additionally need improved and harmonized collection systems, digitalization, improved sorting, etc.
Additionally, many brands demand specific requirements for recycled materials. **Numerous brands do not accept materials developed under a mass balance approach** as they wish to know the exact recycled content in their products.

Policy aspects are also relevant to the progress of chemical and physico-chemical recycling. The regulation on waste is currently under review within the Circular Economy Action Plan and will either be updated or revised. **Evolving regulation makes business models uncertain**. At first, strong regulations and financial incentives for chemical and physico-chemical recycling routes will be necessary to support the industry. These points have been discussed in more detail in part XI.1)b of this report.

Additionally, the experts believe the terminology “commercial scale” cannot be generalized. In many cases (such as for pyrolysis), **scaling-up takes place through modularization**, namely by multiplication of modules for certain processes. In this case, the development of the technology mostly lies in the required learning curve of each developer.
It should also be considered that **different technologies reach commercial scale at different capacities**. It is not possible to assume that all categories of technology will reach commercial scale at a 50 kilotons capacity (for example).

Many projects have been announced and are in the pipeline to reach industrial scale by 2025-2030. The question remains on whether these plants will start-up successfully. Most technologies still need to be de-risked and optimized. Plastics Europe recently announced that **investments in chemical and physico-chemical recycling technologies will go from 2.6 € billion by 2025 up to 7.2 € billion by 2030 in the EU and UK**[356].

<u>Box 26</u>: Specific examples raised by some experts on scaling-up

One expert believes that although pyrolysis plants could be scaled-up by multiplying the number of recycling modules, some developers are **facing scaling-up issues**. Moreover, the pyrolysis oils produced will still need to be turned into plastics and **the ability to introduce large volumes of pyrolysis oils into crackers has not yet been proven**.

Some experts also believe that solvolysis is the technology that is closest to commercial scale currently, followed by high temperature pyrolysis and gasification.

DISAGREEMENTS BETWEEN EXPERTS ON THE TOPIC OF SCALING-UP

Experts disagree on the technical feasibility of the scaling-up process. Indeed, an expert feels **skeptical towards the easiness to scale-up**. As of today, few developers are actually delivering at scale and some of them encounter issues in scaling-up. There are usually high expectations and ambitions related to chemical and physico-chemical recycling. However, **proof of concept is still missing** when it comes to scalability. Yet, another expert considers that most of the existing challenges **do not depend on the ability to up-scale technologies**, but on the ability to build a complete value chain (access to feedstock, collection, and sorting steps to be improved, etc.).

One expert believes that, although it will be possible to produce higher volumes of chemically recycled materials (thanks to regulations and technology developments), **pyrolysis oil production suited for stream crackers will still be low in the coming year**s (due to the low quality of the oil and subsequently a low efficiency towards the targeted products’ quality). From the expert’s point of view, a significant fraction of pyrolysis oil produced through current technologies will go to incineration or fuel, which is obviously not desired. Significant progress on high temperature pyrolysis or catalytic pyrolysis is however expected.

<u>Design for recycling</u>

POINTS OF AGREEMENT BETWEEN EXPERTS

Several experts agree that transitioning to a circular economy will require a portfolio of different solutions (eco-design, reusability, recycling, etc.). The principle of design for recycling has to be a tool of such portfolio, together with chemical and physico-chemical recycling. Design for recyclability can then lead to a better balance between waste quality and products volumes.

<u>Box 27</u>: Specific points raised by some experts on design for recycling

An expert believes that design for recycling **will not directly favor chemical and physico-chemical recycling,** which is only one angle of a much wider topic: design for sustainability.

[356] https://plasticseurope.org/sustainability/circularity/recycling/recycling-technologies/chemical-recycling/

Competition with mechanical recycling

DISAGREEMENTS BETWEEN EXPERTS ON THE TOPIC OF COMPETITION WITH MECHANICAL RECYCLING

Most of the experts agree that there will be some competition between the two forms of recycling, but some experts express different opinions. Arguments are summarized on Table 28.

There will be competition with mechanical recycling	There will not be competition with mechanical recycling
• Mechanical and chemical and physico-chemical recycling are competing **through an uneven regulatory context.** Indeed, European legislation on mechanical recycling is currently very strict. Some mechanical recyclers are demanding to make changes in regulation that will favor circular economy. For competition to be fair, chemical, and mechanical recyclers should be subjected to the same laws in order to create a level playing field. Additionally, there is a lack of definition within existing regulation on recycling. When it comes to chemical and physico-chemical recycling, it is not clear where waste ceases to be waste and becomes a product. • Mechanical and chemical recycling are competing **whenever chemical recycling would be substituting downcycling via mechanical recycling.** Indeed, if chemical recycling allows to produce higher quality recyclates, this option could be favored depending on the specifications required for the end-products. • Currently, there are already examples of some low-quality materials produced via mechanical recycling being purchased to be turned into higher quality monomers by chemical recyclers. Thus, either the output of mechanical recycling would qualify as a waste or the chemical recycling process would qualify as post-treatment. This type of activity further increases existing competition between recyclers. • If a company could meet all its materials' requirements using mechanically recycled materials, it would privilege this solution as it would be cheaper to do so. Consequently, chemical and physico-chemical recycling will mainly be considered whenever customers have specific requirements for their recyclates (e.g., food-grade, etc.). • **The demand for chemically recycled products is higher than the demand for mechanically recycled materials**. Current forecasts already highlight that pyrolysis plants would use too much high-quality polymer waste, which would also be suited for mechanical recycling. In this context, clear incentives, regulations, and specifications are needed to regulate the overall stream distribution to the high added value, low	• Ideally, **higher quality feedstocks would be redirected towards mechanical recycling** (it would be too expensive to treat them through chemical and physico-chemical recycling), while lower quality feedstocks would be sent to chemical and physico-chemical recycling (quality would be too low for mechanical recyclers). If it is possible to recycle mechanically a specific feedstock, this route will be favored as it would be less expensive than chemical and physico-chemical recycling technologies.

environmental impact, and high techno-economic impact solutions.	

Table 28: Arguments in favor and against the competition between mechanical and chemical and physico-chemical recycling (RECORD, 2022)

Competition between "plastic to plastic" and "plastic to fuel"

POINTS OF AGREEMENT BETWEEN EXPERTS

As of today, in the EU, the Waste Framework Directive specifies that **recycling does not include plastic-to-fuel nor energy recovery applications**. Recycling means taking waste and transforming it into a material.

Box 28: Specific examples raised by some experts on the competition between "plastic to plastic" and "plastic to fuel"

An expert believes that **fuel targeted routes should only be needed to accelerate technology development** (i.e., used to develop specific parts of the technology). At the end, each recycling technology should lead to products (including plastics) with the maximum circularity. **Fuels are only intermediate solutions**. The biggest challenge will be jet fuel as there is no circular alternative yet, and the aviation lobby is very strong. Again, clear regulations are required.

It has to be clear that plastic-to-materials, plastic-to-chemicals, and plastic-to-fuel solutions should not compete but complement each other instead. **The portion of waste dedicated to each of these applications will be the determined by market demand, net-zero ambitions, and regulations**. Hence, the subject of competition between plastic-to-plastic and plastic-to-fuel has to be regulated beforehand. Requirements have to be set for both end-of-life options and there is the need to properly trace waste to understand where the materials will end up. Perhaps, in the future, a difference will be made between high-quality recycling and low-quality recycling. In this case, plastic-to-plastic would be qualified as high-quality recycling.

Levers to accelerate the development of chemical and physico-chemical recycling technologies

POINTS OF AGREEMENT BETWEEN EXPERTS

According to most experts, the focus should be on factors facilitating **structuring of the upstream part of the value chain**. This would mainly involve improving collection and sorting systems, as well as avoiding dumping of waste into the environment. Once the upstream of the value chain will have been restructured, the rest of the value chain will be able to adapt at relatively fast and low investment costs. The transformation of the value chain with the aim of reaching circularity will be required. In addition, we should go beyond 1-to-1 collaborations.

Moreover, there is a need for **further transparency regarding technologies** (e.g., LCAs data including GHG emissions, etc.) to understand what can actually be achieved by these processes. It is expected that, in the upcoming months, the JRC will provide a draft report containing an LCA study of different recycling pathways. This document will probably present the common reference and basis on how environmental footprints of different technologies should be calculated.

Finally, from a **regulatory perspective**, it should be ensured that different directives (such as climate, health, waste, etc.) are clear, stable, coherent, and that they do not contradict one another. Sometimes, existing legislation classifies chemical and physico-chemical recycling technologies under incineration due to the presence of thermal treatments. This has an impact on the public acceptance of these recycling methods (notably in France and Spain, Germany is more open).

There is also a need to **harmonize European regulation**. The existing European waste regulation does not ensure that legislation will be harmonized across all Member States. The countries within the EU have the possibility to adapt EU Directives in a slightly different way from one another. This factor generates complexity.

Clear incentives and recycling targets for both end-products and chemicals are needed. It should also be key to consider the "true pricing" of chemical and physico-chemical recycling technologies. Less favorable conditions should be created for non-circular solutions, by using taxes for instance. In this way, the industry will know what the future targets will be and will move to develop strategies, partnerships, value chains and technologies accordingly.

> *<u>Box 29</u>: Specific examples raised by some experts on the levers to accelerate chemical and physico-chemical recycling technologies development*
>
> An expert considers the need to develop comprehensive scenario models (including techno-economic aspects and impact perspective) to allow for **technology decision and overall strategic investments**.

<u>Value chain stakeholders' actions in favor of chemical and physico-chemical recycling development</u>

POINTS OF AGREEMENT BETWEEN EXPERTS

The stakeholders of the value chain should be **clearer about their future roadmaps**. Defining and working towards long-term objectives would help the stakeholders align with other players within the same value chain. Each player can have its own roadmap, yet, if such roadmap does not match with the upstream and downstream steps of the value chain, it will not be deployed.

Also, they should set higher priority for sustainability targets in companies' roadmaps. The credibility of the whole value chain could be increased by **putting more efforts in achieving the milestones** that have been disclosed as part of future roadmaps.

Stakeholders across the value chain should also align on **feedstock specifications and volumes** using backwards integration and thinking (for instance from products and impact perspective).

> *<u>Box 30</u>: Specific examples raised by some experts on value chain stakeholders*
>
> Value chain's actors could also **help governments and other stakeholders** to better understand the overall industry picture by taking all stakeholders' perspectives into account.

2) Limitations of the exercise

The experts' consultation however holds limitations among which:

- <u>The geographical representativeness of the panel</u>: Although 16 Japan based organizations were contacted, no Japan experts have accepted to participate in the working sessions. A few American organizations joined the experts' consultation. However, most experts were European. Thus, there is a lack of geographical representativeness.

- <u>Information sharing</u>: As the working sessions with experts were not covered by NDA, no confidential information should be shared. This may have limited relevant information sharing that would have allowed us to complement our study.

- <u>Publicly available information</u>: Some questions could not have been fully answered as there is still a lack of available information around chemical and physico-chemical recycling, notably on the economic and environmental performances of the processes. This data has not been made public by technology developers. More techno-economic studies should be conducted to better understand the performance of these technologies.

- <u>Panel constitution on specific topics:</u> for some topics, the panel was quite heterogeneous in terms of experts and, especially during the economic session, the floor was shared between only a handful of experts (one or two people). Specific information could not be obtained in this case.

XII. Authors' point of view

Based on the outcomes from the literature review and the experts' consultation, the authors of the study highlighted the following key messages on the relevance of chemical and physico-chemical recycling technologies and their perspectives of development to help reaching plastics circularity.

It has to be noted that classification of chemical and physico-chemical recycling technologies in different overarching categories systematically generates debates. This study on "chemical and physico-chemical" recycling mainly focuses on solvolysis, thermal treatment and dissolution. However, the wording could be adjusted to better reflect reality using for example the terminology "physical and chemical" recycling technologies. For more information, please refer to the paragraph XII.3) below.
Moreover, we invite readers to have a look at the sections III and XI.2) of this report to have a better understanding of the limitations of this study.

Please also note the plastic recycling sector is a fast-moving field. In this context, the key messages presented below should be refined relatively quickly based on current and future work progress around recycling technologies.

1) "Chemical and physico-chemical" recycling technologies are key to help reaching plastics circularity

If it succeeds to reach industrial and commercial scale, chemical and physico-chemical recycling will help overcoming the limitations of mechanical recycling. Mechanical recycling has limits that narrow the range of solutions to reach a true circular economy. As a matter of fact, the available feedstock to produce food-grade recycled material through this technology is scarce. Hence, only some mechanical recycling plants are currently producing recycled PET (and HDPE to a lesser extent) eligible for food-contact and their capacity is very inferior to the market demand. More generally in mechanical recycling, the end-product's quality limits the end market applications due to the variety of input materials, which have different grades, color, or that might contain legacy substances. Mechanical recycling processes may lack the technical ability to remove all these contaminants, which inevitably alters the final output's quality. Ongoing developments (including R&D) on increasing purity of the outputs of mechanical recycling processes might be able to close some of these gaps but the recycling costs would necessarily increase and the approval by the authorities of the food contact nature of the products still required.
In addition to the quality and feedstock issues, the end of life of products that use mechanically recycled plastics raises question about the true circularity of these technologies' output. Indeed, due to the downcycling effect[357] of mechanical recycling technologies, the end-product might not meet the market requirements in terms of quality and purity. Its number of recycling cycles might thus be limited, and the plastic produced might not thus become truly circular.
A wide range of chemical and physico-chemical recycling technologies that individually aim at tackling these issues is developing. Indeed, they could lessen the feedstock requirements to produce high-quality and/or food-grade plastics, due to their ability to remove some contaminants or sometimes problematic legacy substances that mechanical technologies cannot handle properly. This would allow to enlarge the eligible feedstock volume and therefore increase recycled high quality material production. The quality of the plastic produced through chemical and physico-chemical recycling could also meet more demanding purity standards. Such products could hence loop through relatively more recycling cycles than mechanically recycled material.
The recycling ability of these technologies aims at broadening recycling horizons and potentially contribute to achieving a circular economy for plastics.

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[357] Product quality lowering by mechanical recycling. Indeed, a part of pollution remains in the end product due to the additives originally present in the feedstock, that were not removed. The final product might therefore an average standard that no longer meets the quality requirements of some markets.

However, like any process, it has its own limits. As an example, it has been observed that additional sorting and pretreatment steps are often required as a considered chemical and physico-chemical recycling technology cannot treat all types of plastics. In addition, depending on the considered technology, some legacy substances may not be totally removed. Indeed, some studies' results mentioned in the last ECHA report have highlighted the presence of bromine substances in pyrolysis oils. Additionally, it is still not clear to which amount pyrolysis oil can be reused in a steam cracker. Hence, the limitations and uncertainties around chemical and physico-chemical recycling are to be taken into account. These aspects are further detailed in the sections below (in terms of regulatory context, environmental and economic performances, etc.).

Chemical and physico-chemical recycling is complementary to mechanical recycling. In situations where mechanical recycling offers a product of sufficient quality for applications driven by a sophisticated market, mechanical recycling will be more environmentally friendly and cost competitive. It will consequently and naturally be the preferred option of the market. It is however key that a level playing field is ensured between all technologies, especially on regulatory and feedstock access aspects (see **Error! Reference source not found.**and **Error! Reference source not found.**).

Generally, chemical and physico-chemical recycling should be seen as one instrument within a wider range of relevant circular solutions. It is important to acknowledge that chemical and physico-chemical recycling technologies are one of the solutions to a bigger challenge that encompasses resource preservation and climate change mitigation. These processes are dedicated to solving specific issues and such solution should not limit actions that focus on circularity beyond recycling: eco-design, better collection and sorting, reuse, new business models, etc.

2) Dynamism around the development of "chemical and physico-chemical" recycling technologies is massive. However, only a few plants are at industrial scale

The market of chemical and physico-chemical recycling is actively developing. The news is currently flooded with announcements of projects in construction or planned. The recycling capacities are **expected to tenfold** in the next five years if all these announcements are met (see Figure 13). Production volumes should follow the trend and reach unseen levels. There is undoubtedly an infatuation around these technologies on the current recycling market.

To this end, numerous stakeholders of the whole value chain are taking part in this development. Brands are providing support for chemical and physico-chemical recycling technologies as the latter could help them meet their recycled content targets. They are offering financial support in different forms (offtake agreements, joint ventures…). Petrochemical industries are also either developing their own technologies or collaborating with developers themselves to expand on the chemical and physico-chemical recycling market. Waste management companies are as well supporting the growth of chemical and physico-chemical recycling technologies by investing in the upcoming plants or financially contributing to their progress. However, the interest that stakeholders are sharing for these technologies can be modulated. There is an urgent need to structure the value chain and to reorganize several industrial assets to adapt to chemical and physico-chemical recycling's issues and needs (e.g., refining steps usually used by the petrochemical industry to be fully adapted to the treatment of pyrolysis oils). The current craze around chemical and physico-chemical recycling technologies is not yet driving this change. Please note that further details on the structure of the entire value chain are presented at the end of this section.

The potential of these technologies to reach commercial scale however remains to be proven. Numerous stakeholders of the value chain have significantly invested in chemical and physico-chemical recycling technologies. However, a large share of these technologies is currently at pilot or demonstration scale and there are some examples of failures to scaling up (Vinyloop for instance). Very few industrial scale plants are in operation nowadays. Indeed, scaling-up a technology is a long process. Generally, around 10 years are necessary to reach commercial scale from lab scale. This development should be carefully planned. Numerous factors must be taken into account to properly attain commercial scale such as technical, regulatory, economic, or environmental considerations. There may be hence a gap between the interpretation that one can have of the technologies and their real progress, often less optimistic. The bibliography and technology developers' announcements can be misleading on this point. The promises of such announcements should thus be handled with caution.

3) "Chemical and physico-chemical" recycling technologies are very diverse, and each must be considered individually

Classification of chemical and physico-chemical recycling technologies in different overarching categories systematically generates debates. Classifying these technologies might be an arduous process and there is currently no consensus on the terminologies used. Indeed, dissolution processes might not be considered as "chemical" technologies in the sense that they do not usually alter the polymer structure. However, it is arguable that depending on the solvent chosen, there can be a reaction with the polymer. This technology can thus either be considered as physical or chemical and physico-chemical recycling.
This study on "chemical" recycling mainly focuses on solvolysis, thermal treatment and dissolution. However, the wording could be adjusted to better reflect reality using for example the terminology "physical and chemical" recycling technologies.

The nature and number of steps needed to go back to plastics, with the proper specifications, might be very different from one technology to another. The different outputs produced by chemical and physico-chemical recycling technologies are more or less easily reprocessed. Indeed, some technologies are producing monomers that can be directly repolymerized while others need additional steps to transform the output back into plastics.

- For example, pyrolysis processes can either produce monomers (when applied to PMMA or PS feedstock for instance) or a hydrocarbon mix (such as pyrolysis oil). The latter requires several downstream steps before it can be reinjected into a cracker (or be polymerized again if the process applied allows for high content of aromatics in the output oil). Some specific steps usually used by the petrochemical industry can be applied to reprocess pyrolysis oils (such as refining). However, these petrochemical processes are not fully developed for this application yet. This could represent a brake on the development of pyrolysis processes.
- Regarding gasification, the main output is syngas which has to undergo multiple conversion steps to allow for the production of chemical intermediates that could eventually be used again for the production of polymers.
- On the contrary, when producing monomers, the downstream steps are less stringent. However, some depolymerization processes produce a chemical intermediate that would require the addition of the monomer to complete the repolymerization. This monomer is currently a virgin polymer, which calls into question the circularity of the process. Indeed, it is not usually possible to go back to polymers without the addition of some virgin monomers.
- Other recycling technologies, such as dissolution, directly produce purified polymers. These technologies would require less downstream steps.

In general, it has to be noted that the number of pretreatment and purification steps required will depend on the feedstock, the technology, and the desired end-product specifications.

Each technology is specific in terms of feedstock targeted, output produced and operational conditions. Technologies also differ in terms of scale of operations and their ability to handle different feedstocks. Indeed, the challenges associated to the recycling of specialty polymers and commodity polymers are very different. The first category would need a technology able to efficiently treat low quantities of material in a cost-effective manner. The latter on the contrary would need bigger reactors able to handle high volumes of contaminated waste. Dynamics of the market are thus guiding the choice of technology and feedstock.

4) <u>Based on available information, chemical and physico-chemical recycling appears as a solution that could bring environmental benefits. However, the environmental performance of chemically recycled products still needs to be fully demonstrated.</u>

Available information on the environmental performance of chemical and physico-chemical recycling processes demonstrates benefits (notably taking into account the climate change indicator). Benefits of chemical and physico-chemical recycling technologies against conventional virgin production or usual end of life processes (e.g., incineration) are highlighted by technology developers. Indeed, numerous results disclosed show that the processes are less emissive than virgin production (even if more impactful than mechanical recycling).
These benefits also depend on several critical parameters such as:

- The **availability of the feedstock near the plant**. Indeed, the need to source feedstock further away necessitates transportation of the waste, which can deteriorate the environmental performance.
- The **composition of the feedstock**. Purification and pretreatment steps would need to be more thorough and thus more impactful in case of a contaminated feedstock.
- The **technology type**. The further the technology goes back into the polymer production steps, the higher the environmental impacts will become. As an example, pyrolysis breaks down polymer chains to come back to the monomers or initial components. Thus, this process may be energy intensive and have higher environmental impacts.
- The **gap with virgin material environmental performance**. Indeed, some polymers (such as specialty polymers) require lots of energy to be manufactured. Chemical and physico-chemical recycling gains could thus more easily be achieved than for commodity chemicals, whose virgin production process consumes less energy.
- The used **methodology and studied indicators**.
    - Most communications focus on GHG emissions only while circular economy is in the first place about resource preservation. It is key to focus on other indicators such as resources preservation instead of solely on GHG emissions.
    - Taking into account the climate change indicator, the chemical route may be assessed as more impactful than virgin material depending on the end-of-life reference scenario chosen, especially if a landfill reference scenario is chosen. Mechanical recycling can be less impactful ; however it produces lower grade applications (the functional unit is then different).
    - The lack of consensus on the methodology to be used contributes to the multiplication of impact assessments that are not comparable to one another, as they are elaborated using different methodologies. Other factors can have an impact on the environmental performance of the process such as the data used, the geographical area considered and the associated energy mix, etc.

Due to a lack of publicly available data, environmental benefits of chemical and physico-chemical **recycling technologies still have to be largely demonstrated.** Although the LCA figures shared by the technology developers and the public reports usually highlight the environmental benefits of chemical and physico-chemical recycling technologies at first sight, there is currently a lack of publicly available data. This missing information usually includes methodology and assumptions used, which are essential in understanding the presented results. The figures shared by technology providers are often unverifiable. It is thus difficult to prove the environmental benefits of chemical and physico-chemical recycling technologies. Very few developers are indeed publishing a critical review of their environmental data.

Environmental assessment methodologies should evolve to better assess the reality of the value chains and markets. The objective of the transition to circular models is to enhance the value of recycling operations compared to the use of virgin polymer, to appreciate a change of end-of-life treatments, and, overall, to acknowledge the environmental impact of the product that is being sold and put on the market. Current environmental assessment methodologies do not allow a fair comparison between mechanical and chemical and physico-chemical recycling as the differences in terms of output quality and the number of lifecycles of the recycled materials are not accounted for. It is thus necessary to implement a factor rationalizing these differences into the environmental impact assessments. Other aspects should be taken into account such as the expected economy of scale once the technology reaches commercial scale.

The comparison of chemical and physico-chemical recycling impacts with alternative end-of-life treatments reflects the current reality of the market but should evolve over time. The dynamics of change and the effort put in transitioning from a linear to a circular economy must be valued. In this sense, the comparison of chemical and physico-chemical recycling with other end-of-life treatments, such as incineration and landfilling, could be considered at a first step. The environmental assessments of technologies and the associated methodologies will be evolving.

5) In the current context, regulations should not hinder the development of chemical and physico-chemical recycling. Clarification of the current and future regulatory context is expected to ease investment decision making processes

There is currently a lack of harmonized definition. Existing recycling regulations mostly apply to mechanical technologies, leaving a doubt on their application to chemical and physico-chemical recycling technologies. These technologies are not clearly defined nor classified. The application of existing regulations is thus unclear when it comes to chemical and physico-chemical recycling. Among the three geographies studied (Japan, Europe, and USA), not one clearly states its position on chemical and physico-chemical recycling and if these technologies could be qualified as "recycling". There is thus an urgent need for alignment from policy makers on this topic.

There are differences between geographical areas, which do not allow for a level playing field regarding chemical and physico-chemical recycling. The different definitions of a recycled material between the US, Japan and EU may add complexity. Indeed, some states in the United States are promoting several chemical recycling technologies whereas the European regulation is unclear.

A clear legal framework is necessary. In order to be developed, chemical and physico-chemical recycling technologies would need clarity on current and future regulations, uncertainties should be lifted. For example, explicit guidelines should be defined regarding the implementation of the mass balance approach. This approach indeed has the potential to boost the development of recycling technologies during a transition phase. Stable material traceability should however be implemented on the longer term. Regulations should also be clearer regarding the end of waste status and harmonized around the different geographies.

Regulations should ensure a level playing field between all recycling technologies. While regulations should not hinder the development of chemical and physico-chemical recycling it should not bring a competitive advantage to these technologies compared to mechanical recycling or other circular economy solutions such as prevention or reuse. Access to feedstock for both chemical and mechanical recycling, proven environmental benefits for the market and possible associated economic instruments are among the critical aspects to be considered.

6) Feedstock appears as the critical aspect of chemical and physico-chemical recycling development

Policies and programs should ensure that feedstock is available (with sufficient volumes and quality) for all recycling activities. Due to the low volumes of available plastics collected for recycling compared to the recycled material demand, a competition between recyclers is likely to occur for feedstock access. It is thus key to secure sufficient volumes of waste with the proper specifications to ensure the development of chemical and physico-chemical recycling technologies.

The feedstock specifications are of consequent importance for the development of a technology. Although some technology developers claim that preparation of feedstocks is not required, it seems that pretreatment steps (such as the removal of contaminants, crushing, washing, etc.) are nonetheless necessary before entering the recycling process. The higher the quality of the feedstock will be, the less thorough the pretreatment steps will have to be. Access to proper feedstock, in terms of quality and volumes, is therefore key in the technological development of chemical and physico-chemical recycling. A tremendous challenge faces the collection and sorting systems to meet these criteria. This challenge should be addressed country by country due to the significant variety of schemes across geographies.

The ability to meet feedstock specifications is one of the criteria that most impact the economic equation. The feedstock volumes and quality play a tremendous role on the economics of a plant.
First, quality and price of the feedstock directly and largely impact the operational costs. Especially the impact of quality on the yield is critical as it lowers the revenues (by lowering the volumes sold compared to the volume purchased), grows the amount of waste produced and the associated costs and increases the needed quantity of resources, such as energy or solvent, per unit produced.
In addition, the plant structures are dimensioned on these criteria. Low quality feedstock will lead to the necessity of buying higher volumes to reach the necessary amount of polymer of interest. Taking into account the massive impact of CAPEX on the cost structure of chemical and physico-chemical recycling, any oversize of the process and equipment (e.g., reactor) would harm the economics of chemical and physico-chemical recycling.

7) More broadly, the building of the whole value chain is necessary from feedstock supply to the production of the end product

It is necessary to ensure a proper match between the feedstock used, the technology applied and the end-product application. One single technology is not able to treat all types of feedstocks and their specificities. The best match between feedstock composition (including the polymers' type), technology and the desired end-product specifications should be found. It has to be highlighted that the challenges for the chemical and physico-chemical recycling of plastic waste differ from one polymer to another, especially between commodity and specialty polymers. Indeed, volumes of specialty polymers might be scarce and scattered, which would require recycling processes that are efficient in treating lower volumes. As for commodity polymers, the purity of the feedstock might be an issue and the technology used would thus have to be able to handle contaminants.

Partnerships and cooperation along the whole value chain should be implemented. For each technology, a specific value chain should be built suiting the characteristics needed. The following requirements would have to be met to ensure proper scaling up of the technologies:

- **Secure feedstock supply** with waste management companies should be ensured.
- **Agreements with petrochemical companies or polymer manufacturers** to ensure purification steps (such as refining steps for instance) should be completed when needed.
- **Partnerships with polymer manufacturers** that could conduct the repolymerization step should be made.
- **Partnerships with academics** for analyses of the recycled materials should be established.
- **Partnerships with brand-owners** for the purchase of recycled end-products
- **Financing of the plant** should be secured. Diverse sources of funding could be considered (including grants, investments from brand-owners, polymer manufacturers, etc.)

XIII. Conclusion

The aim of this report was to assess current chemical and physico-chemical recycling technologies and their future perspectives of development, focusing on plastic-to-plastic applications.

The solvolysis technologies assessed demonstrated the opportunity of producing a high-purity, virgin-like material that could be suitable for food-grade applications. With projects currently at a relatively advanced development stage, these technologies seem to be the most promising chemical and physico-chemical recycling processes despite a lack of transparency on potential pretreatments and purification steps needed. Their complementarity to mechanical recycling makes their potential market and applications sustainable, as long as the two technologies don't compete for feedstock access. This implies that progress has to be made on existing collection and sorting systems to ensure an appropriate feedstock distribution between recycling processes.
It is also important to ensure that the output of these processes comply with the existing regulations in place (for instance that the monomers can be REACH registered).
The economic viability of this process is however unsure, with potential high costs of pretreatment steps and high investments needed.
Similarly, the environmental benefits of such technologies are difficult to assess and very few technology developers have shared their LCA methodology to this point.

Dissolution technologies are mostly developing towards contaminated stream applications or plastic containing additives, such as plastics containing flame retardants. Indeed, these technologies can, in some cases, treat separately the plastic from its additives and are thus among the only technologies capable of recycling WEEE plastics. However, the opportunity of using the recycled product for food-grade applications still has to be proven. In addition, the use of solvent and its potential environmental and economic impacts is still a point lacking clarity for now.

The thermal treatment technologies have demonstrated their ability to handle relatively mixed waste streams, even though some non-processable inputs have to be removed beforehand. However, these technologies are used both for plastic-to-plastic and plastic-to-fuel applications. Numerous downstream steps are needed to produce a recycled polymer (purification of the hydrocarbon mix, integration in virgin value chains, etc.). This is also the case, although to a lower extent, for technologies focused on PS and PMMA depolymerization. There are thus few examples of advanced plastic-to-plastic facilities.
Moreover, the economic viability of such installations has not been proven, due to the lack of communication from the developers on the costs of feedstock pre-treatment and purification steps.
The environmental benefits of such technologies are also unsure due to a lack of public LCA on these processes and the particularly high energy demand of the different processes.

The main obstacle to the development of these technologies comes from the lack of structure of the entire value chains. Waste resources do not seem to be secured and are mostly directed to incineration or landfill. Partnerships with stakeholders need to be put in place in order to ensure access to feedstock (with sufficient volumes and quality).

Finally, there is generally a regulatory uncertainty on chemical and physico-chemical recycling across the world. Regulatory ambiguity on the topic of chemical and physico-chemical recycling can be found across the three regions studied (Europe, United States and Japan). Exceptions exist. As an example, in some parts of the United States dozens of American states have passed bills to support chemical recycling facilities. No geography has yet ruled on the definition of "recycled material" and the technologies that are eligible for such denomination.
Moreover, the implementation of a mass balance approach currently generates debates among various stakeholders (public authorities, petrochemical industries, NGOs, etc.) and seems not to be accepted in any of the regions studied.

These technologies development can be impacted by several factors. Indeed, the evolution of regulations can help chemical processes to expand to commercial stage by removing some uncertainties. The evolution of eco-design trends will lead to the transformation of feedstock composition. This change in waste composition can be beneficial for recyclers, by avoiding additional costly and environmentally impactful steps of the processes. Simplification of the processes can also be levered by the evolution of collection and sorting techniques sorting. These trends should boost the numerous projects in progress. Indeed, current plans are involving all the actors of the value chain and include ambitious objectives of plant construction in the future years that could be met if the aforementioned criteria are reconciled.

Thanks to the literature review and the authors' point of view, this study can regroup the highlights of chemical and physico-chemical recycling technologies and of their development perspectives. Some uncertainties however remain as these processes are still under development and not all questions can be answered. There is thus a need for more technical-economic data and LCA studies, among others, to fully capture the challenges of chemical and physico-chemical recycling technologies and answer potential concerns from brand owners, recyclers, legislators, and the other stakeholders of the value chain.

Appendix I. Theoretical economic reference models

<u>Please read this note first</u>: To highlight the main factors influencing the price of recycled material, some theoretical economic models were developed. The core objective of this work was to determine the main critical parameters that can impact the cost of chemically recycled material and potentially contribute to its economic competitiveness. The models have been computed based on publicly available information or, when not available, estimated data. The figures thus lack in robustness and precision, especially when estimated.
The results are thus to be interpreted as orders of magnitude of figures. They aim at giving an estimation of the potential costs associated with the different recycling technologies and are not to be interpreted as exact actual figures.

Appendix I.1. Introduction

Three models have been established, each taking into account a different technology:

- **Dissolution of PS**: the cost of the recycled materials has been computed from the purchase of plastic waste to the production of the recycled resin by the technology developer.
- **Hydrolysis of PET**: the cost of the different materials has been computed from the purchase of plastic waste to the production of the monomers – Monomers produced should be ideally comparable to virgin petrol-based monomers in terms of quality.
- **Pyrolysis of polyolefins**: the cost of the different materials has been computed from the purchase of plastic waste to pyrolysis oil production. The oil produced has been compared to the production of naphtha from the petrol-based industry, even though the composition is different.

The scope chosen for the data collection is European.
In all models, similar hypotheses regarding the size of the installation, the energy costs, the efficiency of the different equipment were chosen, in order to ensure the comparability of the three models to one another. The base installation characteristics are:

- An output capacity of 18 000 tons per year of recycled product.
- Load hours of 8 000 hours per year.
- Fixed operating costs (personnel costs, insurance costs, tax…) were not modeled into detail but it was ensured that they were approximately similar as the size of the installation is considered to be the main factor in its end value.

No catalysts were considered in any of the 3 models due to the diversity of options available. Indeed, including a catalyst may significantly change the results and thus harm the comparability of the subsequent data. Similarly, no dangerous waste was considered in any of the 3 models. It was thus assumed that the feedstock bought either does not contain any dangerous components or has been presorted before the process to remove such components.

The following costs **were excluded of our analysis**: patent costs, interests costs linked with capital debt, exchange rate costs and inflation (all costs considered are in €$_{2020}$ without any inflation rate).

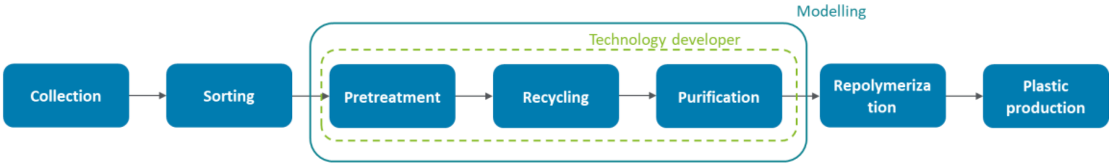
The aim of the models is to compare the costs of chemically and physico-chemically recycled materials with the market price of virgin-based alternatives. The analysis has been conducted by defining two scenarios: a “worst-case” scenario, taking the upper end of each hypothesis, and a “best-case scenario”, which assumes the most favorable hypothesis. These two scenarios have afterwards been averaged to define a final cost of the recycled material, which **does not take into account any commercial margin**, contrary to the prices of the virgin equivalents that they are compared to.

Appendix I.2. PET hydrolysis

The Hydrolysis of PET, as stated in section V.4), produces PTA and MEG as outputs.

Different steps were considered for the cost analysis that was conducted. These steps are represented on Figure 22 below. The perimeter considered starts from the purchase of the waste by the technology

developer (and thus from the pretreatment done in the chemical recycling plant) to the purification of the monomers produced (MEG and PTA). The repolymerization step is thus excluded. In the following paragraphs, the terminology “PET equivalent” designates the quantities of PTA and MEG necessary to produce 18 000 tons of PET, without taking into account any repolymerization losses.
The process of **neutral Hydrolysis** was considered in the thereafter study.



$$\sum costs = pretreatment\ costs + recycling\ costs + purification\ costs + operational\ costs + depreciation\ costs$$

Figure 22: Steps considered for the PET Hydrolysis process (RECORD, 2022)

Depending on the scenario considered, more or less material and energy are needed. The **mass and energy balance** of this process are presented thereafter in Figure 23, for the best case and worst-case scenario.

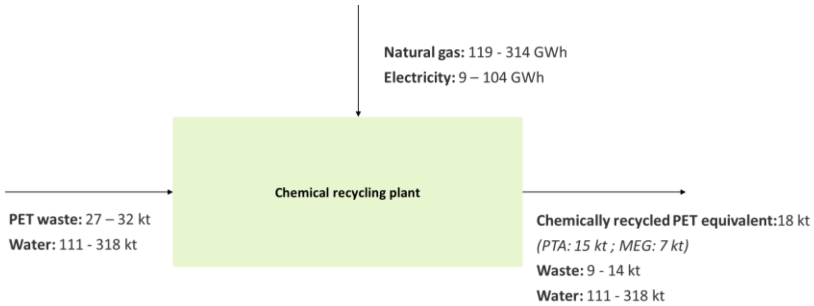


Figure 23: Mass and energy balance of the PET hydrolysis process (RECORD, 2022)

The results of this analysis are presented in Figure 24 below. According to this study, the production of recycled PET equivalent by Hydrolysis costs about **300% more than the price of virgin PTA and MEG** (average value of a minimum and a maximum scenario). The price of the virgin monomers however includes a commercial margin contrary to the costs computed.

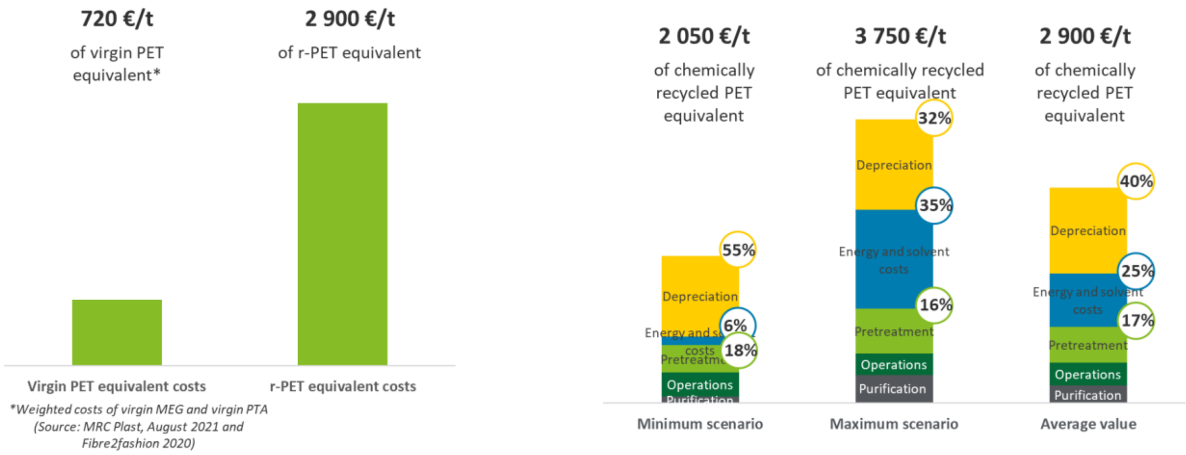


Figure 24: costs of chemically recycled PET equivalent compared with its virgin alternative (left) and breakdown by scenario (right) (RECORD, 2022)

The costs repartition by category and the main hypotheses are presented in Table 29 below.

$$\sum costs =$$

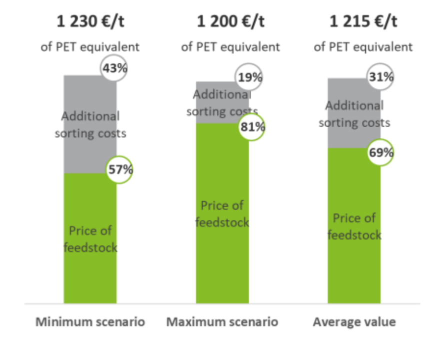
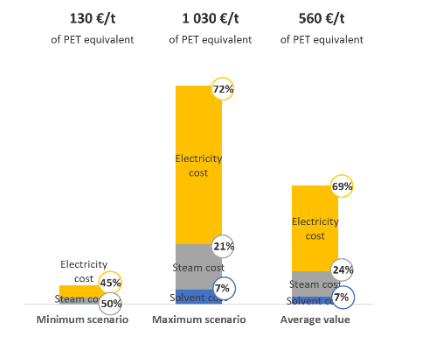
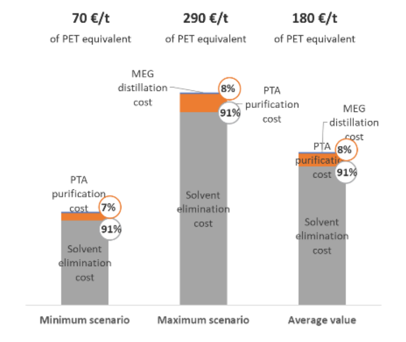
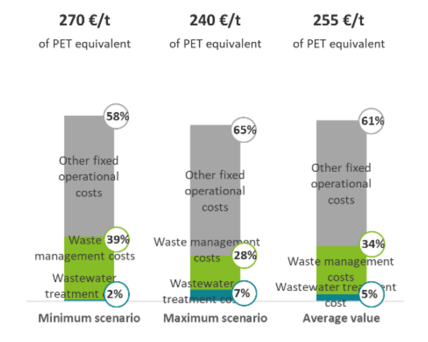
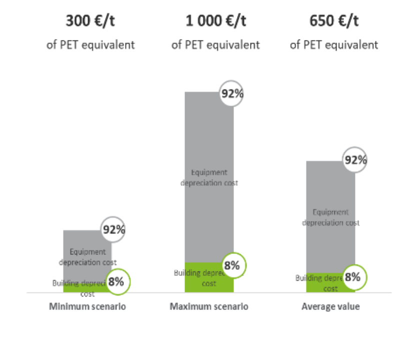
Pretreatment costs +	Energy and solvent costs +	Purification costs +	Other operational costs +	Depreciation costs
				
The pretreatment costs are divided between the **cost of buying the feedstock** for the process and the **costs of the additional sorting necessary** to ensure that the input complies with the process requirements. Two cases were considered: • <u>In the "best case" scenario</u>, the feedstock is assumed to be composed of sorting refusals and **purchased at 400€/t of feedstock**. Due to the relatively bad quality of the feedstock, it was considered **that additional sorting costs were about 300 €/t of feedstock,** as it contains impurities (about 30% of the feedstock weight is assumed). • <u>In the "worst case" scenario</u>, the feedstock is assumed to be cleaner and contains less impurities (about 5%). It was thus considered that it was bought at **600€/t and additional sorting costs of 150 €/t of feedstock** were applied.	The energy costs are divided between the **use of electricity for compression and the use of steam to heat up the reaction media**. The major cost is **electricity**, representing in each scenario more than half of the total costs. Indeed, less electricity than steam is needed but the **cost of electricity in Europe is higher than the cost of natural gas** (used in the boilers to produce steam). The **solvent cost represents the lesser fraction** of the total costs, as the hydrolysis process uses only water. The weight of water needed ranges from 5 to 12 times the weight of PET respectively in the minimum or maximum scenario.	The costs of purification considered were the **costs of distillation of the solvent**, the **purification of PTA** (through crystallization) and the **distillation of MEG**. The costs of mechanical purification operations, such as filtering or mechanical separation, are included in the equipment costs, as they do not require significant variable costs. The most important cost is the **distillation of water, due to the relatively high amount of water** used in the maximum scenario.	The other operational costs (some operational costs have been covered in the recycling or purification costs) are divided between **waste management costs** and **other fixed costs.** **Other fixed costs** include operational labor costs, costs of managers and supervisors, staff overheads, fixed annual maintenance costs, property tax and insurance, building allowance/lease, general overheads, laboratory costs, research & development (R&D), environmental taxes and fixed costs for heat and/or electricity consumption (grid management costs). **Waste management costs** represent the costs needed to eliminate the impurities extracted from the feedstock during the presorting step and the reaction losses. **Water used as a solvent must then be treated** as it might be polluted after the process.	The depreciation costs are divided between **equipment depreciation** costs (92%) and **building depreciation costs** (8%). The equipment lifespan was assumed to be **10 years** whereas the building lifespan is assumed to be **20 years**. The residual value of both is assumed to be null. The investment costs **were computed using different announcements of the technology developers' facilities** and thus include all costs needed to build a chemical recycling plant (i.e., environmental taxes, equipment costs, electricity, and water network costs, building costs…).

Table 29: Hydrolysis cost repartition (RECORD, 2022)

Appendix I.3. PS dissolution

The dissolution of PS, as stated in section VI, produces purified PS as an output.
Different steps were considered for the cost analysis that was conducted. These steps are represented on Figure 25 below. The perimeter considered starts from the purchase of the waste by the technology developer (and thus from the pretreatment done in the physico-chemical recycling plant) to the purification of the PS produced.

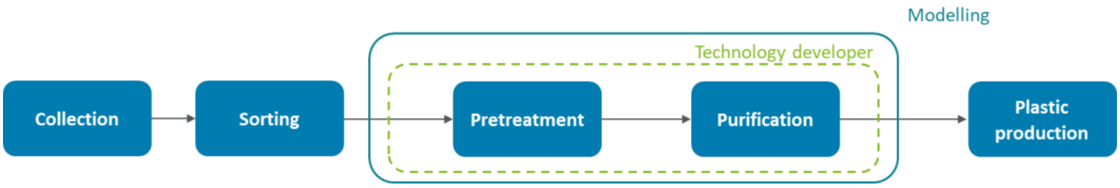


Figure 25: Steps considered for the PS Dissolution process (RECORD, 2022)

Depending on the scenario considered, more or less material and energy are needed. The **mass and energy balance** of this process are presented thereafter on Figure 26, for the best-case and worst-case scenario.

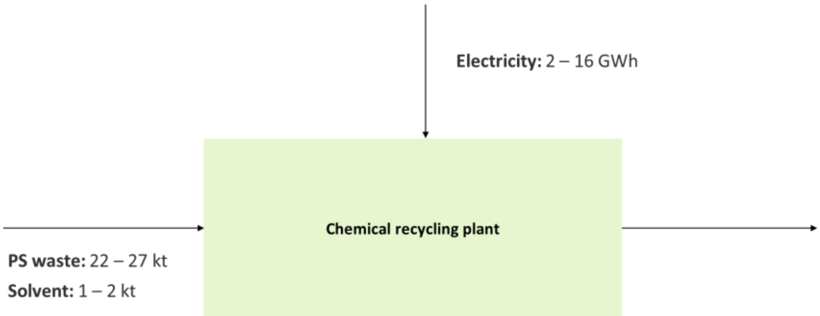


Figure 26: Mass and energy balance of the PS dissolution process (RECORD, 2022)

The results of this analysis are presented in Figure 27 below. According to this study, the production of recycled PS equivalent by dissolution **costs about 80% more than the price of virgin PS**. The price of virgin PS however includes a commercial margin contrary to the costs computed.

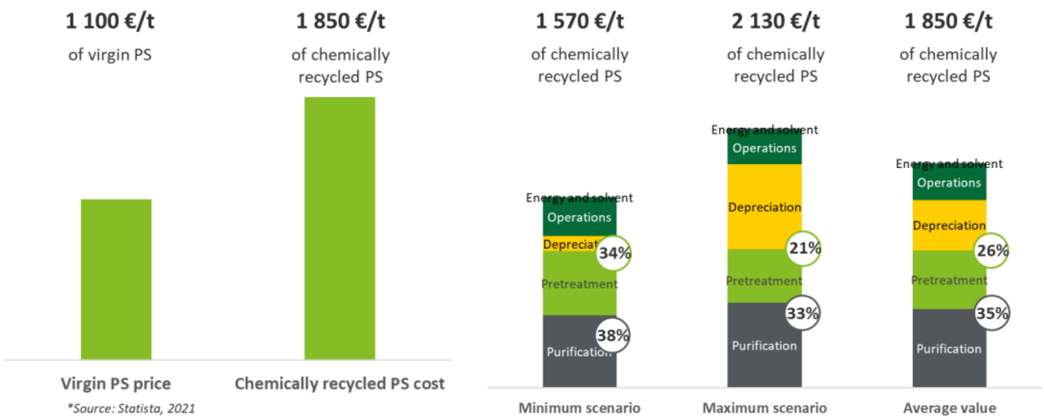


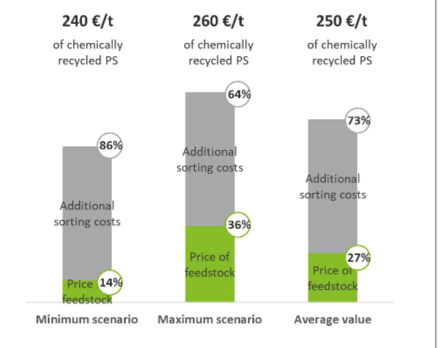
Figure 27: costs of chemically recycled PS compared with its virgin alternative (left) and breakdown by scenario and type of cost (right) (RECORD, 2022)

The variations between the two scenarios are mostly due to the purification steps. Indeed, hypotheses made about the solvent (p-xylene in the best-case scenario and cymene in the worst-case scenario) are contributing to higher purification costs.
Purification costs are the most important costs with 35% of the total costs in the average value.

The costs repartition by category and the main hypotheses are presented in Table 30 below.

$$\sum costs =$$

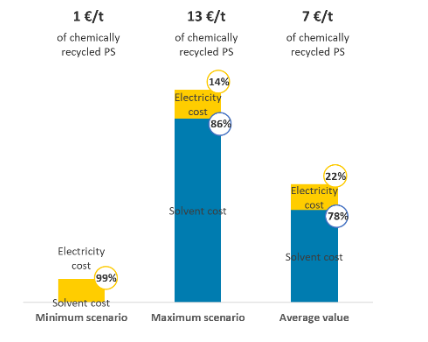
Pretreatment costs ⊕



The pretreatment costs are divided between the **cost of buying the feedstock** for the process and the **costs of additional sorting necessary** to ensure that the input complies with the process requirements.
Two cases were considered:

- <u>In the "best case" scenario,</u> a feedstock price of **50€/t of feedstock** was applied. It was moreover considered that additional sorting costs were about **300 €/t of feedstock**, as the feedstock is assumed to contain about **30% impurities**.
- <u>In the "worst case" scenario</u>, the feedstock is cleaner and contains less impurities (about **5%**). It is assumed to be composed of PS packaging. It was thus considered that it was bought at **200€/t and additional sorting costs of 150 €/t of feedstock** were applied.

Energy and solvent costs ⊕

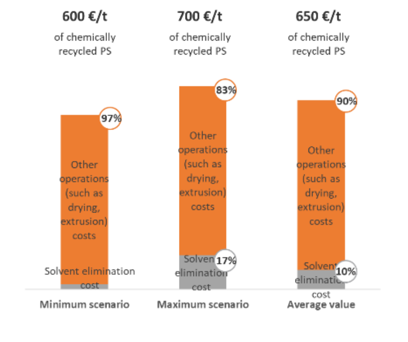


The costs of the recycling process are divided between **the use of electricity to heat up the reaction media** and the **cost of the solvent**.

The major costs in the minimum scenario are **electricity** as the reaction temperature is considered to be 50°C and the **solvent is supposed to be relatively cheap** (p-xylene) and reused in a closed loop (only **2% losses** were considered).

The solvent cost represents the higher fraction of the maximum scenario costs, as it is assumed to be **cymene**, which is a relatively expensive chemical. Losses of 2% were also considered.

Purification costs ⊕



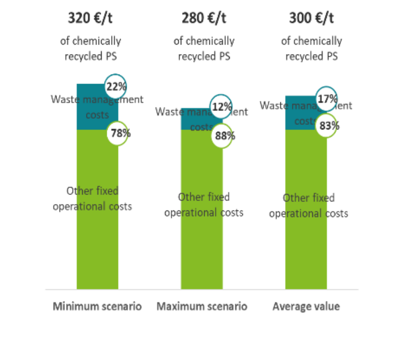
The costs of purification considered were the costs of **distillation of the solvent** and the cost of **purification of chemically recycled PS**.

The distillation of the solvent represents **the energy necessary to heat up the fraction** to remove any residual solvent in it.

PS is purified through **filtering, drying** and is afterwards **extruded**.

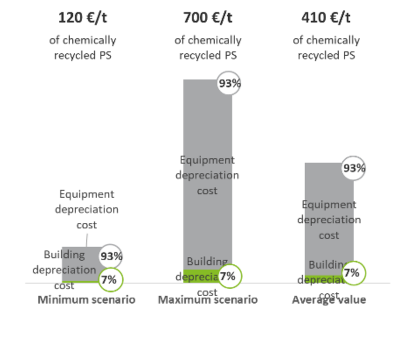
The difference between the two scenarios mostly lies in the **quantity of solvent** used in the reaction.

Other operational costs ⊕



The other operational costs (some operational costs have been covered in the recycling or purification costs) are divided between **waste management costs** and **other fixed costs**.
Other fixed costs include operational labor costs, costs of managers and supervisors, staff overheads, fixed annual maintenance costs, property tax and insurance, building allowance/lease, general overheads, laboratory costs, research & development (R&D), environmental taxes and fixed costs for heat and/or electricity consumption (grid management costs).
Waste management costs represent the costs needed to **eliminate the impurities** extracted from the feedstock during the presorting step and the reaction losses. They were calculated assuming a **140 €/t fee** (cost of landfill).

Depreciation costs



The depreciation costs are divided between **equipment depreciation costs** (93%) and **building depreciation costs** (7%).

The equipment lifespan was assumed to **be 10 years** whereas the building lifespan is assumed to be **20 years**. The residual value of both is assumed to be null.

Start-up costs that may be incurred by the construction of a unique plant and the need to store materials, solvents, etc. **are not considered in this analysis.**

Table 30: Dissolution cost repartition (RECORD, 2022)

Appendix I.4. Pyrolysis of polyolefins

The pyrolysis of polyolefins, as stated in section 1), produces a purified oil as an output, that can be used as a substitute for virgin naphtha. The following economic assessment is centered on fast pyrolysis, as it is the most favorable option to maximize oil yield, and thus to produce plastic.

Different steps were considered for the cost analysis that was conducted. These steps are represented on Figure 28 below. The perimeter considered starts from the purchase of the waste by the technology developer (and thus from the pretreatment done in the chemical recycling plant) to the refining of the pyrolysis oil produced. Steam cracking operations are thus not taken into account in the subsequent model.

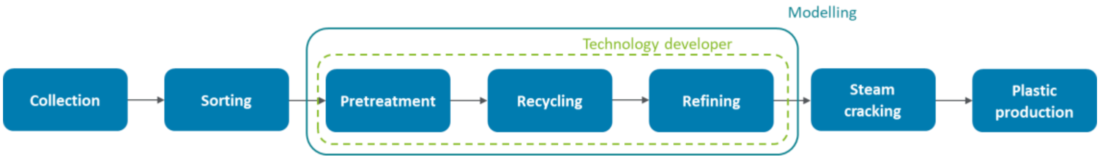


Figure 28: Steps considered for the pyrolysis process (RECORD, 2022)

Depending on the scenario considered, more or less material and energy are needed. The **mass and energy balance** of this process are presented thereafter in *Figure 29*, for the best-case and worst-case scenario.

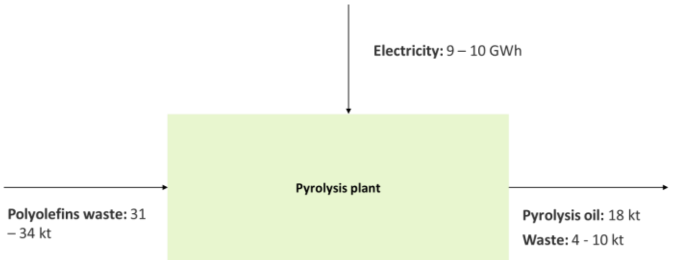


Figure 29: Mass and energy balance of the polyolefin's pyrolysis process (RECORD, 2022)

The results of this analysis are presented in Figure 30 below. According to our analysis, the production of recycled naphtha by pyrolysis costs about 400% more than the price of virgin naphtha. The price of virgin naphtha however includes a commercial margin contrary to the costs computed.

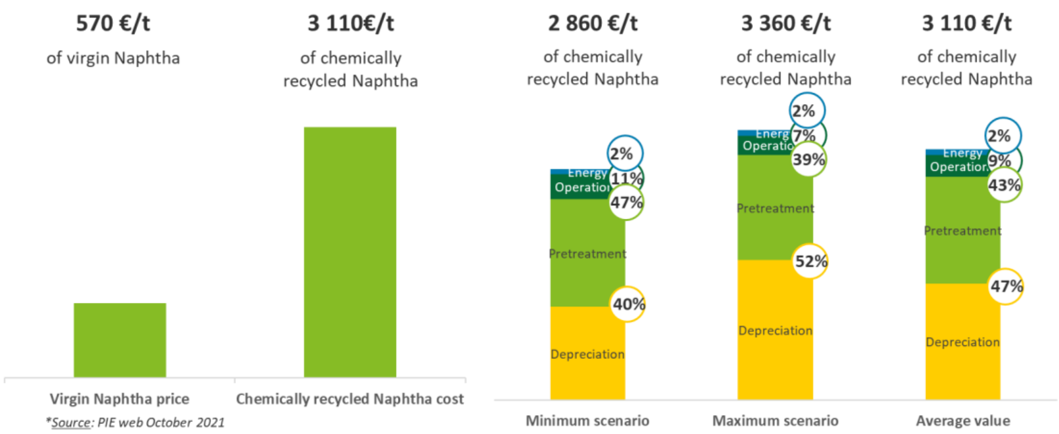
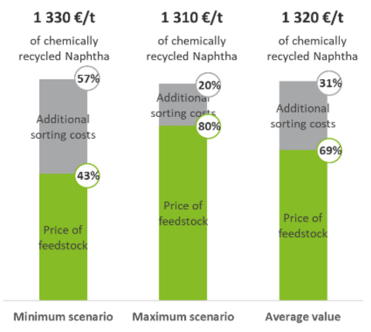


Figure 30: costs of pyrolysis oil compared with its virgin alternative (left) and breakdown by scenario and type of cost (right) (RECORD, 2022)

Depreciation costs are the most important costs with 47 % of the total costs in the average value.

The costs repartition by category and the main hypotheses are presented in Table 31 below.

$$\sum costs =$$

<table>
<tr><th>Pretreatment costs</th><th>+ Energy and solvent costs</th><th>+ Functionning costs</th><th>+ Other operational costs</th><th>+ Depreciation costs</th></tr>
<tr>
<td>
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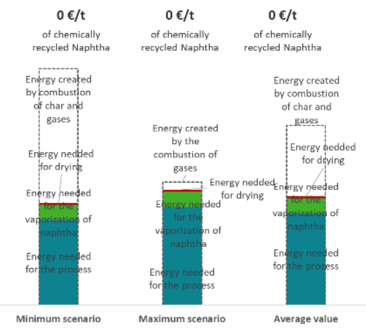
<td>
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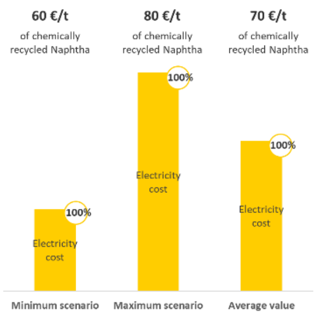
<td>
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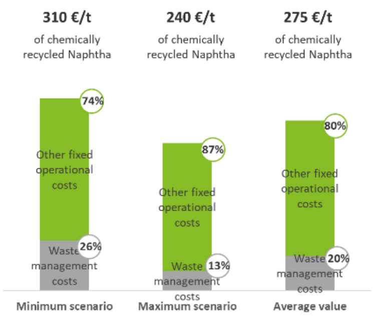
<td>
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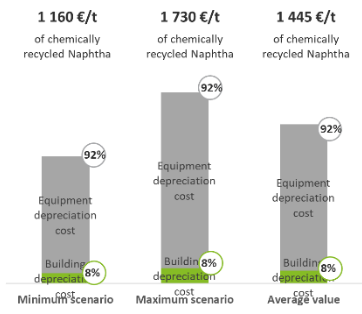
<td>
</td>
</tr>
<tr>
<td>The pretreatment costs are divided between the cost of buying the feedstock for the process and the costs of the additional sorting necessary to ensure that the input complies with the process requirements.
Two cases were considered:
• <u>In the “best case” scenario,</u> a feedstock price of 400 €/t of feedstock was applied. It was moreover considered that additional sorting costs were about 300 €/t of feedstock, as the feedstock purity is low (about 70%).
• <u>In the “worst case” scenario</u>, the feedstock is cleaner and contains less impurities (about 10%). It was thus considered that it was bought at 600 €/t and additional sorting costs of 150 €/t of feedstock were applied.</td>
<td>The energy costs to heat up the reaction media and to purify the oil produced are considered to be null as they are covered by the combustion of char and gases produced.
Thus, the only energy costs considered represents the use of electricity to start up and fuel the different equipment.
The main difference between the two scenario lies in the valorization of char, which is burnt for energy recovery in the minimum scenario and dealt as waste in the maximum scenario.
It is however important to note that if the feedstock contains dangerous compounds, burning char and gases produces might liberate these compounds in the atmosphere. Thus, a treatment of fumes should be added at the chimney (e.g., dry slaughtering with sodium bicarbonate)</td>
<td>The functioning costs of the recycling process represent the use of electricity to start up and fuel the different equipment.
The major costs in the minimum scenario are electricity as the pyrolysis reactor is considered to be self-heating (the high reaction temperatures are reached by burning gases and char). Electricity is thus only needed to startup the installation and provide for the different equipment needs.</td>
<td>The other operational costs (some operational costs have been covered in the recycling or purification costs) are divided between waste management costs and other fixed costs.
Other fixed costs include operational labor costs, costs of managers and supervisors, staff overheads, fixed annual maintenance costs, property tax and insurance, building allowance/lease, general overheads, laboratory costs, research & development (R&D), environmental taxes and fixed costs for heat and/or electricity consumption (grid management costs).
Waste management costs represent the costs needed to eliminate the impurities extracted from the feedstock during the presorting step and the reaction losses. They were calculated assuming a 140 €/t fee (cost of landfill).</td>
<td>The depreciation costs are divided between equipment depreciation costs (93%) and building depreciation costs (7%).

The equipment lifespan was assumed to be 10 years whereas the building lifespan is assumed to be 20 years. The residual value of both is assumed to be null.

Start-up costs that may be incurred by the construction of a unique plant and the need to store materials, solvents, etc. are not considered in this analysis.</td>
</tr>
</table>

Table 31: Pyrolysis cost repartition (RECORD, 2022)

Appendix II. Glossary of abbreviations and units & English-French lexicon

Abbreviation	Definition
ABS	Acrylonitrile Butadiene Styrene
ACC	American Chemistry Council
ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie
Alu	Aluminium
APR	Association of Plastic Recyclers
ASR	Automotive Shredder Residue
BHET	Bis(2-hydroxyethyl) terephthalate
BOPET	Biaxially-oriented polyethylene terephthalate
CHDM	Cyclohexanedimethanol
CO	Carbon monoxide
CO_2	Carbon dioxide
C5/C10/C20/C50	5/10/20/50 carbon building blocks
ECHA	The European Chemicals Agency
EFSA	European Food Safety Authority
DMT	DiMethylTerephtalate
EMF	Ellen MacArthur Foundation
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
(E)PS	Expanded polystyrene
EU	European Union
FDA	Food and Drug Administration
GHG	Greenhouse gas
H_2	Hydrogen
HBCD	Hexabromocyclododecane
HDPE	High density polyethylene
Hydr. mix	Hydrocarbon mix
HIPS	High Impact Polystyrene
H_2S	Hydrogen sulfide
HVC	High-Value Chemicals
JRC	Joint Research Centre
LCA	Lifecycle Analysis
LDPE	Low density polyethylene
MEG	MonoEthylene Glycol
NDA	Non-Disclosure Agreement
NGO	Non-governmental organization
NH_3	Ammonia
NO_x	Nitrogen oxides
PA/PA.6	Polyamide/Nylon 6
PB	Polybutylene
PBT (or PBTP)	Polybutylène téréphtalate
PC	Polycarbonate
PCR	Post-consumer resin
PDMS	Polydimethylsiloxane
PE	Polyethylene
PEN	Poly(oxy-1,2-ethanediyloxycarbonyl-2,6-naphthalenediylcarbonyl
PET	Polytéréphtalate d'éthylène
PIP	Polyisoprene
PMMA	Poly(methyl methacrylate)
PMP	Polymethylpentene
PP	Polypropylene
PRE	Plastic Recyclers Europe

PS	Polystyrene
PTA	Purified terephthalic acid
PTMP	Polytétraméthylène
PU	Polyurethane
PVC	Polyvinyl chloride
r-	Recycled
REACH	Registration, Evaluation, Authorization and Restriction of Chemicals
R&D	Research & Development
WEEE	Waste Electrical and Electronic Equipment Directive
Zn	Zinc

Unit of measure	**Definition**
°C	Degrees Celsius
cm	Centimeters
g/cm_3	Grams per cube centimeter
g $PM_{2.5}$	Grams of particulate matter with volume <2.5 micrometers
GJ	Gigajoules
Kg/h	Kilograms/hour
KJ/mol	Kilojoules per mole
Km	Kilometers
Kt/y	Kilotons a year
KWh	Kilowatt-hour
L	Liters
mm	Millimeters
MJ	Megajoule
Mt	Million metric tons
t	Tons
tCO_2e	Tons of CO_2 equivalent
t/hr	Tons per hour
t/d	Tons per day
t/y	Tons per year
ug	micrograms
wt.%	Percentage by weight
w/w	Weight for/by weight
2D/3D	2 Dimensional / 3 Dimensional

English terminology	**French**
Aminolysis	Amminolyse
Catalyst	Catalyseur
Chemical recycling	Recyclage chimique
Dissolution	Dissolution
Feedstock	Intrant
Hydrolysis	Hydrolyse
Hydrothermal cracking	Craquage hydrothermique
Gasification	Gazéification
Glycolysis	Glycolyse
Granulates	Granulés
Methanolysis	Méthanolyse
Pellets	Granulés
Physico-chemical recycling	Recyclage physico-chimique
Pyrolysis	Pyrolyse
Pyrolysis oil	Huile de pyrolyse
Solvolysis	Solvolyse
Steam cracker	Vapocraqueur

Appendix III. **Bibliography**

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3	Recent Advances in Pre-Treatment of Plastic Packaging Waste	Kol, R. et al. , Current Topics in Recycling. DOI:10.5772/intechopen.99385	2021
4	Recyclage chimique des déchets plastique : état des lieux et perspective	Dr. Arnaud Parenty	2019
5	Recyclage chimique des déchets plastiques : situation et perspectives état de l'art et avis d'experts	RECORD	2015
6	El Dorado of Chemical Recycling, State of play and policy challenges	Zero Waste Europe	2019
7	Mechanism of glycolysis of nylon 6,6 and its model compound by ethylene glycol. Polymer Degradation and Stability. 91. 1545-1555. 10.1016/j.polymdegradstab.2005.09.019.	Kim, Kap Jin & Dhevagoti, Manjula Dhevi & Lee, Jong & Cho, Young & Choe, Eun Kyung.	2006
8	A New Approach to Chemical Recycling of Polyamide 6.6 and Synthesis of Polyurethanes with Recovered Intermediates. J Polym Environ **26,** 4415–4429 https://doi.org/10.1007/s10924-018-1314-4	Datta, J., Błażek, K., Włoch, M. et al	2018
9	Degradation of nylon-6 by glycolysis. Part I: identification of degradation products. J Macromol Sci Pure Appl Chem 35:1489–1505	Hommez B, Goethals E	1998
10	Technologies for chemical recycling of household plastics – A technical review and TRL assessment	Solit and Silveira, Waste Management 105 (2020) 128–138, https://doi.org/10.1016/j.wasman.2020.01.038	2020
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12	Etat de l'Art technico-économique des filières de valorisation des plastiques usagés par Recyclage Chimique, Cas des plastiques issus des DEEE	Gerard Antonini	2020
13	Screening LCA Ioniqa	CE Delft	2018
14	Open loop recycling: A LCA case study of PET bottle to fibre recycling.	Shen L, et al. Resour Conserv Recy doi:10.1016/j.resconrec.2010.06.014	2010
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42	What drives us?	CertPlast. https://www.eucertplast.eu/about	No data
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Appendix IV. List of studied technology developers

Please note this list is not exhaustive and only focuses on the technology developers studied in this report.

Name of the technology developer	Name of the technology	Polymer treated
Agilyx	Non catalytic thermal depolymerization	PS
Annellotech (Plast-Tcat™ technology)	Catalytic thermal depolymerization	Mixed plastics
APK AG	Dissolution	Mixed waste
Aquafil	Hydrolysis	PA6
Arcus Greencycling	Non catalytic thermal depolymerization	Mixed plastics
Bio-BTX	Catalytic thermal depolymerization	Mixed plastics
Borealis	Non catalytic thermal depolymerization	Mixed plastics
BP	Dissolution	PET
Carbios	Enzymatic depolymerization	PET
Carboliq (subsidiary of RECENSO)	Dissolution	Mixed plastics
Cassandra Oil	Catalytic thermal depolymerization	Mixed plastics
Clariter	Non catalytic thermal depolymerization	Mixed plastics
CreaCycle	Dissolution	Mixed plastics
DePoly	Hydrolysis	PET
DuPont Teijin Films (JV between DuPont and Teijin)	Glycolysis	PET
Eastman	Methanolysis, Glycolysis	PET
Emery Oleochemicals	Glycolysis	PU
Showa Denko	Gasification	Mixed plastics
Enerkem	Gasification	Mixed plastics
Enval (spun-out from University of Cambridge)	Non catalytic thermal depolymerization	Mixed plastics
Fuenix Ecogy Group	Non catalytic thermal depolymerization	Mixed plastics
Garbo	Glycolysis	PET
Gr3n	Microwave depolymerization	PET
Greenmantra Technologies	Catalytic thermal depolymerization	PS
H&S anlagentechnik	Glycolysis	PU
IBM Research	Glycolysis	PET
IFPEN/Axens	Glycolysis	PET
Indaver	Non catalytic thermal depolymerization	PS, PE, PP
Ioniqa Technologies	Dissolution	PET
ITERO (previously CGC)	Non catalytic thermal depolymerization	Mixed plastics
JEPLAN	Glycolysis	PET
Karlsruhe Institute of Technology (KIT) and Lyondell Basell	Catalytic thermal depolymerization	Mixed plastics
Loop Industries	Methanolysis	PET
MMAtwo (4 years project launched in 2018)	Non catalytic thermal depolymerization	PMMA
Morssinkhof/Cumapol/DSM-Niaga/DuFor/NHL Stenden University	Glycolysis	PET
Mura Technology (utilises Licella Holdings Pty.'s Cat-HTR™ technology, Renew ELP carries out recycling)	Hydrothermal cracking	Mixed plastics
OMV (partnership with Boréalis)	Non catalytic thermal depolymerization	Mixed plastics

PerPETual Global Technologies	Glycolysis	PET
Petrobras	Enzymatic depolymerization	PET
Plastic Energy	Non catalytic thermal depolymerization	Mixed plastics
Polyloop (ex Vinyloop technology)	Dissolution	PVC
PolyStyreneLoop	Dissolution	PS
Polystyvert	Dissolution	PS
Poseidon Plastics (JV between Green Lizard Technologies Ltd, Panima Capital and Abundia Industries LLC.)	Glycolysis	PET
Pryme	Catalytic thermal depolymerization	Mixed plastics
PureCycle Technologies	Dissolution	PP
Pyrowave	Catalytic thermal depolymerization	PS
Quantafuel	Catalytic thermal depolymerization	Mixed plastics
RAMPF Eco	Glycolysis	PU/PET / PSA, other polyesters (PLA, PC, PHB)
Recycling Technologies UK	Non catalytic thermal depolymerization	Mixed plastics
Renew ELP	Hydrothermal cracking	Mixed plastics
RITTEC	Hydrolysis	PET
Splainex Ecosystems	Non catalytic thermal depolymerization	Mixed plastics
Synova Tech	Gasification	Mixed plastics
SOPREMA	Glycolysis	PET