



El Dorado of Chemical Recycling

State of play and policy challenges

Study

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Executive Summary

Over the last few years the concept of chemical recycling has been promoted by the industry as a potential solution to help curb plastic pollution and waste management as a whole. This report looks into the information available as well as the state of implementation of such technologies in the European context.

Mechanical recycling is a mature industrial process which is well established and expanding in Europe. Yet, plastics cannot be endlessly recycled mechanically without reducing their properties and quality. Besides, not all plastic types can be mechanically recycled. These limits set challenges for plastics recycling and show the need for significant improvements in the end-of-life management of plastics.

Chemical recycling today often refers to technologies that can be classed depending on the level at which they break down the plastic waste. Concretely, the technologies can be divided into 3 types:

- Solvent-based purification. Comprises technologies that go down to the polymer stage. They are capable of decontaminating the plastic but cannot address its degradation. They work only with monostreams (PVC, PS, PE, PP).
- Chemical depolymerisation. Chemical process which turns the plastics back into their monomers. Allows for decontamination but not addressing degradation. Only works with monostreams (PET, PU, PA, PLA, PC, PHA, PEF).
- Thermal depolymerisation and cracking (pyrolysis and gasification) are energy-intensive processes which turn the polymers back into simpler molecules. They are capable of decontaminating polymers and, by bringing plastic back to its original building blocks, addressing the degradation of the material. These technologies can deal with more than one monomer at a time and are also capable of producing fuels. This raises the need for strict regulatory controls to prevent plastic being turned into fuel in lieu of recycling.

Gasification and pyrolysis have been tested since decades as alternatives to waste to energy incineration with very limited results due to the energy balance and the environmental impact. In general, the information available about the environmental performance of chemical recycling technologies as a whole is still extremely limited and requires further research.

In contrast with mechanical recycling, chemical recycling is an industry in its infancy and most plants in the market are in a pilot stage. The potential roll-out of such technologies at industrial scale can only be expected from 2025-2030 and this is an important factor when planning the transition to a Circular Economy and notably the decarbonisation agenda.

For the sake of policy consistency, it is key that the right policy framework is set up in order to, on the one hand, accommodate chemical recycling as complementary to mechanical recycling and, on the other hand, ensure that the carbon stays in the plastic and is not released into the environment. Therefore, allowing plastic to be considered chemical recycling risks creating a loophole in EU Climate and Circular Economy legislation.

With all its potential, chemical recycling can have a role to play in closing the material loop and moving away from disposal and recovery operations, up the waste hierarchy. Nevertheless, the best options to curb plastic pollution from environmental and economic perspective is to invest in reduction and reuse solutions; giving excessive attention to end of pipe solutions could undermine this exercise. For the plastic waste that cannot be avoided via redesign, thermal depolymerisation of mixed plastic could undermine efforts to source separate for mechanical recycling which is more environmentally favourable. Moreover, there is a risk of putting too much expectation on a solution whose potential is yet to be proven and this could delay the necessary efforts in the field of rethinking business models and material redesign.

Chemical recycling could be a complementary solution to mechanical recycling where the latter proves to be unsuited to materially recover plastic because it is too degraded, contaminated or too complex. At the same time, increased collection of high-quality waste and design for reuse and recycling should remain the two priorities in order to increase the recycling rates for plastics and ensuring no plastic escapes the material loop via plastic to fuels. For this to happen ZWE recommends to amend current waste legislation as follows:

- Come up with a clear definition of chemical recycling that excludes any operation that does not result in the production of new plastic.
- Only processes with a lower carbon footprint than the production of plastic from virgin feedstock can be classified as chemical recycling.
- Chemical recycling should be used to deal with degraded and contaminated plastics and never with plastics coming from separate collection.
- Establish verification systems to ensure chemical recycling process outputs plastic and plastic feedstocks; facilities licensed for chemical recycling may not produce fuel for on- or off-site combustion.
- In order to avoid competition with mechanical recycling, but also to differentiate from recovery and disposal operations, a new level in the waste hierarchy should be added for those operations that recover materials from mixed waste that today would end up burned.
- For coherence with EU Climate and Circular Economy agendas EU funding should only be allowed to finance plastic to plastic chemical operations.

1. Introduction

Plastic pollution is a topic that has been gaining traction in recent years and it is already seen as a global challenge. Indeed, our civilization struggles to make an efficient and sustainable use of this material, with 335 million tonnes of plastic produced in 2016 alone which is expected to substantially increase over the next decade¹.

The current plastics system has an estimated annual material value loss of EUR 70-105 billion globally. From an environmental perspective, it is estimated that 75,000 to 300,000 tonnes of microplastics are released into EU habitats annually.

Of the 8,300 million tonnes of plastics produced by humankind since the 1950s, it is estimated that 5,800 million tonnes of plastics, representing 70% of the total amount, have become waste, of which 84% or 4,900 million tonnes, has been disposed of in landfills or in the environment².

In the EU, separate collection rate of plastic waste in 2014 was 37%, whilst the recycling rate after the export of 30% of the plastic waste outside EU borders was estimated to be 13% (2.15 million tonnes). The rejects of the various sorting stages amount to about 1.5 million tonnes³.

From a systemic perspective, given the inefficient way we are managing this resource, it is clear that a big effort will be needed to rethink the way we use plastics today and many single-use applications will need to be reconsidered. Moreover, in a scenario in which two thirds of EU's plastic waste are being landfilled or burned, there is a big opportunity to increase plastic recycling.

Bearing in mind the need to reduce the use of plastic for single-use applications and the necessary diversion from landfill and incineration to mechanical recycling, there is a legitimate question about what to do with those plastics that are too degraded or too contaminated to be reintroduced in the production cycle. Currently this fraction of plastic waste is exported, downcycled or disposed of, but in recent years some technologies have been presented claiming to be able to recycle this waste stream under the name of chemical recycling. This study looks into the state of play of these technologies in the current context and explores their potential for development in the future.

¹ PlasticsEurope, 2018

² Geyer, Jambeck & Law, 2017

³ Deloitte Sustainability, 2017

2. What is plastic chemical recycling?

Plastics are chains of molecules linked together. Each of these molecules is a monomer and the resulting chains are called polymers. This is why many plastics begin with “poly,” such as polyethylene, polystyrene, and polypropylene. Polymers often are made of carbon and hydrogen and sometimes oxygen, nitrogen, sulfur, chlorine, fluorine, phosphorous, or silicon. The term “plastics” encompasses all these various polymers.

In order for these polymers to be of use they need to be given properties such as flexibility, fire resistance, strength, etc. and this is possible thanks to the addition of additives in the production process.

Even though plastic is used as a generic term, every polymer follows a different production process and all have different melting temperatures, which makes it impractical for different polymers to be recycled together. Therefore, quality recycling requires sorting by polymer and also differentiating between the different additives within every family of polymers. For instance, opaque PET should not be recycled with transparent PET.

Almost exclusively, today plastic recycling means sorting, washing and compounding the different polymers into secondary plastics. The process of plastic use and the mechanical recycling cause degradation in the polymer structures which limits the number of times the same polymer can be effectively recycled as the bonds become more and more degraded. Also, mechanical recycling is unable to separate the additives and the non-intentionally added substances that are present in plastic waste; this explains why contaminated plastic cannot be turned into high grade plastic which could be used for food contact applications. As long as recycled plastic use is limited to lower-quality products (“downcycling”), it cannot replace the production of virgin plastic, which is almost entirely sourced from fossil fuels, with all the attendant environmental impacts. The limitations of plastic mechanical recycling open the door to chemical recycling, for the latter can sometimes address the challenges of both polymer degradation and contamination.

The number of technologies comprised in what is commonly referred to as chemical recycling can be divided into three different categories depending on the level of decomposition that the plastic waste will be subject to (see figure 1):

- Solvent-based purification, which decomposes plastics back to the polymer stage.
- Chemical depolymerisation, which turns the plastics back into their monomers via a chemical reaction.
- Thermal depolymerisation (pyrolysis and gasification) which in some cases can be considered as chemical recycling by cracking the polymers back into monomers and further down into hydrocarbons.
- Thermal depolymerisation technology can also produce fuels although in that case it can no longer be considered a form of recycling.

All these outputs (except fuels) are then reprocessed to form new plastics.

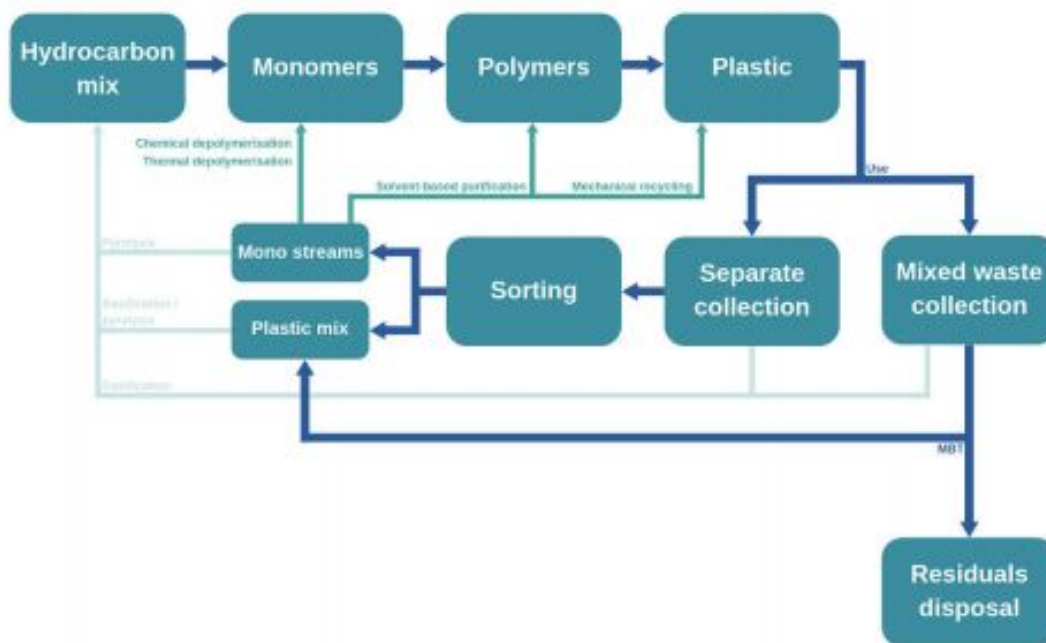


Figure 1: Diagram of different chemical recycling processes
Source: Zero Waste Europe: www.zerowasteurope.eu

| | Feedstock | Output | Decontamination | Ability to treat mixed plastic | Maturity |
|---------------------------------------|--------------------------------|--|-----------------|--------------------------------|---------------------------------------|
| Mechanical recycling | PE, PET, PP, PS | Plastic (made of one or more polymers) | No | Yes* | Industrial scale |
| Solvent-based purification | PVC, PS, polyolefins (PE, PP) | Polymer | Yes | No | Pilot stage |
| Chemical depolymerisation | PET, PU, PA, PLA, PC, PHA, PEF | Monomers | Yes | No | Existing pilot plants for PET, PU, PA |
| Thermal depolymerisation (pyrolysis) | PMMA, PS | Monomers | Yes | No | Pilot stage |
| Cracking (pyrolysis and gasification) | Plastic mix | Hydrocarbon mix | Yes | Yes | Pilot stage |

*Mechanically-recycled mixed plastics can be downcycled into lower-grade uses such as plastic lumber. Mechanical recycling of single resins, such as PET, can produce higher-value products.

Table 1: Technologies of different chemical recycling processes
Source: Zero Waste Europe: www.zerowasteurope.eu

3. Solvent-based purification⁴

3.1 The technology

Solvent-based purification is a process based on the solubility of the polymer in a certain type of solvent: when immersed in this solvent, the plastic dissolves and goes back to the polymer stage. In general, the solvent is chosen so that other impurities such as additives or pigments can be removed through filtration or phase extraction. At the end of these purification steps, the polymer is recovered thanks to an anti-solvent in which the polymer is not soluble. **The solvent-based purification can only deal with homogeneous flows of plastic.** It can treat separately PVC, PS, and polyolefins such as PE and PP. The resulting output is a precipitated polymer, of sufficient purity to be reformulated into plastics in a near virgin quality since the additives, colourants and contaminants are removed at the molecular level. Their use is very diverse, from food packaging to insulating material. The composition due to mixing of different polymer grades (chain lengths or branching for example), remains more or less the same.

Nevertheless, this process raises several issues. First, the purity of the output polymer can vary according to the input and the process parameters: there is always a risk of finding residual contaminants and traces of the solvent. The treatment of the left-over solvent, which can contain plastic additives and contaminants, is not clear.

Then, even though the solvent process does not degrade the quality of the polymer, the latter needs to be processed again to form a new plastic object. As with mechanical recycling, the physical and thermal stress generated by this process decreases the average chain length of the polymer, affecting its quality. Solvent-based purification thus cannot be a perpetual recycling method for plastics.

Besides, the trend to multi-layer packaging continues: 20% of all packaging films are multi-layer⁵. This kind of packaging has some properties, such as a barrier against oxygen or water vapor, that a regular mono-layer packaging cannot have⁶. While solvent-based purification is technically able to separate complex layers of plastic, its practical feasibility remains unproven. This would indeed require additional solvation and separation steps, making the time and energy input needed for solvent removal even more important.

The economic viability of the process also needs to be evaluated. So far, this technology can only take care of homogeneous inputs of plastic. A strict upstream sorting system and the availability of sufficient amounts of plastic monostreams are therefore necessary. In general, mechanical recycling is preferable for monostreams; however, solvent-based purification is better able to process contaminated PS or PVC than mechanical recycling can. While technically feasible, this is not necessarily an economically viable process. The infrastructure and transport costs are also challenging: plastics are lightweight but production volumes need to be high. While the annual plant capacity should be above 10 or 20 kilotons to make the investment pay off,

⁴ Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorselaer, K., Velis, C. & Wagner, M. A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

⁵ APK, Company presentation

⁶ [APK, DSM and APK cooperate on recycling multilayer food packaging films, 2018.](#)

finding sufficient feedstock for a capacity above 40 or 50 kilotonnes⁷ a year will probably be complicated. Striking the balance between capacity and available feedstock is therefore key.

Finally, the environmental impact of this type of processes needs to be further assessed as the energy and mass balance, emissions, solvents manufacturing, etc. are not fully analysed.

Because solvent-based purification goes down to the polymer level, some stakeholders claim that solvent-based purification is equivalent to mechanical recycling and should not be classified as chemical recycling. This lack of clarity is an argument for a clear definition for chemical recycling.

3.2 Industrial stage

As highlighted by the different points raised above, this technology still needs significant development to mature. But even though solvent-based recycling for packaging does not exist at scale, a few pilot plants are already working.

Soft Polyvinyl Chloride (PVC)

PVC is the third most produced plastic worldwide. It is used in pipes and electric cables, but also in clothing. The VinyLoop plant was built in 2002 in Italy to treat 10,000 tonnes a year of PVC. This pilot project was founded by Solvay in order to recycle soft PVC from cables or films. It was closed in June 2018 following the new EU's REACH legislation making it clear that phthalates were hazardous. These phthalates were used in the production of PVC in the past, and it was not economically feasible to separate them through the VinyLoop process⁸.

Polystyrene (PS)

The need for an alternative to mechanical recycling for PS is due to the presence of brominated flame retardant hexabromocyclododecane (HBCD) from old insulation material⁹.

In 2017, PolyStyreneLoop was created with the aim of recycling PS across Europe through the CreaSolv Process. They focus on EPS (Expanded Polystyrene also known as styrofoam) containing HBCD that was used for many years in insulation and packaging. A pilot installation, with an annual capacity of 3,000 tonnes of PS foam waste, was built in Terneuzen (Netherlands). The process, developed by the German company Fraunhofer, works as follows: first the foam is dissolved with a solvent, the addition of a second solvent precipitates the polymer, while contaminants stay in the solution. The solvent is then vaporised and can be reused, as well as the polymer. HBCD remains as a sludge, which is sent to a hazardous waste incinerator with a bromine recovery unit to recover some of the bromine (which can then be used in new flame retardants).

⁷ [IFP Energies Nouvelles](#)

⁸ [Plastics Information Europe, VINYLLOOP Closure of operation in Italy / Phthalates issue under REACH brings down European PVC recycling project 2018](#)

⁹ Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorsselaer, K., Velis, C. & Wagner, M. A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

According to Life Cycle Analyses (LCA), this process performs better than incineration regarding CO₂ equivalent emissions and thus having less of an impact on climate change, but not as good as mechanical recycling. The Polystyrene Loop process would have an impact of about -1.5 tonnes of CO₂ eq./tonne input, while incineration of discarded plastic in a waste-to-energy plant emits 1.6 tonnes of CO₂ eq./tonne input, and mechanical recycling -2.3 tonne CO₂ eq./tonne input¹⁰. An ISO compliant LCA, performed by FH Münster and TÜV Rheinland, shows that the PolyStyreneLoop process performs better (roughly 50% of the impact) than incineration with energy recovery in all the impact categories for the treatment of EPS containing HBCD¹¹.

The project is currently supported by the EU through the LIFE programme and its viability without public intervention is unclear.

The use of this process can be extended to the recycling of EPS packaging, even though most of them do not contain HBCD (being mostly packaging for electrical and electronic equipment). However, from an economic and environmental point of view, it is better to mechanically recycle these EPS flows. But it offers a good alternative when the EPS is contaminated (organic waste, smell).

The Canadian company Polystyvert has also been working on PS recycling since 2011, using a patent-pending technology able to separate contaminants from PS. Agilyx opened a polystyrene recycling plant in Oregon (USA) too.

Polyolefins: Polyethylene (PE) and Polypropylene (PP)

These polymers, together representing more than 50% of the global polymer production volume, can be solvent-purified¹².

Unilever has piloted since 2017 the CreaSolv process in Indonesia to recover PE from multi-layer flexible sachets. According to the company, the plant is processing 3 tonnes of flexible plastic daily to recover the PE and use it to make new sachets¹³.

In the meantime, Procter & Gamble is developing the PureCycle Technologies to purify PP - used in automobile interiors, food and beverage packaging, consumer goods packaging, electronics, construction materials, home furnishing, etc. - for use in home cleaning and hygiene product packaging in the US. This technology consists of a solvent-based purification under high temperature and pressure¹⁴.

Finally, in Europe, APK (Germany) has worked since 2013 on the 'Newcycling technology' to recycle several polymers from multilayer packaging. With this process, they are able to produce LDPE (Low Density PE) and PA

¹⁰ M. Broeren, E. Roos Lindgreen, G. Bergsma, Verkenning chemische recycling - update 2019 Hoe groot zijn - en worden - de kansen voor klimaatbeleid?, CE Delft, 2019

¹¹ PolystyreneLoop, www.polystyreneloop.org

¹² Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorselaer, K., Velis, C. & Wagner, M. *A circular economy for plastics - Insights from research and innovation to inform policy and funding decisions*, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

¹³ [Unilever, 2017](#)

¹⁴ [Newswire, 2017, PureCycle Technologies and P&G introduce technology that enables recycled plastic to be nearly-new quality.](#)

(Polyamides) in a near-virgin quality, which can be used in flexible packaging, technical injection molding, labels/stickers and films/laminates, from PE/PA multilayer film waste.

These multilayer films are first dissolved to obtain two distinct fractions: a solid one, containing PA, and a liquid one, containing the dissolved PE. The solid fraction is washed with different solvents to remove impurities, then separated from the new liquid phase and is finally treated before being extruded or pelletised into PA. In the liquid fraction, the solvent is evaporated and can be reused after condensation, while the PE is extruded. Their plant in Merseburg (Germany) is divided into two parts: mechanical recycling and solvent-based recycling are complementing each other. The total capacity of the plant is 20,000 tonnes input per year¹⁵.

¹⁵ [APK, www.apk-ag.de](http://www.apk-ag.de)

4. Chemical depolymerisation

4.1 The technology

Depolymerisation can be described as the exact reverse of polymerisation. It is mostly used for polymers formed through a polymerisation process called polycondensation. During this condensation, two molecules called monomers join together and lose small molecules such as water or methanol.

The activated bonds formed after polycondensation can be broken exactly where they were formed and “add back” the molecule that was lost. In some cases, it is preferable not to go back to the monomer stage again (total depolymerisation), but to divide the polymer in smaller chains (partial depolymerisation). This reaction usually happens with the help of heat and catalysers¹⁶.

After the purification steps needed to remove colourants and contaminants, the pure monomer is obtained. In most cases, the reactant - which enables to break the bonds - for chemical depolymerisation is the solvent. Depending on the solvent used, the name of the reaction differs:

- Hydrolysis, if the solvent is water.
- Alcoholysis, if the solvent is alcohol (glycolysis for ethylene glycol and methanolysis formethanol).
- Aminolysis, if the solvent is an amine (ammoniac, ethylene diamine, etc.).

Some other techniques are being investigated - supercritical fluids, enzymes, reduction reactions or metathesis - but they are at an early research stage. In the figure below, some typical general reactions are displayed.

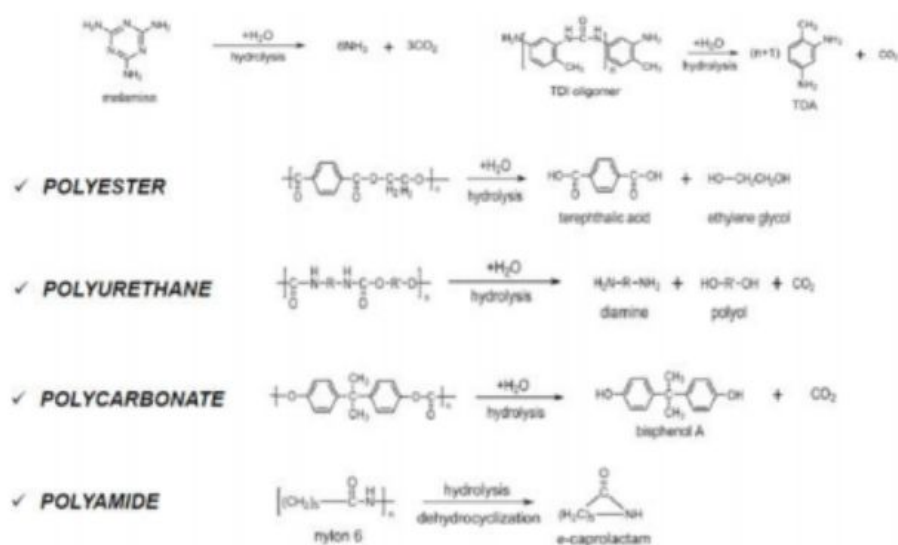


Figure 2: General reactions

Source: Enscm: www.enscm.fr/en/

¹⁶ A. Parenty, C. Dadou-Willmann, 2ACR, Recyclage chimique des déchets plastique : état des lieux et perspectives, 2019

The major possible feedstock for these reactions are: polyesters, polyethylene terephthalate (PET), polyamides (PA), polyurethanes (PU), polylactic acid (PLA), polyhydroxyalkanoates (PHA), polyethylene furanoate (PEF) and polycarbonates (PC). The resulting outputs are single monomer molecules or small polymer chains called dimers or oligomers. These must be polymerised again before the material can be converted into a new plastic product.

Since the resulting output must be polymerised again, the length of the polymer chain is not a problem as it is in mechanical recycling and the plastic can be recycled as many times as wished. The quality of the plastic is then equivalent to the quality of plastic made with virgin polymers. It also implies that the polymer is purified from all the additives that could have contaminated the plastic – from odours to flame retardants or colourants.

However, this technology needs to be performed with heat and sometimes in the presence of a catalyser. The amount of energy required by the process depends on the input material itself as well as the reaction and the separation phase. Multi-layer materials, for example, are more challenging to treat and thus require more energy.

Besides, chemical depolymerisation can be highly selective, provided that it has only one specific input. In order to be efficient, it needs a strict upstream sorting system beforehand.

Moreover, the price difference between the virgin polymer and the recycled one, can be key in the system. If virgin polymers are cheaper than recycled polymers the technology can only be viable if there is market intervention. Hence, as for solvent-based purification, finding sufficient amounts of sorted homogeneous plastic waste, infrastructure and transport are key in the economic viability of the process.

Finally, less information is available on other environmental and systemic impacts of depolymerisation such as yield, leftover by-products or chemical safety of the catalysers.

4.2 Industrial stage

Polyethylene Terephthalate PET

PET is the fourth most produced polymer worldwide. Its applications are mainly for textile (polyester) and plastic packaging, namely PET bottles. Transparent PET can be mechanically recycled, but opaque PET, which is getting more and more common in packaging, is not so easily recyclable¹⁷.

That is why PET is the most widely researched polymer for recycling. Most of the depolymerisation projects are targeting PET flows that are not recycled today, such as packaging PET, textiles or opaque PET bottles.

PET can be depolymerised:

- Through glycolysis to produce Bis-HydroxyEthyl-Terephthalate (BHET). This method is the oldest and simplest. It involves the transesterification of PET with an excess of glycol at temperatures between 180°C and 250°C. A catalyser is usually used to accelerate the process.

¹⁷ Crippa, M., De Wilde, B., Koopmans, R., Leyssens, J., Muncke, J., Ritschkoff A-C., Van Doorselaer, K., Velis, C. & Wagner, M. A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions, 2019 (M. De Smet & M. Linder, Eds.). European Commission, Brussels, Belgium

- Through hydrolysis, at high temperature and pressure, to produce Ethylene Glycol (EG) and Terephthalic Acid (TPA). The main drawbacks are the low purity of TPA and the relative slowness of the process.
- Through methanolysis, at relatively high temperatures (180°C-280°C) and pressure (20-40 atm) to produce Ethylene Glycol (EG) and DiMethyl Terephthalate (DMT)¹⁸.

In the figure 3, some of the ways to depolymerise PET are described.

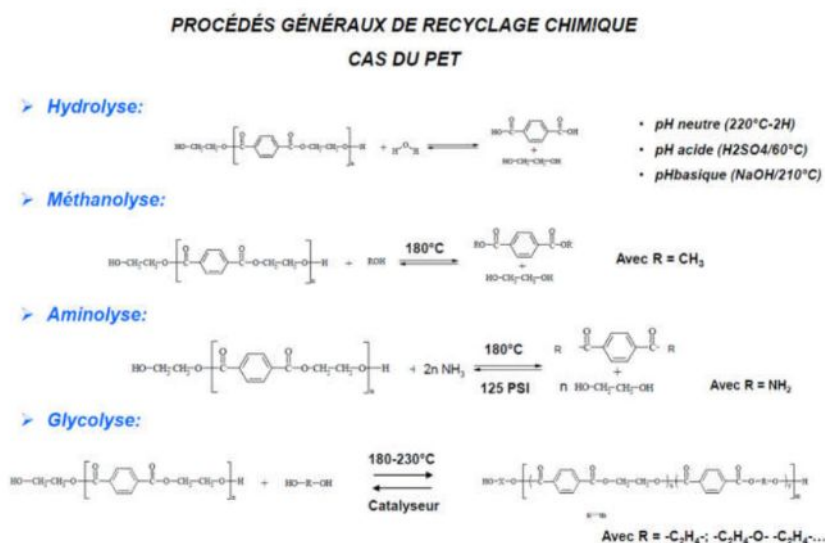


Figure 3: Depolymerisation of PET
Source: Enscm: www.enscm.fr/en/

All these molecules can be repolymerised to form PET again.

Several early stage industrial pilots to depolymerise PET both from packaging and textiles already exist. Garbo (Italy), Ioniqa (Netherlands) and Loop industries (Canada) are some of the most developed ones worldwide.

IONIQA is developing a glycolysis technology involving magnetic fluids to catalyse PET recycling into BHET, enabling it to obtain PET in a virgin quality. Even though the technique is still under development, Ioniqa has completed the funding for the next step: the construction of a production facility with a capacity of 10,000 tonnes a year, which it plans to scale up to 50,000 tonnes. The results of the first screening LCA indicate that the environmental performance of this process is not as good as the performance of mechanical recycling. However, most of the PET waste cannot be mechanically recycled and is currently stored, and could eventually be incinerated. The process developed by IONIQA performs better than incineration or storage on CO₂ equivalent emissions¹⁹.

This process takes place at relatively low temperatures, and the catalyser can be reused many times after applying a magnetic field, keeping the operating costs low²⁰.

¹⁸ Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. Waste Management, 2017

¹⁹ Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. Waste Management, 2017 19 M. Broeren, E. Roos Lindgreen, G. Bergsma, Verkenning chemische recycling - update 2019 and Hoe groot zijn - en worden - de kansen voor klimaatbeleid?, CE Delft, 2019 20.

²⁰ Ioniqa, www.ioniqa.com

GARBO's process, started in 2017 with EU's support, is based on a glycolysis technology with a specific purification system. They are working in collaboration with the University of Modena and Bologna to develop the so called 'ChemPET' project, which claims to be able to deal with almost all the currently non-recoverable PET waste (multi-layer thermoforming scrap and trays, multi-layer film, opaque rigid container, PET fines and dust, black PET trays, PET/PP strapping waste, non-woven fabric and polycotton). Through the reaction with ethylene glycol, PET goes back to BHET. The first plant, based in Cerano, is expected to reach 100 tonnes product per day at the end of 2019²¹.

Loop industries is using a methanolysis process and a specific catalyser to recycle waste PET of all types, including clothes, and break it down without heat or pressure into two monomers: Dimethyl Terephthalate and Mono Ethylene Glycol. Impurities and additives are removed, then repolymerised into new PET plastic, including for food packaging. Started in 2014, this company is working closely with L'Oréal, Danone, Nestlé, Coca-Cola and others. A joint facility with the plastic producing company Indorama Ventures Limited is expected to start its production in the second half of 2020. The production capacity of the plant, located in South Carolina (USA), will be 20,700 metric tonnes. They are also working on securing the feedstock needed for their commercial success²².

The French group Soprema is currently creating a new recycling process within the Sopraloop R&D project launched in 2016. The aim is to combine mechanical recycling and depolymerisation to turn PET packaging waste into polyols used for insulating foam in the construction sector. This project is supported by Citeo (French Producer Responsibility Organisation for packaging) and the ADEME (French Environment and Energy Management Agency). A pilot unit should be created in 2019 to recycle around 5,000 tonnes of PET a year, and could double in the following years. GR3N in Switzerland is using microwaves to catalyse the hydrolysis reaction. This patented technology called DEMETO (DEpolymerisation by MicrowavE TechnolOgy) is able to depolymerise continuously a wide range of different PET types (from colored packaging to textiles) by reducing the reaction time from 180 to 10 minutes. The pilot plant has been running since 2014 and GR3N is currently looking for more funding (€ 3.0 million) to build the first full scale pilot plant, which should produce PET equivalents suitable to all types of applications and cheaper than virgin ones²³.

IFPEN Axens (France) is developing a modular system that can be directly connected to a PET production unit. So far, their glycolysis project, that enables to produce PET monomers from opaque PET waste, is at the beginning of the pilot stage²⁴.

The project lead by Carbios and TechnipFMC (France) to recycle PET waste through hydrolysis with enzymatic catalysis (PETase²⁵), should be taken to the industrial scale in 2021 in Lyon²⁶. The first demonstrator is planned for this year.

In Japan, the company JEPLAN already owns two plants to chemically recycle PET from clothes and non-opaque PET bottles. With this technology, the BHET monomer is produced by depolymerising polyester in

²¹ Garbo & European Commission 2018.

²² Loop Industries, Securities & exchange commission Edgar Filing, www.filings.iirdirect.net/data/1504678/000165495419005416/loop_10k.pdf, 2019 and Loop Industries, Supplying Demand and Transforming a Market, and Loop Industries, www.loopindustries.com/en/tech and www.loopindustries.com/assets/docs/Loop_IR%20Deck_Public_20190507.pdf, 2019

²³ GR3N, www.gr3n-recycling.com

²⁴ IFP Energies Nouvelles, www.ifpenergiesnouvelles.fr/innovation-et-industrie/nos-expertises/climat-et-environnement/recyclage-des-plastiques/nos-solutions

²⁵ H Saporta, L'enzyme du PET nourrit le débat, Plastiques & Caoutchouc Magazine, 2018, www.plastiques-caoutchoucs.com/l-enzyme-du-PET-nourrit-le-debat.html

²⁶ Carbios, Carbios and TechnipFMC sign a contract on PET enzymatic biorecycling, www.carbios.fr/en/carbios-and-technipfmc-sign-a-contract-on-pet-enzymatic-biorecycling_2017

an ethylene glycol solvent, with a metal catalyst and heat. The product of this reaction is then filtered with activated carbon to remove the colorants coming from the caps and the labels.

Through an ion-exchange resin, impurities and the metal catalyser are removed. BHET is then crystallised at 20°C. The ethylene glycol can thus be removed, and the resulting BHET is re-polymerised into PET that can be reused in bottles or clothes²⁷.

PerPETual Global Technologies is based in the UK but the manufacturing and processing facilities are located in India, Turkey and South Korea. In their plant in Nashik (India), they daily convert over 2 million PET bottles into yarns through glycolysis, and are willing to increase the capacity in 2019. Their partners include big brands such as H&M, Adidas, Decathlon and Zara²⁸.

Finally, Eastman (USA) is currently running an engineering feasibility study for a commercial-scale methanolysis facility to recycle PET waste. The type of PET feedstock they are dealing with remains unknown. Their goal is to be operating a full-scale recycling facility by the end of 2021²⁹.

Polyurethanes and polyurethane resins (PU/PURs)

PU/PURs are collectively the fifth most produced plastics in the world. Chemical recycling through depolymerisation is at its early stages for these plastics. However, a few companies, including RAMPF Eco and H&S Anlagentechnik, have developed processes for recycling PU foams.

The multinational company RAMPF Eco, within their collaboration in the European project URBANREC, is producing polyols for all types of foam (shoes, cushions, insulations, mattresses, etc.) via the glycolysis of polyurethane resins from mattresses and furniture³⁰.

H&S Anlagentechnik has also developed a glycolysis process able to produce high-quality recovered polyols on a production scale from PU rigid foams³¹.

Polyamides (PA)

The Italian company Aquafil³² uses depolymerisation to turn used nylon in a new nylon yarn. The high energy intensity and decontamination costs are economically balanced by the high price of virgin PA, making the process cost-efficient.

²⁷ JEPLAN, www.jeplan.co.jp/en

²⁸ PerPETual Technologies, www.perpetual-global.com/manufacturing

²⁹ Eastman, www.eastman.com

³⁰ RAMPF, www.rampf-group.com/en/news/newsroom/2018/chemical-recycling-expertise-for-european-project-urbanrec

³¹ H&S Anlagentechnik, www.hs-anlagentechnik.de/en/recycling-reactors-for-pu-residues.html

³² ECONYL: "Some see trash. Others see treasure" www.econyl.com/the-process 2018

5. Thermal depolymerisation

Thermal depolymerisation and cracking are mainly based on pyrolysis or gasification techniques. They consist in heating up the plastics, but differ from direct combustion: the latter needs oxygen to be performed, while thermal depolymerisation and cracking work under reducing conditions (with no oxygen for pyrolysis or little oxygen for gasification).

They aim at transforming plastics and most of its additives or contaminants back into basic chemicals. Some polymers are more adapted to these techniques, namely those whose chain contains only carbon atoms: polymers synthesised via polyaddition such as polyolefins (PE or PP), PS and PMMA.

Nonetheless, it is important to distinguish between thermal depolymerisation and cracking:

- Controlled thermal depolymerisation is a selective operation which should correspond to the reverse operation of polymerisation, and produce monomers again. That is why it is also called 'plastic to monomer'.
- Cracking thermal depolymerisation consists in cutting the polymer chain in a non-selective way and produces a wide range of different molecules, leading to a product similar to petroleum fractions. Hence, it is also referred to as 'plastic-to-fuel'³³ even though it can potentially produce new plastics if the right conditions are in place.

5.1 Controlled thermal depolymerisation

Controlled thermal depolymerisation (plastic to monomer) exists for two types of plastics, PMMA and PS, because they present some activated bonds that are easier to break.

Poly (methyl methacrylate) (PMMA) is also known as plexiglass. It is a transparent plastic, often used as an alternative to glass, but also in inks or coatings. It can be pyrolysed specifically at 450°C, producing 99% liquid in which 96% is MMA, the monomer for PMMA³⁴. The company Arkema, within the MMAtwo European project, is currently working on this selective depolymerisation.

For PS, the companies Agilyx (USA) and Pyrowave (Canada) are developing new processes. Pyrowave is planning to recycle PS through a catalytic microwave depolymerisation technology.

Very little information is available on these processes.

5.2 Cracking thermal depolymerisation

In general terms these technologies can in principle produce either monomers for plastic production or fuel, and whether the output will be the former or the latter depends on the inputs to the process but above all on the outputs that it aims to produce. Thermal depolymerisation aiming at producing plastic out of plastic needs to have security of supply and demand and once it is set up it is difficult to change the output. This is why these plants tend to be built next to the facility that will be using the building blocks for new plastic, for instance Plastic Energy is building a depolymerisation plant next to SABIC which commits to buy the production. In practice this means that plastic to fuel depolymerisation is more flexible and mature than plastic to plastic depolymerisation and if left to the market alone without the right regulation it is likely that plastic to fuel

³³ A. Parenty, C. Dadou-Willmann, 2ACR, Recyclage chimique des déchets plastique : état des lieux et perspectives, 2019

³⁴ Dimitris S. Achilias, Chemical Recycling of Polymers. The Case of Poly(methyl methacrylate), Aristotle University of Thessaloniki, 2006

depolymerisation will prevail over plastic to plastic. Because of this opportunity, some companies are deliberately conflating the two and pushing to group together plastic to plastic and plastic to fuel depolymerisation technologies.

Cracking processes are already on the market not only in the USA (Agilyx, Eastman, Plastic2oil, etc.), but also in Europe (Plastic Energy and Recycling Technologies in Great Britain, Recenso in Germany, etc.) and some other initiatives are emerging.

Pyrolysis

In the pyrolysis technique, plastics are broken down into a range of simpler hydrocarbon compounds by heating them in the absence of oxygen. Polymers tend to fragment into smaller hydrocarbon molecules which can be collected as effluents by condensing the hot gases.

Several types of pyrolysis exist:

- Conventional pyrolysis, during which the input is heated at a temperature between 400°C and 600°C.
- Integrated hydrolysis, during which the cracking process takes place in the presence of water at 300°C to 600°C³⁵.

The feedstock is supposed to be quite flexible: the technology can be applied to mixed and contaminated plastics streams. But the reality is different: some oxygenated resins such as PET are coke precursors which need to be avoided to obtain a good yield in liquid fraction, or PVC and brominated plastics, which lead to the production of acids. The formed acids, and especially HCl formed by PVC, will have to be removed (implying additional steps, even though HCl cannot be reused because it will be contaminated) and impose severe metallurgic constraints on the equipment material. Recyclers will mostly target polyolefins (PE or PP). Integrated hydrolysis is less sensitive to the variation in inputs, but it is still challenging to recycle PET, nylon and PVC through this technique.

The composition of the output mix can be controlled to some extent by changing the process parameters such as temperature, but the degradation is not controllable. It presents three different fractions: gas, liquid and solid residue (carbon char). Bond cleavage happens in random positions, leading to a hydrocarbon mix whose composition is similar to oil and can be used directly as fuel.

Pyrolysis enables to clean out additives and contaminants as part of the process. The output can be processed in the same way as oil, using conventional refining technologies to produce value-added chemicals, including new monomers, indistinguishable from virgin-grade ones. Hence, the additional processing infrastructure needed already exists in a mature and efficient value chain.

Plastic Energy owns two pyrolysis plants in Spain, running since 2014 and 2017, to transform LDPE, HDPE, PS and PP into hydrocarbon vapour. The resulting condensable gases are converted into raw diesel, light oil and synthetic gas components. These are then sold to the petrochemical industry to either turn them into virgin plastic, oil or transportation fuels. The other non-condensable gases produced during the process are combusted to produce the energy necessary to run the plant³⁶.

³⁵ M. Broeren, E. Roos Lindgreen, G. Bergsma, Verkenning chemische recycling - update 2019 and Hoe groot zijn - en worden - de kansen voor klimaatbeleid?, CE Delft, 2019

³⁶ Plasticenergy www.plasticenergy.com

Nevertheless, in spite of the simplicity of this technology, pyrolysis has high energy requirements and can lead to the formation of hazardous chemicals such as Polycyclic Aromatic Hydrocarbons (PAH) or dioxins, implying the need for further purification steps. Furthermore, it is only economically viable if the volumes are large enough, and the input stable in terms of quantity, composition and quality. Pyrolysis is indeed expensive: according to the US Energy Information Administration (Department of Energy), the cost to produce 1 kilowatt of energy through pyrolysis is twice the cost of a kilowatt produced with photovoltaic solar energy³⁷.

Finally, considering the fact that turning the output fuel into new plastics requires other energy-consuming steps, there is a risk that the 'plastic-to-fuel' pathway will be preferred by the market.

Today, the main viable market for pyrolysis output is crude diesel for power plants or ships. Besides, to optimise the conversion into plastics, increasing the naphtha fraction is necessary, which is challenging. Encouraging pyrolysis would consequently create a 'linear lock-in' for plastics. Policy intervention is therefore mandatory to ensure this technology is indeed used to close the plastic-to-plastic loop and help decarbonize the economy instead of contributing to it by turning plastic into fuel.

Gasification

The gasification technique consists in heating mixed after-use materials (plastics and possibly biomass), in the presence of limited oxygen. It is able to treat almost every feed composed of organic material.

There are several types of gasification, in which the temperature and other parameters can vary. Medium temperature gasification is less sensitive to fluctuations in composition and moisture than low temperature gasification.

The Texaco gasification process (figure 4) is the most common and well-known technology. The plastic waste is first cracked into synthetic heavy oil and some condensable and non-condensable gas fractions. The non-condensable gases are reused in the liquefaction as fuel (together with natural gas). The oil and condensed gas produced are injected into the entrained gasifier. The gasification is carried out with oxygen and steam at a temperature of 1,200°C – 1,500°C. Finally, a number of cleaning processes are performed (amongst others HCl and HF removal)³⁸.

The gasification output is a mix of predominantly hydrogen and carbon monoxide, smaller quantities of methane and carbon dioxide called syngas. It can be used to produce a variety of chemicals and plastics. It also contains impurities: NH₃, H₂S, NO_x, alkali metals and tars. The purification step is the major contributor to the costs of producing the syngas.

³⁷ M Wilson, C. Arkin, In our opinion: Fueling a fantasy, 2018, www.resource-recycling.com/recycling/2018/04/02/in-our-opinion-fueling-a-fantasy

³⁸ Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. Waste Management, 2017

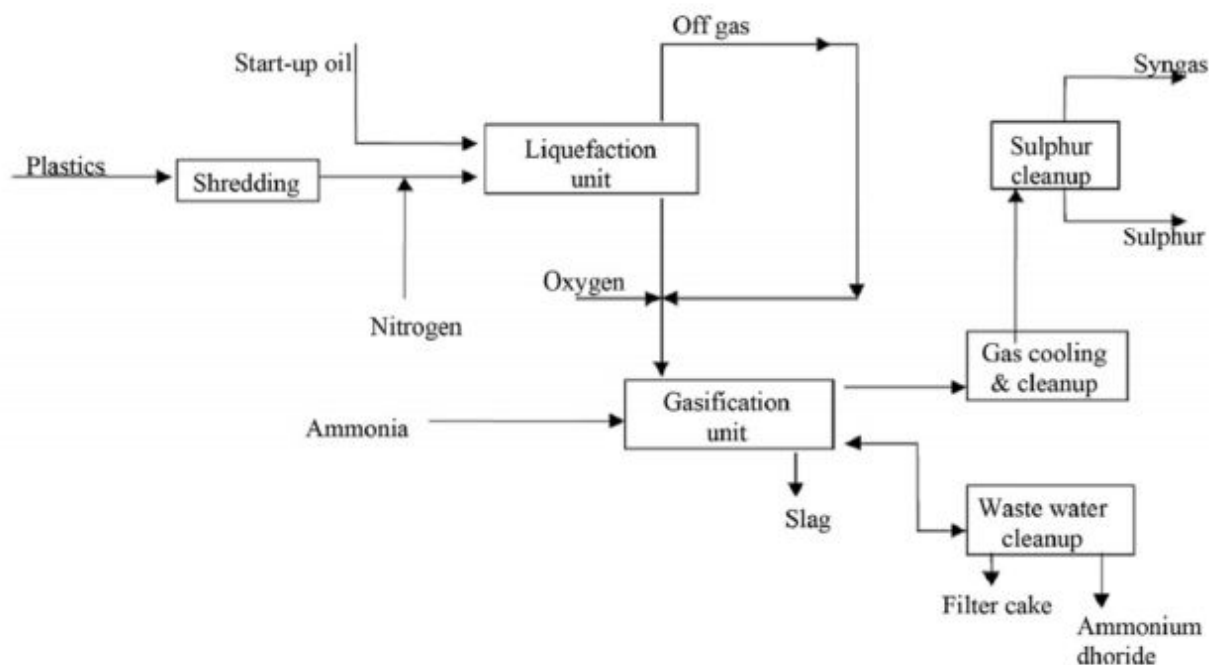


Figure 4: The Texaco gasification process schematic diagram

Source: Brems et al., 2015 *Gasification Of Plastic Waste As Waste- To- Energy Or Waste- To- Syngas Recovery Route, Solid Waste as a Renewable Resource*. Apple Academic Press, pp. 241–263.

However, for low temperature gasification (700°C – 900°C), the syngas is only suitable for energy applications. For medium temperature gasification (900°C – 1,650°C), the syngas is suitable for plastic-to-plastic applications, but only after an additional step to increase the quality of syngas, which is measured by the ratio H₂/CO. There is thus a strong focus on energy production.

Enerkem in Canada is using a medium temperature gasification with a fluidised bed technology to produce fuel (ethanol) and methanol from sorted municipal solid waste (after recycling and composting). A similar project is being developed in Rotterdam (Netherlands): a consortium gathering Air Liquide, Enerkem, Nouryon, the Port of Rotterdam and Shell was created to build the first ‘waste-to-chemicals’ plant in Europe. It should be able to process 360,000 tonnes of waste into 220,000 tonnes of methanol. The conversion from syngas to methanol is usually performed at high temperature and pressure. This methanol can then be converted into chemicals such as acetic acid (for fibres and adhesives), thickening agents and dimethyl ether, which are currently produced almost entirely from fossil fuels³⁹.

Gasification presents more or less the same risks and challenges as pyrolysis. The technology is also energy-intensive and requires large volumes of stable waste in terms of composition and moisture. A pre-treatment is necessary to remove moisture and increase the calorific value of the input, resulting in higher costs. The output chemicals can produce fuels and fertiliser, but they will most likely be used as fuel, as it is the case today.

As with pyrolysis, policy intervention is needed to ensure plastic gasification stays in the plastic-to-plastic loop instead of being diverted to fuel.

³⁹ Ragaert, K., et al. Mechanical and chemical recycling of solid plastic waste. *Waste Management*, 2017

5.3 Environmental impact assessment of chemical recycling

The chemical recycling processes studied in this report are still very new and so far, most of the existing analysis were performed or led by the industries themselves. Therefore, further analysis on the environmental impact –notably analysing plants at scale and not at pilot stages– needs to be performed before a conclusive statement can be made or operating permits given.

The same is true for the energy and mass balance of the technologies analysed. Information available is, at best, insufficient, and at worst discouraging for technologies such as pyrolysis⁴⁰. The health impacts from the emissions of such plants are also unknown.

An ISO compliant LCA, considering the whole plastic product life cycle, in which a realistic energy mix provenance is considered, is a good method to evaluate the consistency of such techniques from an environmental perspective. These calculations should take into account all the necessary purification steps. The results of these analyses should be compared with other existing and mature end of life treatments – mechanical recycling, mechanical and biological treatment (MBT), landfilling and energy recovery incineration.

It is important that the environmental impact assessments look not only at the climate impacts of today but also at the impacts that these technologies will have in the future, in the context of a decarbonising economy.

⁴⁰ Rollinson, A., & Oladejo, J. (2018). 'Patented blunderings', efficiency awareness, and self-sustainability claims in the pyrolysis energy from waste sector

6. Plastic to fuel in the XXI century

This study presents how some of the technologies used to produce plastic from plastic waste via chemical recycling, namely pyrolysis and gasification, can be used to produce fuel. Although these operations use the same core technology as other chemical recycling operations, their outputs, and therefore their impacts on the environment and the plastic economy, are quite different. Therefore from a political and economic perspective it is paramount to differentiate them. There are several reasons for doing so:

1. They risk undermining the Circular Economy agenda⁴¹. Turning plastic into fuel does not reduce the demand for virgin plastic, meaning that new plastic needs to be produced out of fossil sources. These techniques are undermining plastic reduction, the development of sustainable alternatives or innovations, and the incentives to phase out non-recyclable plastics. It prevents the EU from achieving its ambitious goals under the Circular Economy Strategy, including having all plastic packaging placed in the market be reusable or easily recyclable by 2030. As China's ban on recyclable imports is giving an opportunity for real change, plastic-to-fuel is encouraging to stay in this system by convincing consumers and cities that this waste can be "recycled" when the plan is to burn it.
2. It undermines the EU decarbonisation agenda⁴² and the Paris agreement. Since plastic is made overwhelmingly from fossil fuels, plastic-derived fuels are a form of fossil fuel. The EU is currently set in the path to move away from fossil-fuel based sources of energy and plastic-to-fuel opens new doors to continue emitting CO₂ when we should be closing them. Turning plastic waste into fuel doesn't help to close the loop as it is still an energy intensive process that requires new virgin plastic to be produced. As such, plastic-to-fuel could be used to justify an increased virgin plastic production, creating this linear lock-in for plastics. Building new plastic-to-fuel facilities risks lock-ins at both the upstream and downstream ends of the plastic lifecycle: new PTF facilities will require a steady stream of fossil-based plastics produced.

Consequently, in order to avoid creating a legislative loophole in both the Circular Economy and the Climate agendas, it is key that the EU sets the right policies to direct plastic waste to plastic recycling operations, be it plastic to plastic mechanical or chemical recycling.

6.1 The right legal framework for chemical recycling

A clear definition

According to the current EU waste legislation: Art 3.17 (WFD, 2008/98/EC): "recycling" means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations".

⁴¹ www.ec.europa.eu/environment/circular-economy/index_en.htm

⁴² www.ec.europa.eu/clima/policies/strategies/2050_en

Therefore, the Waste Framework Directive's definition of recycling already comprises plastic-to- plastic recovery operations whether the process is mechanical or chemical. However, this poses the problem of blurring the preference that mechanical recycling should have over **chemical recycling and it is important to make explicit that chemical recycling is only suitable for those cases in which plastic waste is too degraded, too complex or too contaminated to be mechanically recycled.**

A definition is also important to differentiate plastic-to-plastic chemical recycling from plastic-to- fuels, given the growing confusion of both terms promoted outside EU borders. For instance, the Chemical Recycling Alliance created by the American Chemistry Council, considers chemical recycling as those technologies that convert post-use plastics into chemicals, fuels and other products⁴³ . Such consideration is at odds with the European waste legislation and it is yet another reason to provide legal certainty to these operations.

A potential definition for chemical recycling that excludes both mechanical recycling and plastic to fuels could be:

“Chemical recycling means any recovery operation by which waste materials that are unfit to be mechanically recycled are reprocessed into building blocks of a material of higher quality than the waste input.”

A new level in the waste hierarchy

Besides a clear definition for chemical recycling, it is recommended to amend the EU waste hierarchy (Art 4) in order to create a new level to accommodate material recovery operations that are not mechanical recycling but whose output allows closure of the material loop. The rationale for this is based on the current available evidence on the environmental impacts of the different operations but also on the understanding of the economic and logistical aspects of current waste management processes. In this respect the waste hierarchy sets the following operations from lowest to highest environmental impact: prevention operations, mechanical recycling, chemical recycling and energy recovery.

Indeed, the process of mechanical recycling has the limitation that it is not possible to mechanically recycle every type of plastics (e.g. opaque PET), plastics which contain toxics (e.g. brominated flame retardants) or plastics that are too degraded. Mechanical recycling also usually entails downgrading the plastic quality, a process known as “downcycling”. Mechanical recycling is consequently not a perpetual recycling method for plastics. This is why chemical recycling could play a role in the Zero Waste Hierarchy, as described in figure 5.

The nature of the plastic waste that is to be chemically recycled is equivalent to what today would be considered to be residual waste, since properly sorted plastic waste would be mechanically recycled. This is another argument for creating a dedicated level in the waste hierarchy to deal with residual waste in a way that allows for avoiding new virgin materials to be used. This is what in the Zero Waste Hierarchy (see figure 5⁴⁴) belongs to the 5th level: “Material and chemical recovery” namely dealing with the discards of sorting processes or with mixed waste with Mechanical Recovery and Biological Treatment operations that recover materials and

⁴³ www.plastics.americanchemistry.com/Chemical-Recycling-Alliance.html

⁴⁴ Zero Waste Europe, A Zero Waste hierarchy for Europe, 2019, www.zerowasteurope.eu/2019/05/a-zero-waste-hierarchy-for-europe

stabilise organic waste, or with chemical recycling whose output are new building blocks for new plastic applications.

In contrast, the technologies that turn plastic to fuel don't allow for plastic waste to achieve its highest and best use and hence in the Zero Waste Hierarchy belong to the 7th level classed as "unacceptable".



Figure 5: A Zero Waste Hierarchy for Europe

Source: www.zerowasteurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/

7. Recommendations & conclusion

Today Chemical Recycling offers a range of potential solutions to the limitations of plastic as a circular material. Indeed, the capacity to upcycle degraded or contaminated plastics is an opportunity to close the loop and detoxify the Circular Economy which should be explored.

However, these technologies are still mostly in a pilot stage and they will not be able to operate at scale until the second half of next decade at the earliest. Considering the speed of change in the way we are using plastic today, it is uncertain how the plastic waste market will look 10 years down the line. Chemical recycling is currently uncompetitive with virgin plastic production and will require large-scale shifts in market conditions to establish itself. On the other hand, the lack of a clear legal definition for chemical recycling - in particular, one that excludes plastic-to-fuel - invites confusion and risks undermining both the Circular Economy and climate goals. If plastic is to become a circular material and the toxics are to be phased out, maybe there will be no need for chemical recycling to deal with contaminated plastics in a world in which plastics should be designed to be less and less toxic. On the other hand, we know that plastics cannot be infinitely recycled and hence a solution for degraded plastics that does not involve downcycling or incineration is worth considering.

Moreover, it is important not to lose sight of the scale of the challenge and the solutions at hand. Whilst chemical recycling can be a tool in the waste management toolbox, one should not forget **that the solution to the plastic challenge is not to be found in how we manage the waste we create, but rather in how to prevent this waste from arising and preserve the value of materials in the economy.**

Indeed, the chemical recycling hype should not divert the attention from the real solution to plastic pollution which is replacing single-use plastics, detoxifying and simplifying new plastics, and designing business models to make efficient use of plastics.

This is especially relevant when it comes to potential EU funding to be made available in the coming years for the transition to a Circular Economy. The EU should avoid repeating past mistakes in waste policy such as the financing of waste-to-energy technologies instead of the higher levels of the waste hierarchy. EU funding should be directed to prevention, reuse operations, and any business model that prevents waste from being created. Too much focus on the residual waste treatment operations will not deliver a real Circular Economy.

With this in mind, a number of question marks are to be addressed in the roll out of the chemical recycling technologies. What are the scale of the plants that will make chemical recycling economically viable considering the costs of collection of such a low-weight material? Can chemical recycling be cost-competitive with virgin plastic in a world in which plastic from fracked gas makes recycling less and less competitive? What is the demand for the chemical recycling outputs of the different recycling processes? What are the real environmental and health impacts of the different chemical recycling processes when operating at scale?

The success of chemical recycling lies in the ability to be complementary to the other waste management processes whilst contributing to move towards a low carbon Circular Economy. At present the level of legal and economic uncertainty is high as is the lack of independent information available. It is key that the EU takes the initiative to regulate and provide the legal certainty that the market needs.

Glossary

| | |
|-----------------------|---|
| | |
| atm | atmosphere (pressure unit) |
| BHET | Bis(2-Hydroxyethyl) terephthalate |
| DMT | Dimethyl Terephthalate |
| EG | Ethylene Glycol |
| EPS | Expanded PolyStyrene |
| HBCD | HexaBromoCycloDodecane (brominated flame retardant) |
| HCl | Chlorhydric Acid |
| HF | Fluorhydric acid |
| H₂S | Hydrogen Sulfide |
| LCA | Life Cycle Analysis |
| LDPE | Low Density Polyethylene |
| NH₃ | Ammonia |
| NO_x | Nitrogen oxides |
| PA | Polyamides |
| PAH | Polycyclic Aromatic Hydrocarbons |
| PC | Polycarbonate |
| PE | Polyethylene |
| PEF | Polyethylene Furanoate |
| PET | Polyethylene Terephthalate |
| PHA | Polyhydroxyalkanoates |
| PLA | Polylactic Acid |
| PMMA | Poly(methyl methacrylate) |
| PP | Polypropylene |
| PS | Polystyrene |
| PU | Polyurethane |
| PVC | Polyvinyl Chloride |
| TPA | Terephthalic Acid |

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Zero Waste Europe is the European network of communities, local leaders, businesses, experts, and change agents working towards the same vision: phasing out waste from our society. We empower communities to redesign their relationship with resources, to adopt smarter lifestyles and sustainable consumption patterns, and to think circular.

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