Chemical Recycling: State of Play

Report for CHEM Trust

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E.1.0 Executive Summary

This report aims to cover the spectrum of technologies that fall under the umbrella of ***chemical recycling***, with a focus on those with outputs that can be reintroduced into plastics manufacturing as virgin equivalents. Some consideration is also given to other processes that produce other chemical feedstocks that can similarly be viewed as recycling or materials recovery. The research underpinning the report has centred on the European context but has drawn on literature published globally. However, it does not purport to provide a comprehensive, worldwide review of all relevant technologies in this rapidly developing industry.

The focus of this report is to detail the technologies that have been developed, determine how mature they are and for which polymers they are aimed at. Their comparative environmental performance is also discussed against key benchmarks including waste to energy incineration (WTE), mechanical recycling and virgin polymer production. Finally, we also discuss some of the key issues that these technologies face including when to leverage these versus other options and how they may fit into European waste legislation.

The process of chemical recycling can be split into three broad technology categories:

- **Solvent Purification** – This uses the principle of solubility to *selectively separate* plastic polymer from any other materials contaminating the plastic waste. The plastic is shredded and dissolved within a solvent that the polymer has high solubility in, but the contaminants have low solubility in. The contaminants will, therefore, remain solid and so can be separated off from the liquid fraction to purify the polymer. Once the purification process is complete, the polymer is extracted from the solution by placing in a non-solvent to re-solidify the polymer, in a process known as precipitation, to allow recovery.
- **Chemical Depolymerisation** - Processes by which a *polymer chain is broken down* through the use of chemicals, have numerous names including chemolysis and solvolysis. Once the depolymerisation has occurred, the monomers are recovered from the reaction mixture and purified, through distillation, precipitation and/or crystallisation, to separate them from contaminants and leave the pure monomer.
- **Thermal Depolymerisation** - also known as thermal cracking and thermolysis, is the process by which a *polymer chain is broken down* using heat treatment. The main focus in this report are variations on the *pyrolysis* technique. The degradation pathway typically involves scission of bonds at random positions in the polymer chain, as opposed to the controlled breakdown seen in chemical depolymerisation. This means that the resulting *pyrolysis oil* is usually composed of a variety of hydrocarbon products which requires further energy intensive purification before it can be used as a feedstock for polymer production in, for example, a steam cracker (replacing naphtha).

The key aspects identified for the three technology types are presented in Table 1, based on the information available to this study.

Table 1: Key Chemical Recycling Technology Aspects

Claim	Solvent Purification	Chemical Depolymerisation	Thermal Depolymerisation
Complexity of downstream product integration	Direct — produces polymers	Indirect — produces monomers that require integration into existing virgin value chain	Indirect — polyolefins produce hydrocarbons that require purification before integration into existing virgin value chain. PS can go direct to monomer.
Virgin-equivalent recycling is possible	No — thermal degradation is likely as in mechanical recycling	Yes — however, losses are variable depending upon specific technology	Yes — but not without significant losses in each recycling loop
Food grade polymers can be produced	Not likely	Yes — polymers indistinguishable from virgin	Yes —polymers indistinguishable from virgin
Removal of contaminants/ additives	Limited/specific	Yes — although relatively 'clean' inputs are needed to ensure viability	Yes — this is inherent to the process
Pre-sorting and/or pre-treatment required	Yes — relatively clean, homogenous plastic waste is required to achieve high yields and non-fuel-based outputs. Contamination handling capabilities are not generally well understood or communicated		
Environmental performance	Lack of verified environmental performance data for the majority of technologies		
Verification of chemical use and by-products	Lack of clarity regarding the solvent types and associated hazardousness for larger scale technologies	Lack of transparency regarding inputs/by-products and their potential	Lack of clarity as to the recycling of by-products and reagents as part of the process

E.1.1 Technical and Commercial Maturity

The following summarises the key conclusions around the technical and commercial maturity of the three overarching technology types:

- **Solvent purification** technologies are likely to be a niche chemical recycling application with the most promising currently being EPS that is contaminated with legacy fire retardants. It is very energy intensive which makes it difficult to compete with mechanical recycling. As the output is a polymer, the process can be treated similarly to mechanical recycling with regard to recycling calculation rules. Importantly, the subsequent reprocessing to remanufacture new plastic products leads to degradation of the polymer chain. As such, this chemical recycling technology does not allow for infinite recycling of the material.
- **Chemical depolymerisation** technologies appear to have the most promise overall, particularly for PET/polyester using glycolysis and hydrolysis variations, with claims to yields of upwards of 90% and produce a pure monomer feedstock. As such, the issues with calculating recycling rate and recycled content are likely to be relatively easy to overcome using similar rules created for mechanical recycling. The linkage between PET packaging and polyester clothing fibres means that this technology could be deployed in interesting ways to improve recycling rates of both kinds of products. However, it is unlikely to be a substitute for the mechanical recycling of PET bottles particularly when they are part of a deposit refund system (DRS) that can provide clean, homogenous material for bottle-to-bottle recycling.
- **Thermal depolymerisation**, which primarily refers to variations of pyrolysis, has seen a large amount of attention as it is a well-established process in the waste industry for producing fuel products. However, deploying it as a way of producing feedstocks that can directly feed into monomer/polymer production is a relatively new application that has yet to be proven commercially. The thermal depolymerisation process itself is far less controlled than chemical depolymerisation, which results in multiple chemical outputs with varying utilisation value. The pyrolysis oil, when used as a substitute for naphtha in a monomer producing steam cracker also results in losses, as monomers are not the only output; fuel gas is also a product that is often fed back into the process to reduce reliance on external fuel sources. Understanding this is key to calculating overall polymer yields from the process.

  Whilst it is typically possible to use a heterogeneous and contaminated feedstock, this reduces yields and currently makes purification for insertion into steam crackers unviable. The purification step has also not been tested at commercial scale and it is unclear whether pyrolysis oil can consistently meet the strict specifications of steam crackers in practice. The requirement for advanced sorting and washing that is being developed to improve mechanical recycling will, therefore, likely also be a requirement.
  Other than for niche applications such as PMMA, the use of pyrolysis to recycle a mixed (but clean) polyolefin stream appears to have the most promise

particularly for applications where specific waste types can be segregated, but are not attractive to mechanical recyclers (e.g. films). A scenario where mixed plastic waste is sorted into multiple streams for chemical and mechanical recycling is likely to be the best use of this technology. This type of chemical recycling is also likely to be the most challenging to determine transparent, fair, implementable and enforceable rules for calculating recycling rate and recycled content as the pathway is not linear or segregated.

E.1.2 Environmental Considerations

From the review of life cycle assessment (LCA) studies conducted for this report, some key considerations begin to arise that should be understood when reading LCAs that focus on chemical recycling. These aspects are likely to have the most influence over the results, particular where global warming potential is the focus:

- **Energy use** is generally the most important aspect. This includes the energy use of the chemical recycling process—which is invariably the aspect that influences both the environmental and economic performance the most—as well as the energy mix of the country in question. The latter particularly affects comparisons between chemical recycling and WTE and, therefore, forward-looking scenarios that show the future projected energy mix should be included.
- **Yield** also tends to be a defining factor that affects how viable a process is. Losses in the system need to be accounted for to accurately calculate this. Studies conducted at lab scale or demonstrator stage are likely to include a number of assumptions around this that may not reflect the reality at scale. There is generally a lack of consistency and transparency around this aspect in particular.
- **Quality of input material streams** will have a large influence on the yield and energy use as generally, the cleaner the stream the higher the yield and lower the energy use (less purification is needed). Determining realistic scenarios for this is key, especially where post- consumer household plastic waste is concerned. Achieving a high level of input quality will also need to take into account the local collection method and the necessary sorting processes. This aspect is likely to be very geographically specific and it is currently unclear whether this can be achieved at scale.
- **Quality of output material streams** are also important and LCAs should seek to characterise the quality of these outputs for both mechanical and chemical recycling in order to fairly compare. Recognising that a great deal of mechanically recycled plastic is not used in virgin grade equivalent applications can help to determine which product/material types are most likely to be suitable for chemical recycling.

Additionally, the following general observations and conclusions can also be made, which are informed by available information from LCAs that have been conducted both publicly and behind closed doors:

- Most studies only focus on comparisons with WTE or virgin production of fuels and polymer precursors. These comparisons provide a narrow perspective that cannot form the basis of strategic, long-term decision making. Therefore, forward-looking scenarios that show the future projected waste management alternatives for plastic, such as reuse or mechanical recycling in relation to established EU or national targets should be included.

- One of the key aspects that is missing from the environmental assessments to date, is a systems perspective aimed at understanding how these technologies might be deployed in reality. Studies tend to focus on comparative assertions and not where different technologies might complement each other.
- Even when compared with a relatively poorly performing mechanical recycling scenario, current pyrolysis oil to monomer processes appear to be too energy intensive to compete.
- Pyrolysis appears to only be viable for waste streams that cannot be effectively mechanically recycled. However, this should not move the focus from initiatives to reduce or prevent this type of waste, or to cease looking for alternatives that can be effectively mechanically recycled as the current evidence suggests that these are still preferable environmental options.
- To invest in pyrolysis infrastructure to treat all types of currently unrecyclable plastic might ‘lock in’ increased environmental impacts over the long term in a similar way in which the shift towards WTE has done so in countries that have invested heavily in incinerators. A joined-up policy on plastic use in the future should consider this and other aspects such as any move towards bio-based plastics (particularly ‘drop-in’ versions of current plastics such as bio-PET or bio-PP). Whilst current LCA results suggest most chemical recycling is an improvement on WTE, this may not be the case for bio-based plastics particularly for climate change impacts.

E.1.3 Key Conclusion

Throughout this report the overriding finding is that there is a general lack of transparency or robust evidence base that can be used to verify claims or generate firm conclusions around the viability of many technologies. This is due, in part, to the sheer number of smaller, lab scale examples that demonstrate possibility rather than viability. At the commercial scale (or close to it), the competition to be first to market is strong and this appears to limit publicly available evidence. This also means that caution must be exercised as a lack of evidence can mean either a knowledge gap or that the answer is less favourable.

In the interests of confirming the role, scale and scope of these technologies, there is an urgent need for more transparency within the chemical recycling industry. There is evidence to indicate that at least some technologies have promise, but important details around mass flows, chemical use and the viability of the processes in real-life waste management circumstances are largely incomplete. Investment should be reserved for those organisations that freely engage to improve the understanding around these missing elements.

Contents

1.0 Definitions and Acronyms

Bio-based polymer	A polymer composed or derived in whole or in part of biological products from biomass
'Drop-in' bio-based plastics	Ability to be exchanged directly with their fossil-based counterpart
(E) PS	(Expanded) Polystyrene
HDPE	High Density Polyethylene
LCA	Life Cycle Assessment
PA	Polyamide (nylon)
PET	Polyethylene Terephthalate
PLA	Polylactic acid
PMMA	Polymethyl methacrylate
Polyolefin	A family of polyethylene and polypropylene thermoplastics
PP	Polypropylene
PU	Polyurethane
WTE	Waste to Energy – residual waste incineration with energy recovery via electricity generation and sometimes heat recovery

2.0 Introduction

The term plastic denotes a broad range of materials, both natural and synthetic, that have two main features. The first is the chemical structure, which is comprised of small, organic chemicals called monomers that are linked together in long chains to form polymers.[1] The term organic here describes substances composed predominantly of carbon and hydrogen. The second is the material's malleability during manufacturing, allowing the substance to be moulded into shape with ease – a property that has led to its widespread use.

The versatility of plastics has led to their use within myriad industries globally. In 2018, it is estimated that 359 million tonnes of plastics were produced— an increase of 3.1% from 2017[2]. This utilisation, however, comes at a cost. The continued use of fossil fuels used in the production of virgin material, as well as the ever-increasing build-up of plastic waste that is not recycled, has served to highlight the difficulties faced by the industry to minimise its environmental impact.

As such, the diversion of plastic from landfill is of great importance to minimise the use of raw materials and reduce waste. The increasing move towards waste to energy incineration (WTE) plants is problematic for plastics that contribute highly to greenhouse gas (GHG) emissions. Mechanical recycling seeks to retain the value of the material and use it for new products, but the increasing diversity and dispersion of polymers makes this a significant challenge. Initiatives to improve identification and sorting, alongside the effort to rationalise polymer use, are aimed at increasing recycling rates, however, this might not be enough. As such, chemical recycling technologies are increasingly being looked to as a way of filling the gaps where mechanical recycling is not feasible.

Chemical recycling is defined by Crippa et al. as:

> *"any reprocessing technology using chemical agents or processes that directly affect either the formulation of the plastic or the polymer itself."*[3]

Put simply, the concept is to recycle plastics by changing their material structure. Plastics are composed predominantly of polymers, which are often combined with other chemical additives to tailor the properties of the plastic for use.[4] Mechanical recycling technology cannot effectively separate the additives from the polymer, nor any non-intentionally added substances that have entered the plastic waste during use or

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[1] European Chemicals Agency (2012) Guidance for monomers and polymers

[2] Plastics Europe (2019) Plastics – the Facts 2019

[3] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[4] American Chemistry Council *The Basics of Plastic Manufacturing*, https://plastics.americanchemistry.com/How-Plastics-Are-Made/

reprocessing.[5,6,7,8] This, in turn can limit the recycled material's subsequent use. Chemical recycling aims to address this issue by separating the polymer from the other contaminants within the waste. This can either be through selective purification of the whole polymer chains from contaminants (purification), or by breaking down the polymer back into its monomers or other simpler chemicals (depolymerisation) which can be subsequently repolymerised. However, it is important to note that chemical recycling technologies are not exclusively processes that reproduce feedstocks for plastics recycling.

As such, this report aims to cover the spectrum of technologies that fall under the umbrella of chemical recycling, with a focus on those with outputs that can be reintroduced into plastics manufacturing as virgin equivalents. Some consideration is also given to other processes that produce other chemical feedstocks that can similarly be viewed as recycling or recovery. The focus of this report is to detail the technologies that have been developed, determine how mature they are and for which polymers they are aimed at. Their comparative environmental performance is also discussed against key benchmarks including WTE, mechanical recycling and virgin polymer production. Finally, we also discuss some of the key issues that these technologies face including when to leverage these versus other options and how they may fit into European waste legislation. The research has centred on the European context but has drawn on literature published globally. However, it does not purport to provide a comprehensive, worldwide review of all relevant technologies in this rapidly developing industry.

Important Note:

Throughout this report the overriding finding is that there is a general lack of transparency or clear evidence base that can be used to back up claims or generate firm conclusions around the viability of many technologies. This is due, in part, to the sheer number of smaller, lab scale examples that demonstrate possibility rather than viability. At the commercial scale (or close to it), the competition to be first to market is strong and this appears to limit publicly available evidence. This also means that caution must be exercised as a lack of evidence can mean either a knowledge gap or that the answer is less favourable.

A distinction is made throughout to highlight where claims are being made by interested parties; and where the evidence supports this and where this is lacking.

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[5] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[6] Horodytska, O., Cabanes, A., and Fullana, A. (2020) Non-intentionally added substances (NIAS) in recycled plastics, *Chemosphere*, Vol.251, p.126373

[7] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[8] Webb, H.K., Arnott, J., Crawford, R.J., and Ivanova, E.P. (2013) Plastic Degradation and Its Environmental Implications with Special Reference to Poly(ethylene terephthalate), *Polymers*, Vol.5, No.1, pp.1–18

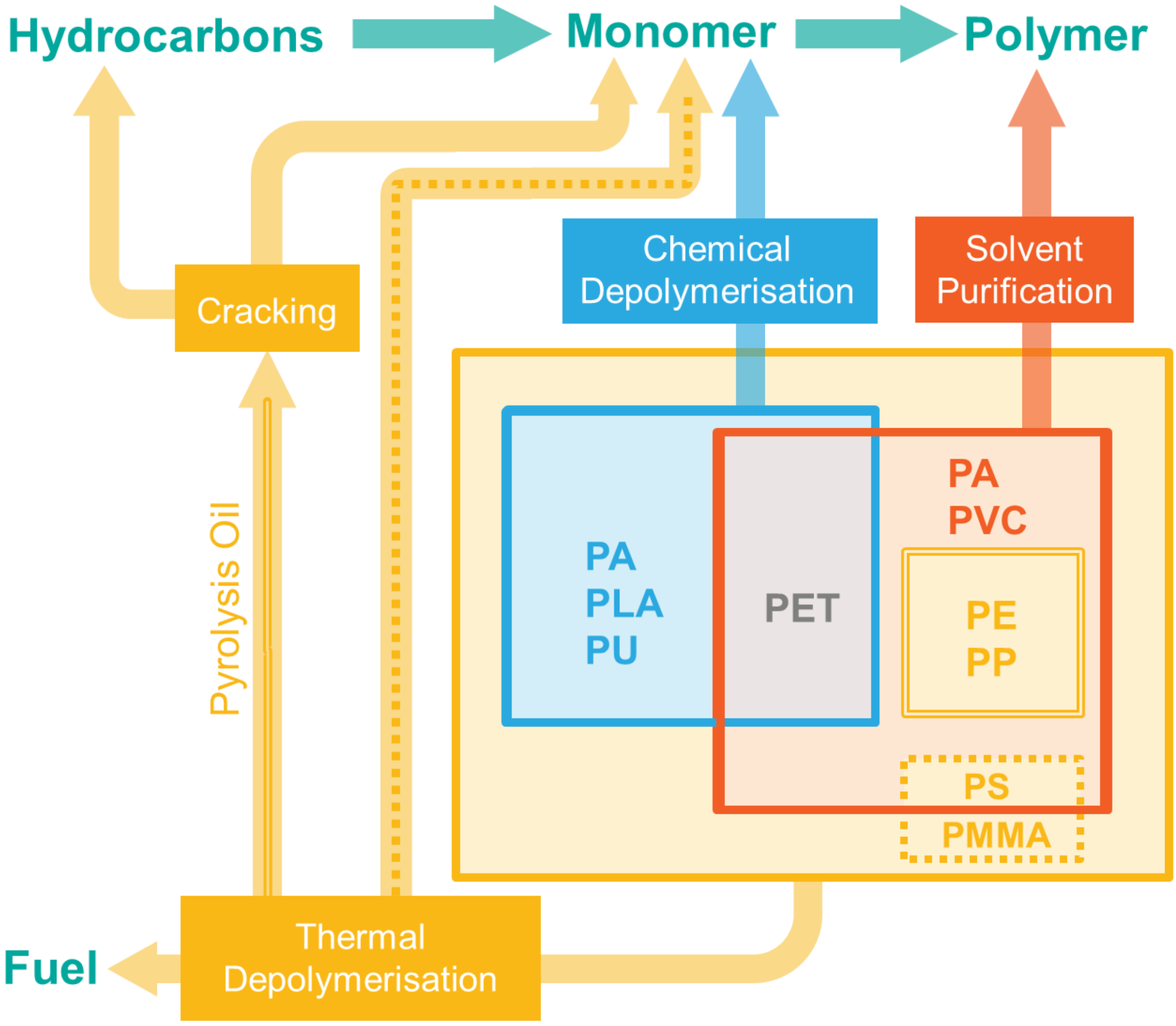
3.0 Categorising Chemical Recycling Technologies

The process of chemical recycling or recovery can be split into three broad technology categories:

- Solvent Purification
- Chemical Depolymerisation
- Thermal Depolymerisation

Figure 1 shows, for each technology, the main deployment pathways that are currently or may potentially be employed for different polymers to achieve different outputs along the plastics value chain.

Figure 1: Chemical Recycling Technologies



4.0 Chemical Recycling Technologies

4.1 Solvent Purification

4.1.1 Process Overview

The basis of solvent purification is to use the principle of solubility to selectively separate plastic polymer from any other materials contaminating the plastic waste.[9] These contaminants typically consist of:

- Additives such as flame retardants, stabilisers, impact modifiers, colourants and pigments;
- Non-target polymers; and
- Non-Intentionally Added Substances (NIAS), which are compounds both absorbed and produced within the plastic material during use. This can include side products from the manufacturing process, as well as degradation products, both from partial breakdown of the polymer itself as well as the additives contained within the plastic.[10,11,12]

The plastic is shredded and dissolved within a solvent that the polymer has high solubility in, but the contaminants have low solubility in. The contaminants will, therefore, remain solid and so can be separated off from the liquid fraction to purify the polymer. Once the purification process is complete, the polymer is extracted from the solution by placing in a non-solvent to re-solidify the polymer, in a process known as precipitation, to allow recovery.[13] Subsequent treatment of the polymer then follow, including filtration, washing and drying, to remove the non-solvent, resulting in the purified polymer.[14]

Table 2 shows the current applications for solvent purification by polymer type and waste streams. Given the technology's effectiveness is primarily dependent on solubility, it can theoretically be applied to almost any polymer, provided a suitable solvent can be found that is selective for the desired polymer to be recovered. It is likely, therefore, that niche applications for the technology will surface. However, viability of these technologies on a

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[9] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[10] Zhao, Y.-B., Lv, X.-D., and Ni, H.-G. (2018) Solvent-based separation and recycling of waste plastics: A review, *Chemosphere*, Vol.209, pp.707–720

[11] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[12] (2018) *Food Packaging Forum* https://www.foodpackagingforum.org/food-packaging-health/non-intentionally-added-substances-nias

[13] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[14] Zhao, Y.-B., Lv, X.-D., and Ni, H.-G. (2018) Solvent-based separation and recycling of waste plastics: A review, *Chemosphere*, Vol.209, pp.707–720

commercial scale is dependent predominantly on the homogeneity of the waste stream, and the associated solvent and energy inputs required to ensure effective purification.

Table 2: Solvent Purification Applications

Polymer	Waste Stream
Polystyrene (PS)	Expanded polystyrene foam (EPS) Household PS waste
Polyethylene Terephthalate (PET)	Polyester/cotton textile Packaging
Polyethylene (PE)	Multilayer sachets
Polyamide (PA)	
Polypropylene (PP)	Carpets

The effectiveness of polymer purification is very dependent on understanding the exact contaminants within the waste input. However, there is a lack of clarity for the majority of technologies regarding the impurities dealt with, technologies often only citing "contaminants".

Technically, if all the types of polymer contained within the plastic waste are known, as well as the full range of contaminants, the process could be used to purify multi-material waste streams, provided there were sufficient stages of solvent selection. Theoretically this could avoid the costs associated with segregated collection and advanced sorting infrastructure required to separate specific polymer types.[15] However, the added complexity required to ensure selectivity for each polymer type leads to higher environmental and economic costs from increased solvent, energy and time inputs. As such, the majority of technologies in this area of recycling that have progressed beyond laboratory stage remain focused on single plastic waste streams, often requiring pre-treatment.

Screening and sorting of the materials is a common pre-treatment step to separate external contaminants such as stickers, glue, tape etc. Mechanical treatments such as drying and crushing are also utilised to further prepare the plastic for purification.[16,17] Even following purification, the risk of residual impurities is still often an issue due to the

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[15] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[16] Giraf Results on behalf of PolyStyreneLoop (2019) Guideline on the Collection and Pre-treatment of polystyrene foams for PolyStyreneLoop, September 2019, https://polystyreneloop.eu/wp-content/uploads/2020/03/20190909_guideline-on-collection-and-pretreatment.pdf

[17] GreenBlue Worn Again: A Solution for PET/Cotton Blended Fabrics

reduction in the material properties compared with the virgin polymer[18]. Of equal concern are remnant contaminants that are hazardous in nature. These will necessitate more extensive purifications in order to effectively remove them from the product, which can be a barrier to commercial success. This issue has been clearly demonstrated in Solvay's efforts to purify Polyvinyl Chloride (PVC) waste, a plastic prevalent in myriad products including pipes, electric cables and flooring. Its VinyLoop technology, while commercially viable, was hindered by the EU REACH Regulation deeming that the remnant phthalate contaminants in the recycled PVC to be hazardous and could therefore only be used in certain types of product. Although recent PVC products excluded these plasticisers, older legacy PVC that VinylLoop was targeting for recycling, did not. Separating these contaminants was too extensive to be economically viable, leading to closure of the plant.[19]

Another consideration is that the polymers resulting from solvent purification, as with mechanical recycling, must then be further processed to produce new plastic products. This will typically include melt and extrusion steps, which subjects the polymer chains to both physical and thermal stress and leads to some degradation of the polymer chains.[20,21]As such, while this method of chemical recycling allows effective recovery of the polymers for reintroduction into plastics manufacturing, the degradation of the chains over time means that the technology is not a method that will allow the infinite recycling of plastic materials.[22,23]

Processes can often involve a number of solvents, used in a staged manner, to ensure effective removal of impurities. This is often a necessity as some contaminants may also dissolve in the same solvent as the polymer. As such subsequent dissolution/precipitation steps are needed with different solvents to separate all contamination from the polymer.

There are numerous examples of laboratory scale procedures demonstrating the range of solvent/non-solvent combinations that can be utilised for selective purification, dependent on the type polymer. PS, for example, can be dissolved effectively (provided the appropriate process conditions) in dichloromethane, toluene and limonene solvents; but will precipitate out again when mixed with methanol, water or hexane. However, practical application of these techniques must consider a range of factors including the quantity of solvents required and their cost, the toxicity of the substances, the specificity they have for the polymer target and the viability of solvent recycling.[24] In general, the

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[18] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[19] (2018) https://www.plasteurope.com/news/VINYLOOP_t240095/

[20] Capone, C., Landro, L.D., Inzoli, F., Penco, M., and Sartore, L. (2007) Thermal and mechanical degradation during polymer extrusion processing, *Polymer Engineering & Science*, Vol.47, No.11, pp.1813–1819

[21] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

[22] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[23] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[24] Zhao, Y.-B., Lv, X.-D., and Ni, H.-G. (2018) Solvent-based separation and recycling of waste plastics: A review, *Chemosphere*, Vol.209, pp.707–720

technologies approaching commercial scale have designed the process to allow solvent recovery, selectively removing the contaminants they contain from the purification, for reuse in subsequent purifications. Companies also typically note the use of non-hazardous solvents in their processes. While on a lab scale, there are demonstrated examples of environmentally benign solvents that can dissolve specific polymers, at plant level there is little detail as to precisely which solvents are utilised, nor the quantities required, making general claims regarding toxicity difficult to verify.[25,26] Using hazardous solvents could limit the end use of recycled polymer, particularly for food contact materials. As such, extensive drying of the polymer is often carried out to ensure the contamination is as minimal as possible. However, this is a highly time and energy intensive process, therefore, a balance is required between purity and cost.[27,28] It is perhaps for this reason that there is a current lack of technologies producing food grade outputs.

4.1.2 Example Technologies

Currently, solvent purification is a chemical recycling technique that is yet to reach commercial scale. There are, however, examples of companies that are working towards, or have already reached, the pilot plant stage (details of companies and scales can be found in Appendix A.1.1).

PolyStyreneLoop has developed an approach to selectively purify foamed polystyrene (PS) from industrial insulation waste. The foam contains Hexabromocyclododecane (HBCD), a flame retardant, from which the PS is separated. The resulting PS requires further washing and drying steps after the purification to deal with residual HBCD and solvent, although these contaminants are not separated entirely from the recycled material. The waste PS stream contains carbon black and graphite impurities that are not removed by the purification process, resulting in a product that is black, not white as with the virgin equivalent. However, the physical properties of the plastic material remain comparable to the virgin material.[29] Overall, 1.1 tonnes of pre-sorted PS foam can produce 1 tonne of ‘clean’ PS; a 91% yield with <100 ppm of HBCD. Following solvent recovery, the resulting HBCD sludge is processed in order to recover bromine for reuse within new flame retardants.

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[25] Zhao, Y.-B., Lv, X.-D., and Ni, H.-G. (2018) Solvent-based separation and recycling of waste plastics: A review, *Chemosphere*, Vol.209, pp.707–720

[26] Sherwood, J. (2019) Closed-loop Recycling of Polymers Using Solvents, *Johnson Matthey Technology Review*

[27] Sherwood, J. (2019) Closed-loop Recycling of Polymers Using Solvents, *Johnson Matthey Technology Review*

[28] Kaiser, K., Schmid, M., and Schlummer, M. (2017) Recycling of Polymer-Based Multilayer Packaging: A Review, *Recycling*, Vol.3, p.1

[29] Giraf Results on behalf of PolyStyreneLoop (2019) Guideline on the Collection and Pre-treatment of polystyrene foams for PolyStyreneLoop, September 2019, https://polystyreneloop.eu/wp-content/uploads/2020/03/20190909_guideline-on-collection-and-pretreatment.pdf

Polystyvert is another business working with PS, targeting household post-consumer waste.[30] Its technology, developed in conjunction with oil company Total, uses a solvent extracted from naturally occurring essential oils to dissolve the polystyrene waste selectively from contaminants.[31] The resulting PS retains the same properties as the virgin material. However, there is no detail concerning the associated PS yield.[32] It is also claimed the process effectively screens out contaminants such as ink, pigments and additives, however, it is unclear what happens to these contaminants after separation.

As previously described, in order to minimise the number of purification steps needed for decontamination, a more homogenous waste stream is often required. It can be a challenge, however, to secure sufficient input tonnages to make the process commercially successful. Some companies, therefore, are looking to capitalise on waste streams that are already collected in large quantities. Worn Again Technologies has developed a technology that is able to process PET/cotton blend fabrics, which make up 35% of the clothing waste stream not utilised by re-use networks. The technology captures both the PET and cellulose outputs for recycling, as well as recovering the solvents for reuse in the process. However, while the system can also tolerate other contaminants within the textile, this must be no more than 20% of the input material before efficiency is eroded beyond acceptable levels. As such, this requires stringent monitoring of the incoming material to ensure it is suitable for the technology. Worn Again Technologies is also looking to valorise contaminants in its waste stream, exploring the collection and reuse of the waste dyes from the process, as well as working on the purification of the elastane material found within clothing.[33] The company is in the process of developing a larger scale demonstration plant, from which it plans to test various inputs to understand yield and quality impacts on the product.[34]

While most other technologies are targeting a single plastic polymer for purification, APK has developed its Newcycling technology to target mixed polymer waste. The plastic inputs go through washing and density separating steps, followed by a solvent purification process that allows recovery of more than one polymer type.[35] At present, this process has only been demonstrated for multilayer polyethylene (PE)/Polyamide (PA) films[36], from which both polymers are recovered.[37]

4.1.3 Environmental Performance

CE Delft, funded by the Dutch government, conducted several studies screening (simplified, early stage, focusing on climate change impacts) LCA studies of chemical

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[30] (2018) https://www.prnewswire.com/news-releases/total-and-polystyvert-join-forces-on-the-recycling-of-household-post-consumer-polystyrene-300641098.html

[31] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[32] http://www.polystyvert.com/en/technology/

[33] (2017) GreenBlue Worn Again: A Solution for PET/Cotton Blended Fabrics

[34] (2020) https://wornagain.co.uk/worn-again-press-release-jan-2020/

[35] https://www.apk-ag.de/en/newcycling/process/

[36] (2019) https://www.plasteurope.com/news/APK_t241633/

[37] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

recycling technologies with the aim of determining where they may fit within Dutch waste management.[38,39] Detail on assumptions and data sources is limited and not overly transparent as the published reports are summaries that lack the detail necessary for effective scrutiny. The study compared WTE with PolyStyreneLoop's solvent purification of EPS. The study found improved climate change benefits compared with WTE. The study also assessed magnetic catalytic glycolysis (Ioniqa Technologies' chemical depolymerisation process for PET – see Section 4.2) and pyrolysis (thermal depolymerisation — see Section 4.3) and came to similar conclusions although PolyStyreneLoop's solvolysis process appears to be the most energy intensive of the three variants, but with improved yields.

A study commissioned directly by PolyStyreneLoop found that compared with WTE, the process reduced climate change impacts by 47%[40] — this is in contrast to CE Delft's study which calculated a net *benefit* in climate change impacts (~170% reduction). As neither study has published the details and assumptions, it is unclear why these differences occur.

Importantly, both studies did not include a comparative recycling scenario—this is due to PolyStyreneLoop not targeting EPS that can be mechanically recycled (e.g. packaging waste). The fire retardant (HBCD) in older, pre 2016, EPS building insulation materials prevents mechanical recycling. This is likely to be the preferred process for dealing with decades of insulation EPS when buildings are demolished or refurbished, but not a long-term prospect for EPS recycling more generally due to the reality of higher energy requirements. This means that the Polystyvert process—for which no environmental information has been published—will have to significantly improve on PolyStyreneLoop's process to make the targeting of household EPS environmentally and financially viable.

4.1.4 Technical and Commercial Maturity

Overall, while the literature reports myriad purification methods for a variety of plastic polymers on a laboratory scale, recycling through solvent purification is yet to reach commercial scale, (excluding the now closed VinyLoop plant) with those that are approaching it (pilot plant stage) all requiring very specific waste stream inputs to ensure successful purification.[41,42,43]

While some note applicability to wider waste streams (e.g. Polystyvert targeting all post-consumer PS waste and APK targeting mixed plastic waste), these technologies are not yet demonstrating their ability to manage nonhomogeneous waste streams at

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[38] Lindgreen, E.R., and Bergsma, G. (2018) Summary of Ioniqa LCA: Screening carbon footprint analysis

[39] Martijn Broeren, Erik Roos Lindgreen, and Geert Bergsma (2019) *Verkenning chemische recycling - update 2019. Hoe groot zijn - en worden - de kansen voor klimaatbeleid?*, Report for Ministry of EZK, April 2019

[40] Demacsek, C., Tange, L., Reichenecker, A., and Altnau, G. (2019) PolyStyreneLoop – The circular economy in action, *IOP Conference Series: Earth and Environmental Science*, Vol.323, p.012149

[41] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[42] Sherwood, J. (2019) Closed-loop Recycling of Polymers Using Solvents, *Johnson Matthey Technology Review*

[43] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

commercial scale. At present, therefore, this would necessitate specific sorting infrastructure be in place to ensure a high purity of waste inputs.

Of the technologies identified, most make reference to the recovery of process by-products. For example, the majority claim that the solvents used are non-hazardous (the veracity of this, however, is uncertain due to the lack of transparency around which particular solvents are used) and can be recovered and reused within subsequent purifications. A few (e.g. PolyStyreneLoop, Worn Again Technologies) also mention the recovery of contaminants from the waste stream for valorisation. While the information available is far from clear, this does provide a sense that to achieve viability even at pilot scale, technologies must consider not just the polymer yield, but how other outputs can be effectively recovered for reuse.

Across the different technologies, there is a distinct lack of clarity as to the process conditions and the associated energy inputs required for the process. Laboratory level procedures often require energy inputs in the form of heat and pressure to ensure efficient dissolution[44] and subsequent recovery (filtration, drying etc). While wide ranging temperatures (20 – 220°C) and timescales (0.5 – 4h) have been mentioned for some technologies, the majority of the detail focusses only on specific steps within the process; therefore, it is unclear as to the total energy inputs of the purification technologies.[45,46,47,48] Most of the literature notes that, in general, solvent purification necessitates high energy requirements, which raises questions with regards to economic and environmental viability on a larger scale. This may mean that waste streams which have no possible mechanical recycling alternative (and are therefore typically incinerated) are likely to be the most viable, as waste producers can be charged a fee for the treatment of their waste.

It is also important to note that, despite the ability to recover polymers of a quality comparable to virgin material, the subsequent reprocessing to remanufacture new plastic products leads to degradation of the polymer chain. As such, this chemical recycling technology does not allow for infinite recycling of the material.

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[44] Zhao, Y.-B., Lv, X.-D., and Ni, H.-G. (2018) Solvent-based separation and recycling of waste plastics: A review, *Chemosphere*, Vol.209, pp.707–720

[45] Walker, A. (2014) *Process for extracting polyester from an article*

[46] Sherwood, J. (2019) Closed-loop Recycling of Polymers Using Solvents, *Johnson Matthey Technology Review*

[47] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[48] Layman, J.M., Gunnerson, M., Schonemann, H., and Williams, K. (2017) *Method for purifying contaminated polypropylene*

4.1.4.1 Summary

Table 3 provides a summary of the overarching capabilities and limitations of solvent purification, both in the context of the general process, as well as its current demonstrated maturity as a technology.

Table 3: Solvent Purification, Capabilities and Limitations

Advantages	Disadvantages
• Has been demonstrated to separate polycotton textile blends. • Environmentally benign solvents have been tested successfully at a lab scale. • Generally allows recovery of the solvent for reuse. • The process has been demonstrated to recover non-target by-products for valorisation.	• Can currently handle only material inputs that are largely homogenous in nature. • Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification. • Typically necessitates high energy requirements, in particular the post-purification drying stages. • Typically cannot remove contaminants entirely. • Has not been demonstrated to provide food-grade outputs. • Lack of clarity regarding the solvent types and toxicities for larger scale examples. • Does not allow for limitless recycling of the material, due to thermal degradation of the chains during reprocessing and conversion to form new plastic products. • Current lack of clarity regarding environmental performance. • Yet to demonstrate economic viability on a commercial scale.

4.2 Chemical Depolymerisation

4.2.1 Process Overview

The process by which a polymer chain is broken down through the use of chemicals, has numerous names including depolymerisation[49,50], chemolysis and solvolysis.[51,52] These are collectively referred to as "chemical depolymerisation" throughout this report.

The waste plastic feedstock is first pre-treated to remove any solid contaminants before it enters the depolymerisation process. Chemicals are then used to break down the polymer into either shorter chain oligomers (partial depolymerisation), or the monomers (full depolymerisation) from which it was formed.

Once the depolymerisation has occurred, the monomers are recovered from the reaction mixture and purified, through distillation, precipitation and/or crystallisation, to separate them from contaminants and leave the pure monomer.[53,54] In principle, given the recycled monomers are not dependent on the different polymer grades within the waste plastic, the resulting outputs are of identical quality to the primary raw material.[55,56]

The chemical depolymerisation process is only possible for certain types of plastic, the most relevant examples being Polyethylene Terephthalate (PET) and other polyesters, Polyurethane (PU), Polyamides (PA) and Polylactic Acid (PLA). These are collectively known as condensation polymers, due to the way in which they are formed. Polymerisation occurs through two routes, dependent on the chemical structure of the monomer; ***addition polymerisation***, where the monomer structure contains multiple bonds, one of which is broken to allow formation of a carbon—carbon bond; and ***condensation polymerisation,*** where the monomer forms a bond with another

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[49] British Plastic Federation *Chemical Recycling 101*, accessed 14 August 2020, https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx#_edn3

[50] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[51] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

[52] Bartolome, L., Imran, M., Cho, B., Al-Masry, W., and Kim, D. (2012) Recent Developments in the Chemical Recycling of PET, *Material Recycling - Trends and Perspectives* (16 March 2012)

[53] Gallagher, F.G. (1996) *Monomer recovery process for contaminated polymers*

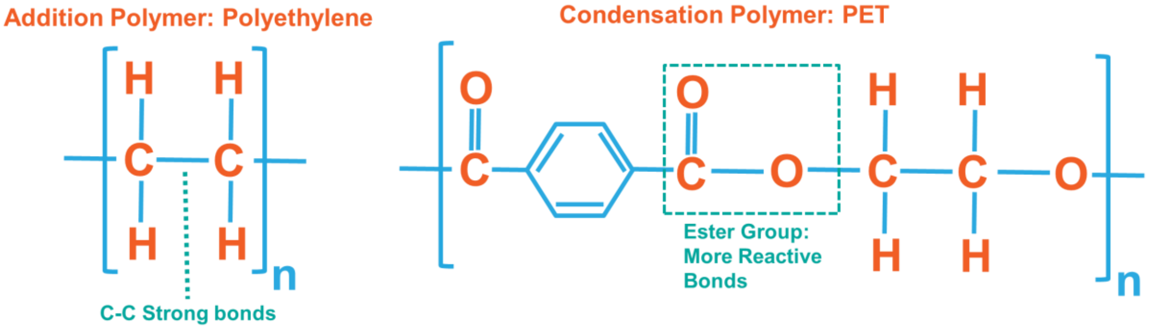
[54] Raheem, A.B., Noor, Z.Z., Hassan, A., Abd Hamid, M.K., Samsudin, S.A., and Sabeen, A.H. (2019) Current developments in chemical recycling of post-consumer polyethylene terephthalate wastes for new materials production: A review, *Journal of Cleaner Production*, Vol.225, pp.1052–1064

[55] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[56] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

monomer by ejecting a small molecule (often water) as a by-product.[57] These condensation polymers are susceptible to depolymerisation because of the type of bonds holding the monomers together. PET, for example, is joined by ester bonds which consist of a carbon atom bonded to oxygen. These different elements make the bond more reactive, compared with the more inert C-C bonds in addition polymers (See Figure 2). This facilitates the depolymerisation process by adding back the small molecule that was lost.[58,59,60]

Figure 2: Examples of Addition and Condensation Polymers



The way in which the depolymerisation process works for each polymer is essentially the same; the bonds holding monomers together being broken apart. However, the reaction pathway by which the chemical linkages are broken depends on the small molecule utilised for depolymerisation. There are five main chemical inputs, each with a distinct reaction pathway and, therefore, a different monomer output, as demonstrated for PET in Table 4.[61,62,63,64]

Glycolysis, hydrolysis, and methanolysis are all pathways that have demonstrated success at pilot plant level or larger, glycolysis being the most advanced in terms of demonstrating commercial viability on a larger scale. For aminolysis and ammonolysis,

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[57] McKeen, L.W. (2019) 1 - Introduction to Plastics and Polymers, in McKeen, L.W., (ed.), *The Effect of UV Light and Weather on Plastics and Elastomers (Fourth Edition)* (1 January 2019) William Andrew Publishing, pp.1–20

[58] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[59] British Plastic Federation *Chemical Recycling 101*, accessed 14 August 2020, https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx#_edn3

[60] Libre Texts (2020) Map: Organic Chemistry (Bruice)

[61] British Plastic Federation *Chemical Recycling 101*, accessed 14 August 2020, https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx#_edn3

[62] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[63] Kárpáti, L., Fogarassy, F., Kovácsik, D., and Vargha, V. (2019) One-Pot Depolymerization and Polycondensation of PET Based Random Oligo- and Polyesters, *Journal of Polymers and the Environment*, Vol.27, No.10, pp.2167–2181

[64] Hoang, C.N., and Dang, Y.H. (2017) Aminolysis of poly(ethylene terephthalate) waste bottle with tetra/hexamethylene diamine and characterization of alpha, ohmega-diamine products, *Science and Technology Development Journal - Natural Sciences*, Vol.1, No.T2, pp.101–113

while there are laboratory level demonstrations of depolymerisation through these methods, there is no evidence to date that these have progressed beyond laboratory scale. The literature does note with regards to aminolysis that this may be due to the use of hazardous chemicals with potentially high cost disincentivising their use on a larger scale.[65,66,67]

Table 4: PET Depolymerisation Products by Chemical Input

Chemical Input	Reaction Pathway	Monomer Output	Other Product(s)
Glycol	Glycolysis	Bis(2-Hydroxyethyl) terephthalate **(BHET)**	Ethylene Glycol
Water	Hydrolysis	Terephthalic Acid **(TPA)**	Ethylene Glycol
Methanol	Methanolysis	Dimethyl Terephthalate **(DMT)**	Ethylene Glycol
Amines	Aminolysis	bis(2-hydroxy ethylene)terephthalamide **(BHETA)**	-
Ammonia	Ammonolysis	Terephthalamide	Ethylene Glycol

A common factor within all these pathways is the utilisation of catalysts – chemical substances that help to increase the rate of the reaction[68] by interacting with the reaction materials[69], to aid the reaction process. The glycolysis process, for example, is slow and often incomplete without the use of a catalyst.[70] These rate enhancers are often developed specifically for the process, examples including ionic liquid complexes or

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[65] Al-Sabagh, A.M., Yehia, F.Z., Eshaq, Gh., Rabie, A.M., and ElMetwally, A.E. (2016) Greener routes for recycling of polyethylene terephthalate, *Egyptian Journal of Petroleum*, Vol.25, No.1, pp.53–64

[66] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[67] Langer, E., Bortel, K., Waskiewicz, S., and Lenartowicz-Klik, M. (2020) 5 - Methods of PET Recycling, in Langer, E., Bortel, K., Waskiewicz, S., and Lenartowicz-Klik, M., (eds.), *Plasticizers Derived from Post-Consumer PET* (1 January 2020) William Andrew Publishing, pp.127–171

[68] Catalysts Europe *What are* catalysts, accessed 14 August 2020, https://catalystseurope.eu/index.php/what-are-catalysts

[69] BASF Catalysts, *What is a Catalyst,* accessed 14 August 2020 https://catalysts.basf.com/about-us/what-is-a-catalyst

[70] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

biological catalysts such as enzymes (see Appendix A.1.2 for further detail). The use of these substances, however, can be an issue in the process, not only because of the cost often associated with producing them, but also the need to separate them from the monomer products following the reaction.

Other processes described in the literature that increase the effectiveness of depolymerisation and decontamination employ the use of specific solvents and process conditions. Solvents can improve the mixing of the polymer with the chemical inputs, but the quantities required on an industrial scale, as well as their toxicity, can be barriers to viability when scaling up the process from laboratory to plant.[71] Temperature and pressure are also often utilised to reduce the timeframe over which the reaction occurs, however, their use must take into account the associated energy input, which has an impact from both an environmental and economic perspective.[72]

Table 5 shows the current applications for chemical depolymerisation by polymer type and waste stream, comprising polymers that are capable of being depolymerised in this way. In general, while there are a wide variety of technologies exploring chemical depolymerisation, all currently target largely homogenous waste streams rather than mixed plastics. As such, this currently necessitates the use of sorting and pre-treatment processes.

For PET, bottles and polyester fibre are most commonly targeted (see Table 5). However, given that mechanical recycling of PET bottles is well established and therefore competitive, some have looked to target other material streams for which there are no or fewer recycling solutions, such as packaging with pigments, or food trays.

There are far fewer reported technologies approaching commercial scale operation for PU, PA or PLA. A notable exception is Nylon (a type of polyamide), for which there is a well-established technology (Econyl by Aquafil) recovering the fibre from monofilament fishing lines and nets and textile waste.

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[71] Al-Sabagh, A.M., Yehia, F.Z., Eshaq, Gh., Rabie, A.M., and ElMetwally, A.E. (2016) Greener routes for recycling of polyethylene terephthalate, *Egyptian Journal of Petroleum*, Vol.25, No.1, pp.53–64

[72] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

Table 5: Chemical Depolymerisation Applications

Polymer	Waste Stream
Polyethylene Terephthalate (PET)	• Bottles • Packaging waste e.g. food packaging, trays • Mixed PET waste • Textiles including polyester, polyester/cotton blends and carpet
Polyurethanes (PU)	• Mattresses (flexible foam) • Rigid foam
Polyamides (PA)	• Fishing lines and nets • Textiles including apparel, fabric and carpet waste
Polylactic Acid (PLA)	• Beverage cups

4.2.2 Example Technologies

Given the variety of materials and inputs that can be utilised within the chemical depolymerisation process, there are a wide variety of distinct technologies being explored by companies in an effort to commercialise this mechanism for recycling. However, there is a consistent lack of information regarding demonstrated process yields at plant level. If provided at all, they are often referred to only in the technology patents, as opposed to the input and output quantities at plant level (Jeplan, Ioniqa Technologies, Carbios). There is also little supporting explanation as to how these yields have been calculated, which is dependent on when the mass of the material entering and exiting the recycling process is measured. Only one, Nan Ya Plastic's ECOGREEN glycolysis process, has provided mass flows for the material processed and the associated outputs with a correspondingly lower reported yield compared to competing technologies (see Table 6). As such, there is a distinct lack of clarity as to the technical effectiveness of these technologies, despite the fact that a number are already running commercial operations, or are working towards industrial scale demonstration. Nevertheless, it appears that upwards of 90% yield may be possible when a clean, homogenous PET source is used. A full description of the technologies at varying scales can be found in Appendix 4.2.

Table 6: Examples of Chemical Depolymerisation Process Yields

Reaction Pathway	Company	Input	Yield
Glycolysis	Jeplan	PET bottles and fibre	98%[73]
	Ioniqa Technologies	PET bottles	93%[74]
	Nan Ya Plastics	PET bottle flake	76%[75]
Hydrolysis	Carbios	PET bottles	90%[76]
	Gr3n	PET bottles, textiles, food packaging	98-99%[77]

4.2.3 Environmental Performance

Dutch government funded research by CE Delft (introduced in Section 4.1.3) also assessed the Ioniqa Technologies glycolysis depolymerisation process for PET in comparison to typical mechanical recycling.[78,79] Whilst both were considered to have similar (undisclosed) yields and therefore climate change benefits, the close to tenfold increase in energy requirement of the Ioniqa Technologies process means that mechanical recycling was still considered the most favourable overall.

Gr3n has conducted its own study[80], which remains unpublished and thus unverifiable. The result suggested that producing PET via their process results in a 38.5% net reduction in climate change impacts compared with virgin production. The process impacts appear to be similar for both Gr3n (1.3 CO_2e/kg) and Ioniqa Technologies (1 kg CO_2e/kg, reported in the CE Delft study) although Gr3n has the higher claimed yield. As such, mechanical recycling still appears to be preferable, if possible. However, Gr3n is

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[73] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[74] ARTIGAS, M.V., MESTROM, L., GROOT, R.D., PHILIPPI, V., Sanchez, C.G., and HOOGHOUDT, T. (2014) *Polymer degradation*

[75] Nan Ya Plastics Corp. ECOGREEN: 100% Post-consumer Recycled Polyester, https://www.npc.com.tw/j2npc/zhtw/proddoc/%E7%92%B0%E4%BF%9D%E7%B5%B2%E7%B9%94%E5%B8%83%E7%A8%AE/ECOGREEN?docid=F000000791&pdid=F00000079

[76] (2020) https://carbios.fr/en/carbios-announces-the-publication-of-an-article-on-its-enzymatic-recycling-technology-in-the-prestigious-scientific-journal-nature/

[77] https://www.demeto.eu/mission

[78] Lindgreen, E.R., and Bergsma, G. (2018) Summary of Ioniqa LCA: Screening carbon footprint analysis

[79] Martijn Broeren, Erik Roos Lindgreen, and Geert Bergsma (2019) *Verkenning chemische recycling - update 2019. Hoe groot zijn - en worden - de kansen voor klimaatbeleid?*, Report for Ministry of EZK, April 2019

[80] Maurizio Crippa (2017) *Long life to plastic!*, June 2017

targeting its technology to address the issues with unavoidable contaminants in mechanically recycled PET, essentially degrading it over multiple cycles to the point at which it cannot be used for all applications—clear bottles for example. As one of the key benefits of chemical depolymerisation is the ability to separate the polymer from any contaminants (including additives), this aspect should not be ignored. However, this is challenging to incorporate into an environmental assessment. This is discussed further in Section 4.3.3.

Aquafil's Econyl polyamide (nylon) recycling plant has been operating at a commercial scale for a number of years and therefore has collected some historic process data. Econyl's Environmental Product Declaration (EPD)[81] for creating raw PA6 from recycled PA[82] waste indicates that 1.7kg of CO_2e are emitted for every kg produced. The EPD does not compare this with alternatives, but European production of virgin PA emits around 6.7 kg of CO_2e per kg.[83] No comparison can be made with any alternative recycling technologies as the recycling of fishing nets and carpets (the primary feedstocks for Econyl) is particularly challenging and not typically undertaken. Also, as identified with other chemical recycling technologies, even energy intensive operations perform better than WTE.

4.2.4 Technical and Commercial Maturity

Overall, the process of chemical depolymerisation has received significant attention, given the myriad ways in which the mechanism can be utilised to ensure polymer degradation and subsequent purification of monomer products.

There are a number of technologies producing commercial outputs, all of which, interestingly, utilise monomers for the production of recycled yarns for textile applications. While there is some variation with regards to the waste inputs, the majority of technologies in development have focussed on PET waste (mostly bottle) streams as an input.

In general, the glycolysis pathway is the most developed when it comes technologies that are reaching, or have reached, commercial demonstration, in comparison to methanolysis and hydrolysis. Across the technologies, however, there is a notable lack of information as to the processes and, as such, the viability from a technical and commercial perspective. Process yields, chemical/catalyst inputs, process conditions and methods for monomer purification, while mentioned by some technologies, are by and large not detailed sufficient clarity to provide understanding of each technology overall.

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[81] An independently verified document that communicates transparent and comparable information about the life-cycle environmental impact of products.

[82] Aquafil (2013) *ENVIRONMENTAL PRODUCT DECLARATION for ECONYL POLYMER*, December 2013

[83] PlasticsEurope (2014) *Eco-profiles and Environmental Product Declarations of the European Plastics Manufacturers: Polyamide 6 (PA6)*, February 2014

It is clear that there is a variation between technologies as to the use of catalysts, solvents and other chemical reagents. Where mentioned, however, the processes are often designed to ensure these can be recovered for reuse. Process conditions also vary significantly, some operating at low temperatures and pressure, with others favouring the higher energy inputs to minimise reaction times.

Another consideration for the maturity of the various technologies, notably absent from the majority of processes, is how they deal with contamination. As already stated, a number require pre-treatment/sorting steps to refine the waste inputs, which are largely homogenous. However, while there is some mention of additives such as pigments and colourants, in general there is little understanding as to the extent of contamination, nor the types of contaminants in general, that these technologies can handle. There is equally almost no mention of any hazardous materials, either utilised in the depolymerisation process or produced as by-products, an important consideration for large-scale viability.

As such, with the exception of the Econyl process which targets PA fishing and textile waste, the viability and commercial success of these chemical recycling technologies long-term, both from an environmental and economic perspective, is unclear.

4.2.4.1 Summary

Table 7 provides a summary of the overarching capabilities and limitations of chemical depolymerisation, both in the context of the general process, as well as its current demonstrated maturity as a technology.

Table 7: Chemical Depolymerisation, Capabilities and Limitations

Advantages	Disadvantages
• Monomer outputs can be utilised to produce plastic products of equal quality to virgin equivalents, potentially suitable for food contact applications. • Demonstrated examples of systems that allow the recovery and reuse of chemical reagents such as catalysts and solvents. • High yields demonstrated for a number of technologies. • Demonstration of commercial viability for bottle and fibre inputs.	• Typically requires homogenous waste streams as an input, often requiring extensive pre-treatment/sorting technologies. • Lack of information concerning the quantities of chemical reagents and other supplementary materials e.g. catalysts. • Lack of clarity as to the overall energy inputs associated with the technologies, processes often requiring high energy inputs. • Lack of yield information at plant level. • General lack of understanding around the level of contamination that the technologies can handle, nor how the contaminants are dealt with following monomer purification. • Little consideration in published information given for hazardous inputs/by-products. • Lack of verified environmental performance data for the majority of technologies.

4.3 Thermal Depolymerisation

4.3.1 Process Overview

Thermal depolymerisation, also known as thermal cracking and thermolysis, is the process by which a polymer is broken down into smaller molecules using heat treatment.

Plastic inputs initially go through a number of pre-treatment steps, including cleaning, drying and shredding, before being placed in a reactor and subjected to high temperatures, causing depolymerisation. The resulting hydrocarbon fragments then go through subsequent distillation and purification steps in order to recover the products.[84]

There are two main approaches to thermal depolymerisation, delignated by the use of oxygen as a reagent within the process. *Pyrolysis*, also known as *thermal cracking*, utilises high temperatures in the absence of oxygen, while *gasification* employs low volumes of oxygen to aid the degradation process. The volume of oxygen utilised and the associated reaction conditions are crucial to control the degradation and avoid incineration of the plastic inputs.[85,86] Gasification typically occurs at high temperatures (700 - 1500°C), converting plastic inputs into a gaseous mixture of carbon dioxide, carbon monoxide, hydrogen, methane, water and other light hydrocarbons, collectively known as synthesis gas (syngas).[87] Syngas can be used as a precursor to synthetic natural gas, although it has a substantially lower calorific value compared with natural gas. It can also be utilised to produce chemical feedstocks such as ethanol, methanol and ammonia. However, while some of these feedstocks can in principle be utilised to reproduce plastics precursors, this would require significant subsequent processing stages to convert the raw syngas products into new materials. It is perhaps for this reason that there is little demonstrated evidence of this depolymerisation technology as a mechanism to remanufacture plastics. Most commonly demonstrated at commercial scale, if the gas itself is not used directly as an energy source, is the production of ethanol to be utilised as fuel. As such, this technology is more likely to be used either to produce simpler chemical feedstocks, or for energy recovery.[88,89,90]

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[84] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

[85] Vijayakumar, A., and Sebastian, J. (2018) Pyrolysis process to produce fuel from different types of plastic – a review

[86] Rollinson, A.N., and Oladejo, J. (2020) Chemical Recycling: Status, Sustainability and Environmental Impacts

[87] Solis, M., and Silveira, S. (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment, *Waste Management*, Vol.105, pp.128–138

[88] Vierhout, R. (2019) Biofuels and chemicals from mixed waste: The Enerkem contribution to sustainability and circular economy, European Technology and Innovation Platform Bioenergy, 2019, https://www.etipbioenergy.eu/images/SPM9_Presentations/Day1/5_%20ETIP%20B%20SPM9_R.%20Vierhout_Enerkem.pdf

[89] https://enerkem.com/process-technology/carbon-recycling/

[90] https://sierraenergy.com/fastox-gasifier-feedstock-overview/

Pyrolysis typically takes place at moderate to high temperatures (300 - 900°C) and at atmospheric pressure to afford a liquid fraction, known as pyrolysis/pyrolytic oil, as well as char and gaseous by-products. The conventional process can be adapted in a number of ways to alter the reaction conditions and so the outputs:[91]

- **Plasma pyrolysis:** The utilisation of thermal plasma as an energy source to reduce reaction times significantly through extremely high temperatures.[92] The main product is syngas, a gaseous mixture of light hydrocarbons, the components of which it is claimed can be utilised as chemical feedstocks for plastics production, however there is no evidence of this to date;
- **Microwave assisted pyrolysis:** The use of microwave energy to increase both temperature and reaction speed while providing more control of the process, in order to reach higher conversion rates for the polymer.
- **Catalytic cracking:** The introduction of a catalyst (metal oxides, cobalt complexes, silicate zeolites etc.) to reduce processing temperatures and increase yields of high value products within the pyrolysis oil.
- **Hydrocracking:** This involves the addition of hydrogen at very high pressure and intermediate temperatures to increase oil yield and quality.

Table 8 shows the different waste streams targeted by current thermal depolymerisation technologies, as well as the associated polymers and the resulting end products. While there are laboratory examples of thermal depolymerisation pathways for polymers such as PET[93] and PVC[94], the majority of technologies focussed on specific polymers utilise more inert polymers such as polyolefins and polystyrene, which can be broken down into simple molecules and are produced in large quantities. This is because the more heterogenous nature of other polymers often leads to a more contaminated product that is economically unviable to purify.[95] However, unlike solvent purification and chemical depolymerisation, the waste stream does not need to be entirely homogenous.

It is important to note that for all these polymers, the degradation pathway typically involves scission of bonds at random positions in the polymer chain, as opposed to the controlled breakdown seen in chemical depolymerisation. This means that the resulting pyrolysis oil is usually composed of a variety of hydrocarbon products. Whilst the ratio of different products can be controlled to some degree, their subsequent isolation is often an expensive process, due to the complex purification processes required. In order to

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[91] Solis, M., and Silveira, S. (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment, *Waste Management*, Vol.105, pp.128–138

[92] Tang, L., Huang, H., Hao, H., and Zhao, K. (2013) Development of plasma pyrolysis/gasification systems for energy efficient and environmentally sound waste disposal, *Journal of Electrostatics*, Vol.71, No.5, pp.839–847

[93] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[94] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

[95] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

make this economically viable, this often requires large input quantities to produce sufficient volumes of the desired end products.[96,97]

Table 8: Thermal Depolymerisation Applications

Polymer	Waste Stream
Polystyrene (PS)	• EPS foam • High impact PS
Poly(methyl methacrylate) (PMMA)	• Pre- and post-consumer PMMA
Polyethylene (PE) – HDPE and LDPE	• Films • Bags • Packaging
Mixed polyolefin & polystyrene (PP, HDPE, LDPE, PS)	• Mixed plastic waste

While there are pilot and commercial scale plants in operation producing chemical feedstocks, either for plastics manufacturing (monomers, precursors) or for other valuable chemicals, it is often in tandem with the production of fuels in order to make the process economically viable in the current market. Even in this situation, the costs can prove a barrier to long-term production. An example being the Sapporo Plastics Recycling plant which opened in 2000 to produce both chemical feedstocks and fuel, from 15,000t/a of mixed plastic waste. It was closed ten years later due to financial issues.[98] The long-term economic viability of thermal depolymerisation, therefore, will be dependent on whether the demand for these recycled feedstocks alone can balance the energy and purification costs required to produce them.[99,100,101]

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[96] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[97] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[99] Miandad, R., Rehan, M., Barakat, M.A., et al. (2019) Catalytic Pyrolysis of Plastic Waste: Moving Toward Pyrolysis Based Biorefineries, *Frontiers in Energy Research*, Vol.7

[100] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

[101] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

Despite this, there are examples of technologies utilising thermal depolymerisation processes that feed directly or indirectly into the production of plastics, namely for polystyrene and poly(methyl methacrylate). This is due to the chemical structure of the polymers with more reactive bonds linking the chains together, which are preferentially broken to produce the monomer at higher yields. However, these technologies require homogenous inputs, necessitating more extensive upstream sorting processes.[102] The majority of other technologies approaching, or at, commercial production levels, therefore, have been developed for mixed plastic waste inputs.

It is important to note the challenges in calculating yield for thermal depolymerisation. The heterogenous mixture of products, which are produced in a variety of fractions (liquid, gas, char), as well as the introduction of other chemicals into the final products mean that tracking the conversion of waste to product is highly complex. As such, for the most part it is unclear as to the mass flows into and out of these technologies, and at what point they are measured.

Table 9 shows the claimed yields from some of the companies that are running operational plants. In most cases the calculation method is not provided, but it can be assumed that the majority are based on mass. The majority produce a pyrolysis oil with varying claimed yields of 70-75%. However, further purification is required to make it suitable for use directly in monomer producing steam crackers (as a naphtha substitute, typically used in European ethylene production, for example) and there are further losses due to the fact that the ***mass balance*** for the conversion of pyrolysis oil is different to virgin hydrocarbon feedstocks—this is important as inputs for a steam cracker could be a mix of pyrolysis oil and virgin hydrocarbons and therefore the relative contribution to the output monomer will be different and can only be theoretically calculated rather than measured directly (more detail on how this mass balance, and thus a recycling rate, can be calculated is explored in Section 6.2).

The purification of the pyrolysis oil before it enters the cracker is critical in order to meet strict feedstock specifications (which are not generic and will differ between crackers and may also differ with customer requirements) as contaminants reduce efficiency and equipment life, and lead to lower value outputs.[103] Even so, the ratio of pyrolysis oil to naphtha would need to be kept relatively low because of this and therefore the likelihood of a (commercially viable) cracker running solely or largely on pyrolysis oil is low. However, no ratio limits have been published by any member of the chemicals industry as yet. Therefore, this is likely to mean that the process cannot run independently of virgin polyolefin production.

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[102] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[103] Kandasamy M. Sundaram, and Barbara Stancato (2018) *How Much Is Too Much? -Feed Contaminants and Their Consequences*, Report for CB&I Company, 2018

Table 9: Thermal Depolymerisation Process Yields

Technology	Company	Input	Output	Claimed Yield
Catalytic microwave pyrolysis	Pyrowave	PS	Styrene monomer	95%[104,105]
Pyrolysis	Regenyx	PS	Styrene monomer	81%[106]
	Arkema	PMMA	Methyl Methacrylate monomer	64-85%[107]
	Plastic Energy	Mixed Plastics	Pyrolysis Oil	*70%[108]
	Recycling Technologies (Plaxx)			*75%[109]
	Fuenix (Ecogy technology)			*70%[110]
Microwave pyrolysis	Enval	Alu laminates		*~70%[111]
Catalytic hydrothermal depolymerisation	ReNew ELP (Cat-HTR technology)	Mixed Plastics	Depolymerisation Oil	*85%[112]

*** These yields relate to a pyrolysis oil output and further yield losses would result from purification (~3% or more) in order to be ready for use in a steam cracker. Further losses also result from the pyrolysis oil having a lower 'value' than virgin inputs into a steam cracker and therefore the mass of polymer output is reduced. Steam crackers also typically consume a proportion of the input as energy to run the process unless the process heat is generated electrically.**

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[104] https://www.pyrowave.com/en/pyrowave-technology

[105] Nesseth, D. Unzipping polystyrene's potential: Pyrowave sees a potential resource, *Solid Waste Magazine*

[106] https://www.agilyx.com/application/files/6515/2511/7006/agilyx_apec_emerging_innovation_session.pdf

[107] (2020) https://www.mmatwo.eu/wp-content/uploads/2020/05/MMAtwo_Newsletter_May-2020.pdf

[108] Sphera Solutions GmbH (2020) *Evaluation of pyrolysis with LCA – 3 case studies*, Report for BASF SE, July 2020

[109] (2019) https://www.k-online.de/vis-content/event-k2019/exh-k2019.2591974/K-2019-Recycling-Technologies-Ltd-Paper-k2019.2591974-SUuFUArETzC03XvaWALlsw.pdf

[110] (2019) https://bioenergyinternational.com/biochemicals-materials/dow-and-fuenix-enter-into-a-partnership-for-the-production-of-100-circular-plastic

[111] http://www.enval.com/Documents/Enval_Brochure.pdf

[112] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

There is little published data on the final possible yield of recycled polymer obtained from mixed plastics turned into pyrolysis oil and no company openly promotes an expected yield for this at present as this is not yet being conducted at a commercial scale. The material yields are also likely to vary depending upon how a steam cracker is powered and its efficiencies – often the feedstock itself is partly consumed to provide the energy needed for the reaction to occur which reduces the material yield but removes the need for additional energy sources. Fuel gases that are an output of naphtha cracking (and amount to approximately 20–25% of the energy content of naphtha) can account for around 95% of the process energy demand.[113] Specific information around such efficiencies is generally considered proprietary information and it is unclear to what extent generalisations can be made which is therefore problematic when also generalising final material yields or environmental impacts. However, it is clear that any pyrolysis oil that is converted to fuel gas during the process would only be considered a recovery operation, rather than recycling; this will likely always be a limiting factor to achieving higher polymer to polymer yields. If the chemicals industry transitioned to (renewable) electricity for its energy requirements (which both DOW[114] and BASF[115] have pledged to do) it is unclear how this would change the outputs as fuel gas would still be a by-product unless the process can be tailored to reduce this in favour of ethylene production.

The yields of the thermal depolymerisation processes themselves, as well as the output composition, can be heavily influenced through the use of specific process conditions and the introduction of catalysts. Temperature is a key consideration for thermal depolymerisation. Higher temperatures lead to more extensive breakdown of the input, which in general increases the ability to handle more heterogenous inputs such as mixed waste, reducing the need for more extensive, and costly, sorting and purification steps. On the other hand, these higher energy inputs can be economically prohibitive. As such, technologies must balance both thermal and purification energy requirements to ensure product purity (i.e. pyrolysis oil that is pure enough to meet the specifications of steam crackers to produce monomers).

Catalysts can also help to reduce these energy requirements, by lowering the temperature at which the depolymerisation must occur, as well as increasing process yields. However, a common issue encountered is the presence of specific contaminants in the waste stream that deactivate the catalyst, necessitating pre-treatment.[116]

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[113] Ren, T., Patel, M., and Blok, K. (2006) Olefins from conventional and heavy feedstocks: Energy use in steam cracking and alternative processes, *Energy*, Vol.31, pp.425–451

[114] https://www.shell.com/business-customers/chemicals/media-releases/2020-media-releases/dow-and-shell-team-up-to-develop-electric-cracking-technology.html

[115] https://www.plasteurope.com/news/BASF_t241514/

[116] Solis, M., and Silveira, S. (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment, *Waste Management*, Vol.105, pp.128–138

An advantage of pyrolysis is the concurrent separation of additives and other impurities within the waste plastic. If hydrocarbon based, these impurities can form useable products as part of the pyrolysis oil. Alternatively, they end up as char (mostly carbon), allowing easy separation from the desired end products. However, in practice the process, particularly for mixed plastic waste, can lead to the formation of hazardous by-products such as toxic polycyclic aromatic hydrocarbons and dioxins during the degradation process.[117,118] PVC and other waste inputs containing halogens (chlorine, bromine etc), are also highly problematic as their breakdown lead to the production of acidic halogen gases such as hydrogen chloride. These have serious impacts being both toxic and causing thermal decomposition of the depolymerisation equipment. This, therefore, necessitates extensive purification to effectively remove. Even where these contaminants are successfully separated, they are often too contaminated themselves to allow reuse and as such require safe disposal.

As with other chemical recycling technologies, the issue of remnant contaminants from both additives and by-products is often a barrier to viability as the processes required to sufficiently reduce their presence are often too costly.[119,120,121]

4.3.2 Environmental Performance

For the purposes of this report the focus is on studies that identify the environmental performance of chemical recycling processes that produce end products of virgin-like plastic or other valuable chemical products that can substitute virgin equivalents. There is a reasonable body of work that has focused on thermal chemical recycling that produces a fuel product (e.g. pyrolysis- waste to fuel) as an alternative to incineration producing energy (waste to energy). However, comparisons of technologies that can be considered recycling are the focus here.

There is generally a lack of published studies that reference a specific technology and because companies are not often transparent about their proprietary technologies it is not always possible to make connections between studies and the technology provider. Several companies do make environmental claims based on their own unverifiable calculations. For example, Pyrowave claim: *"Low energy consumption (roughly 1 to 1.5 kWh/kg of processed materials), which is approximately 10 times less energy than*

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[117] (2018) https://www.food.gov.uk/business-guidance/polycyclic-aromatic-hydrocarbons

[118] (2017) https://www.niehs.nih.gov/health/topics/agents/dioxins/index.cfm

[119] Crippa, M., De Wilde, B., Koopmans, R., et al. (2019) A circular economy for plastics – Insights from research and innovation to inform policy and funding decisions

[120] Solis, M., and Silveira, S. (2020) Technologies for chemical recycling of household plastics – A technical review and TRL assessment, *Waste Management*, Vol.105, pp.128–138

[121] Ragaert, K., Delva, L., and Van Geem, K. (2017) Mechanical and chemical recycling of solid plastic waste, *Waste Management*, Vol.69, pp.24–58

making styrene from virgin resources…" [122] Whilst this comparison is numerically correct, there is no way of verifying the process data from Pyrowave.

The majority of studies are third party comparisons of technologies based on lab or demonstrator sized plants, or even theoretical performance, and as such more work needs to be undertaken to validate many of the assumptions.

In the US, a carbon footprint study of HDPE pyrolysis separated from household waste focused on a comparison with virgin polymer production.[123] A theoretical mass balance is included, which describes all of the inputs and outputs of the proposed process. Accordingly, per kg of HDPE input the valuable outputs consist of ethylene (19%), propylene (13%), aromatics (4%), simple hydrocarbons, primarily butane (59%). The monomers are produced via a cryogenic separation process rather than via cracking. Importantly, the LCA stops short of including the polymerisation process to produce either PE or PP from the resulting monomers which makes it difficult to compare with mechanical recycling. The emissions associated with the process are also allocated to the outputs by their mass—the process of allocation in LCA can influence the results substantially, and there are a number of approaches with no particular best practice that can be applied to chemical recycling. Comparing studies with different allocation methods (economic for example) can lead to flawed conclusions. Equally the studies themselves should check how sensitive the results are to the differences.

The results are presented as a comparison with virgin monomer production for which the benefit in climate change terms appears to vary from being similar up to a 30% reduction. However, the production of hydrocarbons for fuel was found to be worse overall in every scenario, which may be problematic given this is the largest output. The authors also suggest that given the highest process impacts are those associated with the monomer separation, that reducing monomer output in favour of hydrocarbons may be preferable. However, this is likely only to be the case from the narrow perspective of this study rather than considering the whole life cycle from a systems perspective.

The energy mix was also found to be an important factor, to the point where the results would be different from State to State within the US, demonstrating that generalising conclusions between geographies may not be appropriate.

A similar study from a European average perspective (noting that results can only be indicative as there is no 'European average'), determined that the benefits were much greater for the same scenario of PE pyrolysis oil to ethylene rather than cracking from

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[122] https://www.pyrowave.com/medias/iw/PYROWAVE-2019_ENG_PDF.pdf

[123] Gracida-Alvarez, U.R., Winjobi, O., Sacramento-Rivero, J.C., and Shonnard, D.R. (2019) System Analyses of High-Value Chemicals and Fuels from a Waste High-Density Polyethylene Refinery. Part 2: Carbon Footprint Analysis and Regional Electricity Effects, *ACS Sustainable Chemistry & Engineering*, Vol.7, No.22, pp.18267–18278

naphtha.[124] The reason for this is that the other co-products (propylene and benzene) are considered to be avoided products[125] and, therefore, the system is credited with this benefit. This is methodologically unsound and results in artificially inflating the benefits. Without these credits, the environmental impact of the process compared to virgin ethylene production is very similar. The study also includes a *waste scenario*, where it is appropriate to include the credits from avoided products. The results show that the process is preferable to both WTE and landfill.

Both the US and European studies include very rudimentary sorting processes typical of current practices, with no particular comments on the quality of material stream that can be expected in reality. The studies also do not make any comparisons with other recycling technologies for context.

Another study investigated the different pyrolysis heating temperatures and catalysts to determine the environmental impact relative to the end products that were produced under different conditions.[126] Lower temperatures produced higher proportions of fuel oils, rather than higher grade hydrocarbons. Higher temperatures produced more valuable outputs (i.e. naphtha), but at a significant energy cost. When compared with the climate change impacts from production of the outputs from virgin fossil fuels the results showed that there are clear trade-offs associated with aiming for valuable outputs, which suggests that the energy expenditure is not always justified. These results echo the findings of the technology overview in Section 4.3.1, which point towards the economic case being hard to justify for polymer to monomer recycling, with the continued focus on fuel products being easier to achieve.

A 2020 study by BASF (for which Eunomia was on the peer review panel for) focused on how pyrolysis oil produced by the company Plastic Energy from mixed plastic (polyolefin) waste originating from Germany could be valorised further to replace naphtha in BASF's steam cracker producing ethylene for polyethylene production.[127] This study is the most comprehensive investigation into the key issue of creating pure monomers via pyrolysis and includes advanced sorting steps to remove impurities from the mixed plastics and an additional pyrolysis oil purification stage. This later stage, as previously discussed, is critical to meeting the feedstock specifications of a steam cracker and is also a step that

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[124] Somoza-Tornos, A., Gonzalez-Garay, A., Pozo, C., Graells, M., Espuña, A., and Guillén-Gosálbez, G. (2020) Realizing the Potential High Benefits of Circular Economy in the Chemical Industry: Ethylene Monomer Recovery via Polyethylene Pyrolysis, *ACS Sustainable Chemistry & Engineering*, Vol.8, No.9, pp.3561–3572

[125] Avoid product or avoided burden is an approach used primarily for allocating environmental burden in recycling where a "credit" is awarded for recycled material as there is no need for it to be produced from virgin material.

[126] Andras Angyal, Balint Simon, Norbert Miskolczi, and Laszlo Prof. Bartha (2009) LIFE CYCLE ANALYSIS OF MUNICIPAL PLASTIC WASTES CRACKING, paper given at 11th INTERNATIONAL CONFERENCE ON ENVIRONMENTAL SCIENCE AND TECHNOLOGY, Chania, Crete, GREECE, September 2009

[127] Sphera Solutions GmbH (2020) *Evaluation of pyrolysis with LCA – 3 case studies*, Report for BASF SE, July 2020

is not yet proven at scale. The study itself relies upon lab scale testing and expert judgements for the data in the step and therefore represents a significant unknown at this stage that could affect overall system performance.

This is the first such study to adopt the ***mass balance*** approach (another method of allocation) for determining what proportion of the end product can be attributed to the inputted pyrolysis oil, in order to assign avoided product benefits. This method is still somewhat in its infancy and, therefore, results associated with it should be treated with caution—this is discussed in more detail in Section 6.2 as this has direct implications on how recycling rates are calculated.

Consistent with other studies, the comparison with WTE shows pyrolysis is more favourable and the difference increases by 2030 with a decarbonised energy mix. This is because any fossil fuel burning will perform poorly from a climate change perspective in comparison to the expected high level of renewable energy by 2030. However, no studies have yet looked at the impact of using bio-based alternatives to conventional fossil based plastics e.g. bio-PET. Whilst these are chemically identical to their fossil based counterparts, the carbon is sequestered for a short period and therefore releasing it by burning is less impactful in climate change terms. If there were to be a wholesale move towards renewable, bio-based plastic feedstocks in the future, this might negate a lot of the benefit that pyrolysis has over WTE currently. This means a long term vison of both moving to bio-based plastics and investing significantly in chemical recycling might not be compatible.

The comparison with mechanical recycling requires a more theoretical approach as the issue of the quality of the output has bearing on the results. The BASF study used the Circular Footprint Formula (CFF) developed by the Joint Research Centre (JRC) and assumed mechanically recycled polymers from mixed plastic waste had an economic value 50% of that of virgin polymers. PE from pyrolysis oil was considered to be virgin grade and of the same value. Despite this, mechanical recycling still performed around 10% better from a climate change perspective due to higher energy use and lower yields of the pyrolysis process. A sensitivity analysis showed that if the value of the mixed stream could be increased to 75%, the performance gap would increase to around 20%. This demonstrates the importance of understanding the capability of a particular technology system to produce quality outputs; the closer mechanical recycling can get to virgin grade outputs, the more favourable it will be (and improvement and innovation is by no means static here). Therefore, at this stage pyrolysis appears to be primarily suitable for plastic waste streams that cannot be mechanically recycled.

4.3.3 Technical and Commercial Maturity

While thermal depolymerisation is a degradation mechanism that has received significant attention, it has so far failed to achieve commercially viability long-term on an industrial scale due to the trade-offs between energy inputs and quality of output. However, there are emerging examples of both pilot and commercial scale processes that are working to ensure more efficient pathways with sufficient degradation at lower temperatures or over shorter timescales, to afford useful products in high yield that can be easily separated.

A number have looked to catalysts (both energetic and chemical) and novel mechanisms for heat generation to minimise external energy inputs. Others are looking to capitalise on the process' flexibility with regards to waste input. By developing processes that can accept as wide a range of materials as possible, it minimises the upstream sorting and pre-treatments required for more homogenous waste inputs. However, there is a consistent lack of clarity with regards to how the overall process operates to ensure it is both economically and environmentally sound. Pre- and post-treatment steps are a common requirement to ensure high process yields, however, it is often unclear what happens to the contaminants and by-products produced. Similarly, while many processes require catalysts and supplementary chemicals for depolymerisation and purification, there is little information as to the quantities required or whether they can be reused or recycled themselves. The impact of hazardous by-products is also only mentioned in the context of specific inputs, notably PVC.

Uncertainty regarding the yields of individual feedstocks is also an important consideration. While yield is typically mentioned in the context of the pyrolysis oil produced from depolymerisation, there are very few examples of technologies that detail the subsequent quantities of feedstocks produced, nor their subsequent use. While many companies claim products that can be utilised for plastics manufacturing and other high-value chemicals, most are also coupled to fuel production to a greater or lesser extent. The purification process required to produce fuel grade material is relatively simple in comparison to chemical feedstock isolation. This, combined with the cost required to convert these feedstocks into high-value materials and the infancy of recycled chemical supply chains, are likely factors that have so far locked these technologies into plastics-to-fuel pathways, rather than recycling. Given the thermal processes that are pursuing the sole production of feedstocks are yet to reach industrial scale, the long-term viability is unclear in the context of commercial success.

As such, understanding as to the technical and commercial maturity of this method of plastics recycling, from both an economic and environmental perspective, is limited. While a number of technologies show promise, as yet there is little certainty that these processes can effectively integrate into the existing market as viable alternatives for plastics recycling.

4.3.3.1 Summary

Table 10 provides a summary of the overarching capabilities and limitations of thermal depolymerisation, both in the context of the general process, as well as its current demonstrated maturity as a technology.

Table 10: Thermal Depolymerisation, Capabilities and Limitations

Advantages	Disadvantages
• Can typically accept more heterogenous mixtures of waste as an input, but at the expense of output quality and utility (recovery as a fuel). • Can be applied to certain waste streams that are currently unrecyclable. • When purified, outputs can be used to manufacture plastics and other high-value chemicals, of equal quality to virgin feedstocks. • High temperatures utilised to effectively decontaminate the waste inputs.	• Requires a homogenous source of plastic waste to provide higher level (i.e. monomer) outputs. • The random nature of the depolymerisation process leads to a complex mixture of products, requiring costly purification systems to isolate usable products. • Current thermal depolymerisation outputs are skewed towards the lower cost production of fuel. • No clarity as to the recycling of by-products and reagents as part of the process. • Steam cracking of pyrolysis oil to create monomers typically results in a proportion of the input being converted to energy (recovery) to run the process. • Requires the existing virgin polymer value chain (steam cracking) to produce monomers. • No environmental performance data currently available for the majority of technology providers.

5.0 Environmental Considerations

From the review of life cycle assessment (LCA) studies conducted for this report some key considerations begin to arise that should be understood when reading LCAs that focus on chemical recycling:

- **Energy use** is generally, the most important aspect. This includes the energy use of the chemical recycling process, which is invariably the aspect that influences both the environmental and economic performance the most, but also the energy mix of the country in question. The latter particularly affects comparisons between chemical recycling and WTE and, therefore, forward-looking scenarios that show the future projected energy mix should be included.
- **Yield** also tends to be a defining factor that affects how viable a process is. Losses in the system need to be accounted for to accurately calculate this. Studies conducted at lab scale or demonstrator stage are likely to include a number of assumptions around this that may not reflect the reality at scale.
- **Input material streams** will have a large influence on the yield and energy use as generally, the cleaner the stream the higher the yield and lower the energy use (less purification is needed). Determining realistic scenarios for this is key especially where post- consumer household plastic waste is concerned. Achieving a high level of input quality will also need to take into account the local collection method and the necessary sorting processes. This aspect is likely to be very geographically specific.
- **Output material streams** are also important and LCAs should seek to characterise the quality of these outputs for both mechanical and chemical recycling in order to fairly compare. Recognising that a great deal of mechanically recycled plastic is not used in virgin grade equivalent applications can help to determine which product/material types are most likely to be suitable for chemical recycling.
- **Scenarios**: Most LCAs attempt to investigate at least one of two key scenarios.
    - **Waste scenario** – investigating the environmental impacts of treating plastic waste, usually with comparisons between chemical recycling and other end of life treatments such as mechanical recycling, incineration and landfill.
    - **Product scenario** - investigating the environmental impacts of producing plastic material (or other intermediate products such as hydrocarbons and monomers)

  The subtle difference in perspective between these two scenarios may lead to different results and conclusions, but also be of more interest to different stakeholders in the value chain. Ideally both should be considered within a study and further down the line studies should be conducted that are expanded to include the entire life cycle and so allow comparisons between different prospective overall systems:

All of the studies that exist currently should be considered as early-stage investigations rather than providing a firm scientific basis for long term decision making. Modelling of hypothetical processes is the stage that most are at; consequently, the methodologies can vary widely and, therefore, true comparisons between studies are not possible. Equally, the way each study allocates the impacts between the often complex processes and co-products is also difficult to decipher, particularly for non-experts. Very few commercial (or even demonstrator) plants operate and, therefore, robust and representative data is largely absent. At this time, the focus is on determining the specific scenarios where chemical recycling technologies might be beneficial. This can then direct funding and research into demonstrating these concepts at scale.

At present, just about all studies assume the plastic waste is received 'burden free' which is acceptable when looking at narrow 'snapshots' of the lifecycle, but the upstream impacts are important to consider when looking to determine where plastic as a material should be used and where better alternatives exist. No studies exist at present that look at scenarios for changes in the nature of plastics waste (e.g. switches to different polymers or design changes to packaging) that might lead to different conclusions around how it is dealt with.

Generally, chemical recycling performs worse than mechanical recycling due to the comparatively high energy demand. There appears to be potential to outperform if chemical recycling yields are either higher or the quality of the output is improved, however, neither has proven to be the case so far. Chemical recycling is usually an improvement over WTE, particularly in future scenarios (circa 2030 onwards) where decarbonisation of the electricity grid reduces the benefits from incineration. This is valid for plastics that are otherwise not recyclable and, therefore, mechanical recycling is not an option. Importantly however, there is no evidence of any study that takes into account, from a systems perspective, whether it is preferable to look at different, more recyclable packaging systems, rather than continuing in a business-as-usual fashion whilst deploying chemical recycling. As analysis of current chemical recycling technologies appears to suggest mechanical recycling is preferable, logically a move towards packaging that can be processed this way is likely to also be preferable.

The Dutch government funded CE Delft study encompasses the general conclusions of most studies with:,[128]

> *"Magnetic depolymerization [Ioniqa Technologies depolymerisation process for PET] and solvolysis [PolyStyreneLoop solvent purification of EPS] score in terms of climate impact similar to mechanical recycling but need fairly specific input. Gasification and pyrolysis [thermal depolymerisation] impose less stringent*

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[128] Martijn Broeren, Erik Roos Lindgreen, and Geert Bergsma (2019) *Verkenning chemische recycling - update 2019. Hoe groot zijn - en worden - de kansen voor klimaatbeleid?*, Report for Ministry of EZK, April 2019

> *requirements on inputs, but also achieve less environmental benefit." (translated from Dutch)*

It appears that the need for advanced identification, sorting and segregation processes required to improve mechanical recycling will also be required for the majority of chemical recycling applications in order to reach the highest yields and environmental benefits.

A European overview of many of the key chemical recycling technologies for the main types of polymers (PE, PET, PP, PS) compared with WTE, cement kiln fuel and mechanical recycling,[129] provides the most comprehensive comparison of technologies and their relative impacts. However, it is also somewhat lacking in detail to allow many of the key background assumptions to be assessed.

For global warming potential (GWP) impacts, the study found that all polymers treated under all chemical recycling technologies were preferable to WTE. This was particularly the case for any technologies that resulted in monomer outputs (polyolefins in catalytic pyrolysis and PET in hydrolysis or similar). As a feedstock in a cement kiln, only monomer recycling proved beneficial although the study assumed that lignite was being substituted, which is a scenario that is becoming less common.

According to the study, compared with mechanical recycling, all technologies that produce low value chemicals perform comparatively poorly. Monomer recycling, however, was found to perform comparably to mechanical recycling, although as with much of the evidence base, these results are difficult to verify due to the lack of data transparency.

The study does emphasise one of the key drivers of environmental impact; the balance between energy inputs and yield. There are several ways to increase yield for many technologies, but this comes at an energy cost. The study estimates that a megajoule of thermal energy would require an additional 3% point increase on average and that yields of 85-90% are required to be comparable with mechanical recycling. With maximum yields currently around 75% for all technologies apart from PET hydrolysis and glycolysis (which has reported yields above 90%), the technologies have some way to go.

5.1 Systemic Considerations

One of the key aspects that is missing from the environmental assessments to date, is a systems perspective aimed at understanding how these technologies might be deployed in reality. Studies tend to focus on comparative assertions and not where different technologies might complement each other.

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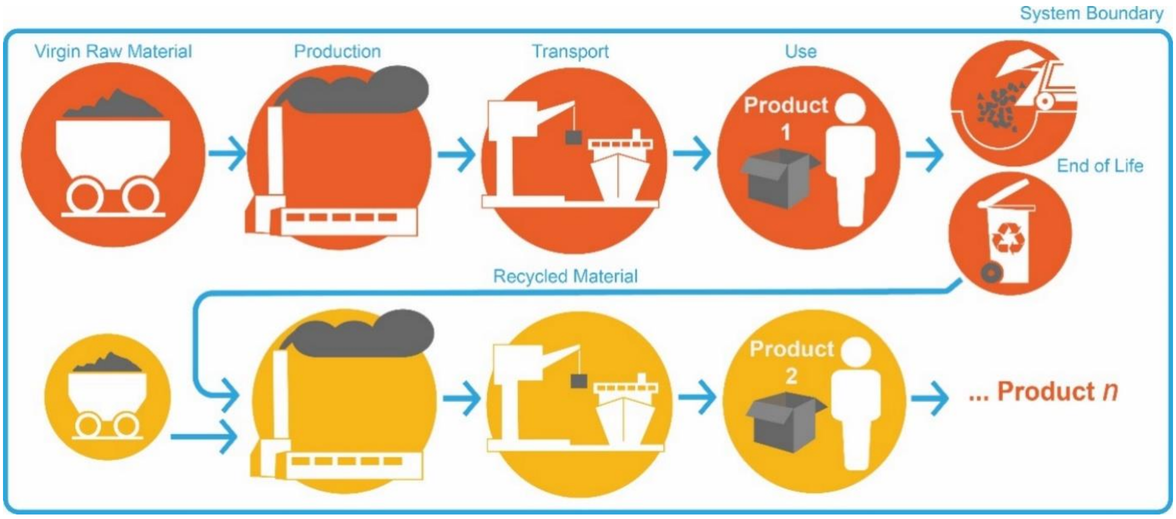
[129] Meys, R., Frick, F., Westhues, S., Sternberg, A., Klankermayer, J., and Bardow, A. (2020) Towards a circular economy for plastic packaging wastes – the environmental potential of chemical recycling, *Resources, Conservation and Recycling*, Vol.162, p.105010

The three main claims that are often made about chemical recycling more generally are; that infinite virgin-grade recycling is possible; food grade end products can be produced; and, the removal of contaminations/additives is possible. Whilst these aspects vary considerably between technologies (summarised in Section 7.0), the latter two (if substantiated) are likely to be key drivers for specific applications of chemical recycling becoming more widespread where mechanical recycling is not currently viable.

When considering the concept of ‘infinite recycling’ PET chemical depolymerisation technologies appear to be the most promising. However, this is not a factor that is currently considered in the current body of LCA studies—in much the same way that materials such as aluminium are often considered either recycled, or not. Mechanically recycled PET is relatively widespread, but will become more prevalent due to the ‘pull’ from brand owners who are increasingly being required to incorporate recycled content (and have targets at EU level to do so for bottles). This will begin to push the limits of what is possible as the material reaches contaminant limits in subsequent cycles. LCA could be used to investigate the trade-offs between chemical and mechanical recycling over multiple cycles. This can be achieved by expanding the **system boundary** to include more than one life cycle as demonstrated in Figure 3. This could help determine the key tipping points for each recycling method and how they might complement each other. However, it remains to be seen how this could function in practice without an advanced form of material sorting and selection that could identify polymers at the limit of contaminant levels and be redirected towards chemical depolymerisation.

The place for chemical recycling is often proposed as a means of treating material streams that mechanical recycling cannot or does not want to handle. However, some of the same barriers are still likely to exist; for example, PET trays are not typically recycled as they are hard to collect and separate due to being somewhat brittle compared to bottles. If a separate PET tray material stream could reliably be produced through design changes or advanced sorting, this stream could also be available for mechanical recycling. It is therefore important to ascertain that the barriers to mechanical recycling are also not the same for chemical recycling.

Figure 3: Expanding the LCA System Boundary for Material Circularity



6.0 Measurement

6.1 Calculating Recycling Rate

The measurement of recycling rates that are required to meet EU recycling targets has been the subject of much debate and resulted in an updated measurement method for packaging, which Member States are required to report against by 2022.[130] In principle, the ***calculation point*** for mechanical recycling is typically now at the washed flake stage where the plastic waste enters a recycling process and is the first point at which it can substitute a virgin equivalent.[131] Previously, recycling was often measured at the collection stage, or after initial separation (sorting) of plastics from other materials. This means that residual liquids, labels, lids and other contaminants, as well as other sorting losses, will no longer be counted as part of the reported recycling rate. Turning the polymer into a fuel for combustion (e.g. pyrolysis oil) or directly combusting it for energy recovery are not considered to be recycling under European law (these are classed as '***recovery***' and sit below recycling in the waste hierarchy). For chemical recycling, there is likely to be a grey area that has yet to be tested, where chemicals are produced that are not directly burned, but may be used as additives in fuels or lubrications in engines; these are burned, but substitute primary chemical production. As discussed previously in this report, it is likely (particularly for pyrolysis) that these 'lower order' chemicals and hydrocarbons may be easier and less energy intensive to produce from varied and heterogeneous plastic wastes compared with upgrading to monomers. If these are not directly or indirectly burned it is still likely that any resulting chemicals (used in coatings and adhesives, for example) can be categorised as recycling under EU law as it stands and, therefore, can be used to meet plastic recycling targets.

This is likely to result in discussions around whether the production of other chemicals should be categorised on the same level as plastic to plastic recycling. Some of the key aspects that need to be considered include:

- **The health and environmental impact of different process outputs** – as discussed, for some technologies (notably pyrolysis) there appears to be a trade-off between energy inputs and aiming for 'higher order' outputs. At this stage, the environmental data is not sufficient to determine whether this trade-off would lead to better or worse environmental outcomes overall.

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[130] COMMISSION IMPLEMENTING DECISION (EU) 2019/ 665 - of 17 April 2019 - amending Decision 2005/ 270/ EC establishing the formats relating to the database system pursuant to European Parliament and Council Directive 94/ 62/ EC on packaging and packaging waste - (notified under document C(2019) 2805), p.21

[131] Plastic separated by polymers that does not undergo further processing before entering pelletisation, extrusion, or moulding operations; Plastic flakes that do not undergo further processing before their use in a final product.

- **The continued reliance on virgin plastic** – diverting material to non-plastic uses would lock in an increased reliance on virgin polymers in the future as the recycled feedstocks are used elsewhere.
- **Specific chemicals** – much of the information round which useful chemicals might be produced is somewhat non-specific, which makes judgements challenging. Equally, in the same way as the reliance on virgin polymers could be locked-in, this is also the case for these chemicals, which may or may not always be needed.
- **Comparison with mechanical recycling** – it is also important to recognise that a large part of mechanical recycling does not result in virgin-equivalent outputs and, therefore, setting a 'plastic to plastic' requirement for chemical recycling may be considered to be setting the standard higher.

The calculation also becomes even more complex if some of the outputs are combusted in the process to generate energy, in order to run these technologies in a self-sufficient way. This may influence where the ***calculation point*** is placed, as the pyrolysis process might be considered to be a ***preliminary treatment***; in which case the calculation point might be set afterwards. At the least, any front-end sorting stage that is used to arrive at a clean, usable material stream would be considered a preliminary treatment, in the same way that it already is for mechanical recycling.

6.2 Recycled Content

Linked to the calculation of recycling rate is how the recycled content of a plastic product can be measured if the feedstock comes from chemical recycling. This will become increasingly important as EU recycled content targets are likely to become more prevalent, beginning in 2025 with the 25% minimum for PET beverage bottles and followed by 30% for all plastic beverage bottles by 2030 under the Single Use Plastics (SUP) Directive.[132] The EU Commission is currently determining how this will be measured, and by 1st January 2022 has to adopt implementing acts laying down the rules for the calculation and verification of these targets, which is likely to set the precedent for future recycled content legislation, as well as influencing industry standards.

For chemical recycling, the key challenge is likely to be traceability. Whilst outputs from mechanical recycling can be sold as such and integrated with virgin material at a known ratio, this is less easy with products from chemical recycling (particularly thermal depolymerisation). One factor is the way in which the chemicals industry value chain functions and the scale of polymer production operations. For example, if purified pyrolysis oil (as a naphtha substitute) is sent to a steam cracker—which might have an annual capacity of one million tonnes or more— it would not be kept separate from the other virgin feedstocks. This means that although the input of pyrolysis-derived naphtha substitute might be known, the exact recycled content of the output is almost impossible

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[132] European Commission (2019) Directive (EU) 2019/904 on the reduction of the impact of certain plastic products on the environment

to determine, as all outputs would be chemically identical. The same also applies for chemical depolymerisation technologies with a monomer output, albeit with perhaps less overall process complexity. Unless the facility also has the capability to polymerise (which does not appear to be the business model that many are applying, with the possible exception of Econyl), then the monomer will be sent to larger polymer production facilities where it will be mixed with virgin monomers. The exception to this issue is solvent purification technologies, which generally produces polymers as an end product. This can be considered analogous to mechanical recycling and might be categorised in the same fashion from a recycled content point of view.

An Ellen MacArthur Foundation (EMF) published report authored by prominent members of the chemicals industry, advocates for the ***mass balance*** method of traceability for recycled content from chemical recycling technologies.[133] The key concept of mass balance is that it does not matter what happens during intermediate processes, as long as the input matches the output. The report argues that whilst the concept is similar to ‘book and claim’ certification (e.g. renewable energy offsetting certificates), the chemical production system is physically interconnected and, therefore, traceability can be guaranteed, as what enters and exists the system can easily be physically accounted for. Whilst this concept is sound, the more difficult aspect is the allocating rules. This is straightforward for chemical depolymerisation where a pure monomer is the output; in this instance a mass allocation is suitable i.e. 1kg of rBHET is equivalent to 1kg vBHET. However, this becomes more difficult for pyrolysis processes where the pyrolysis oil is used to substitute hydrocarbons such as naphtha. This is because 1 kg of pyrolysis oil will not produce 1 kg of ethylene in a steam cracker. For such cases, the EMF report advocates an allocation method that uses the lower heating value (LHV) of the chemical, which is an established way to measure and characterise hydrocarbons. The result is that a greater mass of pyrolysis oil would be required to produce the ethylene than the virgin equivalent (this is the method also practiced and endorsed by BASF in their LCA study in Section 4.3.2.). This method also leaves the door open for other chemical products to be classed as recycled and measured using this same methodology. As discussed, this issue needs to be considered from a wider perspective to determine whether this is an desirable way forward given the highlighted issues.

It is also important to recognise that mass balance is not one singular method, and there are several proposed approaches to achieving it. There is likely to be no perfect solution as the complexity of the value chain makes precise measurement and traceability problematic. Equally, the process needs to be administered in such a way that transparency is maintained and enforcement of clear standards is possible, otherwise credibility and confidence in the products produced will be lost. This aspect is particularly apparent when considering how the end product is traded and marketed. For example, if the recycled content of the final polymer is the average of all inputs to the process (batch level— Figure 5) or whether it is allocated to specific products (group

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[133] Enabling a circular Economy for Chemicals with the Mass Balance Approach

level—Figure 4); the former is more transparent, but will likely mean that each product can only claim a small fraction of recycled content (as it is evenly distributed regardless). The latter is less transparent and means that rather than the material being traded as recycled, it is the 'right' to claim recycled content that is traded (i.e. the link becomes abstract rather than physical by the time it reaches the consumer). Unlike mass balance approaches for other commodities such as sustainability labelling of food products, the key issue is not, 'if?', but 'when?' virgin and recycled inputs are integrated.

A measure that sits between these two is the site level mass balance (Figure 6), which takes into account the average inputs into a plant over a given period. Figure 4 to Figure 6 show a simplified version of these systems (losses excluded) which demonstrates that only the batch mass balance process can produce a physical product that exactly matches the claimed recycled content (e.g. a 50% recycled content claim actually contains this amount), although it could ultimately be attributed variously to different products. At the extreme it is possible at the group level that 100% virgin material output from a particular plant could be claimed as 100% recycled if a customer of that region requires it and there are 'credits' within the group available. Such an approach seems likely to give rise to issues with consumer communication.

Much of the chemicals industry advocates the more flexible approach offered by the group level mass balance as proposed in the EMF report (referred to as 'qualified credit transfers'). Physically aggregating recycled inputs into one plant introduces logistical costs and impacts, whereas processing in a local plant reduces these, but is only advantageous if a system of credit trading between owned facilities is possible. Claims of prohibitive transport costs and redundant assets if a strict, segregated approach is taken have yet to be explored fully along with any comparative environmental impacts from a systems perspective. This also highlights that there are still remaining questions around whether there is a limit for the ratio of naphtha to pyrolysis oil in a steam cracker that prevents recycled inputs being aggregated physically at a smaller number of plants and that spreading the pyrolysis oil out across multiple plants mitigates issues relating to potential feedstock lower quality through dilution. Ultimately, whether the use of 'credits' becomes an issue will be determined by how effectively the system can be transparently audited and whether there is consumer acceptance of this as a practice which would require the support of consumer groups. This may also lead to a different perception of value to the consumer of mechanically recycled versus chemically recycled products which might be a consideration for brand owners and affect the price they are willing to pay.

In terms of auditing, the EMF report also advocates a form of self-regulating system for verification that places a high importance on internationally agreed ISO standards being developed by the chemicals industry. This would essentially be a voluntary and somewhat loose set of guidelines that individual countries adopt through regulation. As indicated, the EU is taking a different approach, beginning with the recycled content rules aimed at beverage bottles. In this way, standardisation is likely to be driven by regulation rather than the reverse. An industry-led initiative will be unlikely to materialise fully in time for when the target requirements become law. It therefore seems likely that the measurement method that is developed by the EU will inform global standards, particularly as brand owners will want to report their commitments under one measurement method globally.

Figure 4: Group Level Mass Balance

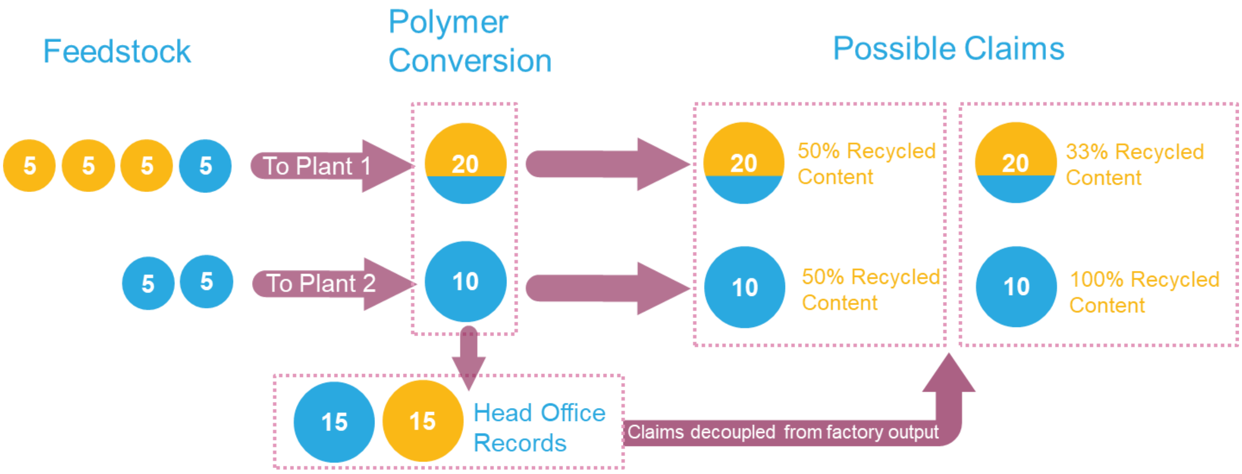


Figure 5: Batch Level Mass Balance

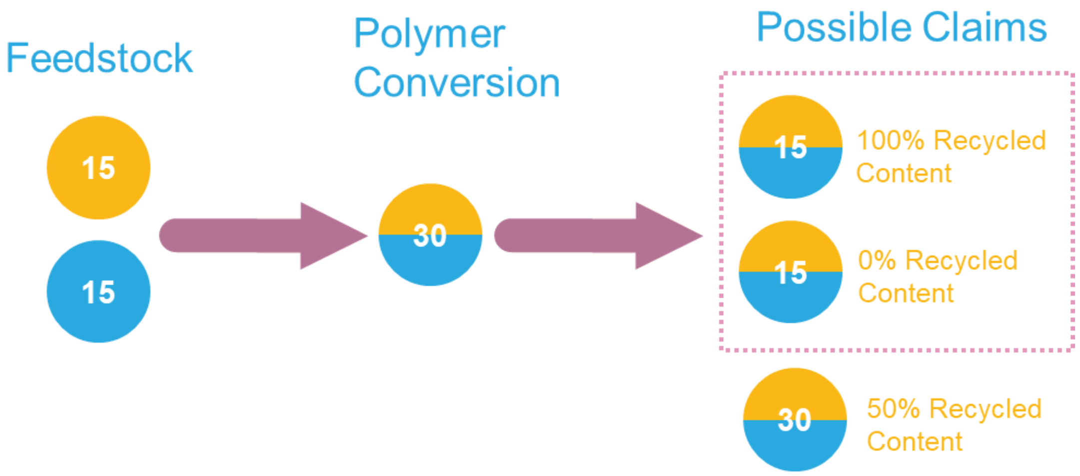
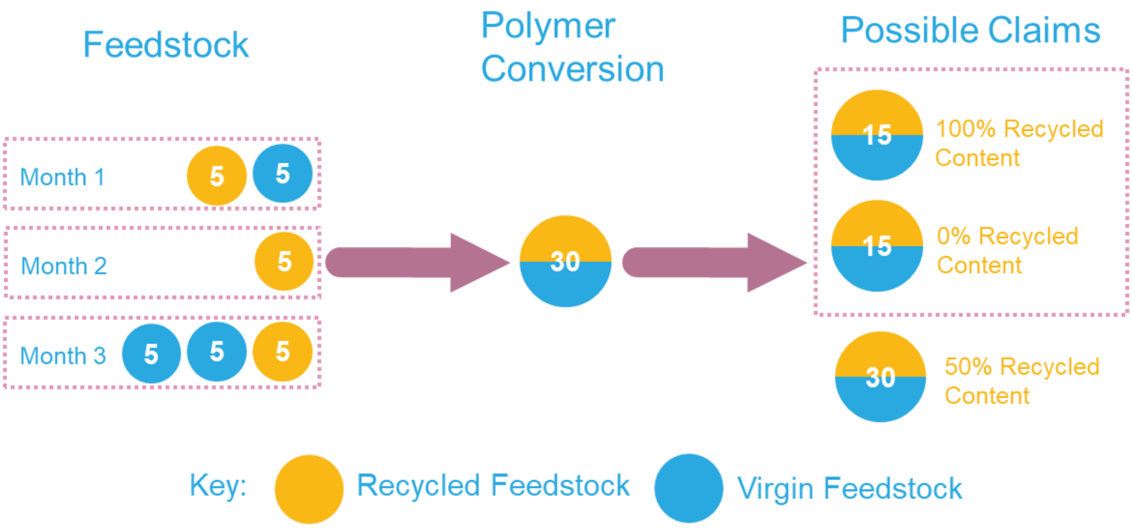


Figure 6: Site Level Mass Balance



7.0 Conclusions

The general conclusion through the research conducted for this report is that the evidence base for the significant adoption of chemical recycling technologies is limited, lacking detail and it remains unclear what role they might play (a full summary list of advantages and disadvantages is provided in Table 12).

There are promising niche applications, but significant hurdles, in terms of efficiencies and validating the quality of inputs and outputs, are yet to be overcome. Table 11 summarises some of the key claims for polymer outputs that are often made for chemical recycling that mechanical recycling struggles to achieve. Whilst some technologies live up to these claims, there are often significant caveats. The ‘infinite loop’ is technically possible as the material itself isn’t degraded during each recycling ‘loop’ (solvent purification is the exception to this due to the thermal degradation that take place), but in practice this is not without —often significant—losses for each lifecycle and therefore a significant amount of virgin polymer would still need to be produced to meet any shortfall. Particularly for pyrolysis, monomers cannot be produced independently of the current virgin polymer supply chain and the use of virgin naphtha is needed to dilute contaminants in a steam cracker.

Table 11: Key Claims for Chemical Recycling Technologies

Claim	Solvent Purification	Chemical Depolymerisation	Thermal Depolymerisation
Infinite virgin-grade recycling is possible	No	Yes – losses are variable depending upon specific technology	Yes – but not without significant losses in each loop
Food grade end products can be produced	Not likely	Yes – this is inherent to the process	Yes – only if the outputs are used for monomer/polymer production
Removal of contaminations/ additives	Limited/Specific	Yes – although relatively ‘clean’ inputs are needed to make it viable	Yes– only if the outputs are used for monomer/polymer production

Food contact safety Regulations[134] on recycled plastic intended to come into contact with food, exempt recycled material made by “chemical depolymerization”. This Regulation is a significant hurdle for mechanical recyclers particularly for materials other than PET. Although there are yet to be any commercialised outputs of food grade materials, this is technically possible for both chemical and thermal depolymerisation. Solvent purification does not depolymerise and therefore is likely to be akin to mechanical recycling under Regulations (i.e. not exempt).

The following summarises the key conclusions around the technical and commercial maturity of the three overarching technology types:

- **Solvent purification** technologies are likely to be a niche chemical recycling application with the most promising currently being EPS that is contaminated with legacy fire retardants. It is very energy intensive which makes it difficult to compete with mechanical recycling. As the output is a polymer, the process can be treated similarly to mechanical recycling with regard to recycling calculation rules. Importantly, the subsequent reprocessing to remanufacture new plastic products leads to degradation of the polymer chain. As such, this chemical recycling technology does not allow for infinite recycling of the material.
- **Chemical depolymerisation** technologies appear to have the most promise overall, particularly for PET/polyester using glycolysis and hydrolysis variations, with claims to yields of upwards of 90% and produce a pure monomer feedstock. As such, the issues with calculating recycling rate and recycled content are likely to be relatively easy to overcome using similar rules created for mechanical recycling. The linkage between PET packaging and polyester clothing fibres means that this technology could be deployed in interesting ways to improve recycling rates of both kinds of products. However, it is unlikely to be a substitute for the mechanical recycling of PET bottles particularly when they are part of a deposit refund system (DRS) that can provide clean, homogenous material for bottle-to-bottle recycling.

  Thermal depolymerisation, which primarily refers to variations of pyrolysis, has seen a large amount of attention as it is a well-established process in the waste industry for producing fuel products. However, deploying it as a way of producing feedstocks that can directly feed into monomer/polymer production is a relatively new application that has yet to be proven commercially. The thermal depolymerisation process itself is far less controlled than chemical depolymerisation, which results in multiple chemical outputs with varying utilisation value. The pyrolysis oil, when used as a substitute for naphtha in a monomer producing steam cracker also results in losses as monomers are not the

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[134] European Commission (2008) *Commission Regulation (EC) No 282/2008 of 27 March 2008 on recycled plastic materials and articles intended to come into contact with foods and amending Regulation (EC) No 2023/2006 (Text with EEA relevance)*, 2008, https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32008R0282

only output; fuel gas is also a product that is often fed back into the process to reduce reliance on external fuel sources. Understanding this is key to calculating overall polymer yields from the process.

Whilst it is typically possible to use a heterogeneous and contaminated feedstock, this reduces yields and currently makes purification for insertion into steam crackers unviable. The purification step has also not been tested at commercial scale and it is unclear whether pyrolysis oil can consistently meet the strict specifications of steam crackers in practice. The requirement for advanced sorting and washing that is being developed to improve mechanical recycling will, therefore, likely also be a requirement.

Other than for niche applications such as PMMA, the use of pyrolysis to recycle a mixed (but clean) polyolefin stream appears to have the most promise particularly for applications where specific waste types can be segregated, but are not attractive to mechanical recyclers e.g. films. A scenario where mixed plastic waste is sorted into multiple streams for chemical and mechanical recycling is likely to be the best use of this technology. This type of chemical recycling is also likely to be the most challenging to determine, transparent, fair, implementable and enforceable rules for calculating recycling rate and recycled content as the pathway is not linear or segregated.

From an environmental impact perspective, the following general observations and conclusions can also be made based on the existing body of LCAs that have been conducted both publicly and behind closed doors:

- Most studies only focus on comparisons with WTE or virgin production of fuels and polymer precursors. These comparisons provide a narrow perspective that cannot form the basis of strategic, long-term decision making.
- One of the key aspects that is missing from the environmental assessments to date, is a systems perspective aimed at understanding how these technologies might be deployed in reality. Studies tend to focus on comparative assertions and not where different technologies might complement each other.
- Energy use, yield, input and output quality are the key aspects of LCAs that need particular attention, but are rarely all addressed adequately. Studies that are not transparent about these aspects cannot be effectively compared or considered robust.
- LCAs generally fail to characterise the key benefits of some chemical recycling technologies; namely the ability to recycle infinitely and remove all contaminants.
- LCA could be used to investigate the trade-offs between chemical and mechanical recycling over multiple cycles. This can be achieved by expanding the system boundary to include more than one life cycle, which could help to determine the key tipping points for each recycling method and how they might complement each other.

- Even when compared with a relatively poorly performing mechanical recycling scenario, current pyrolysis oil to monomer processes appear to be too energy intensive to compete.
- Pyrolysis appears to only be viable for waste streams that cannot be effectively mechanically recycled. However, this should not move the focus from initiatives to reduce or prevent this type of waste, or to cease looking for alternatives that can be effectively mechanically recycled as the current evidence suggests that these are still preferable environmental options.
- To invest in pyrolysis infrastructure to treat all types of currently unrecyclable plastic might 'lock in' increased environmental impacts over the long term in a similar way in which the shift towards WTE has done so in countries that have invested heavily in incinerators. A joined-up policy on plastic use in the future should consider this and other aspects such as any move towards bio-based plastics (particularly 'drop-in' versions of current plastics such as bio-PET or bio-PP). Whilst current LCA results suggest most chemical recycling is an improvement on WTE, this may not be the case for bio-based plastics particularly for climate change impacts.

All of these conclusions suggest that there is an urgent need for more transparency within the chemicals recycling industry. There is evidence to indicate that at least some technologies have promise, but important details around mass flows, chemical use and the viability of the processes in real-life waste management circumstances are largely incomplete. Investment should be reserved for those organisations that freely engage to improve the understanding around these missing elements.

Table 12: Summary of Advantages and Disadvantages of Chemical Recycling Technologies

Solvent Purification		Chemical Depolymerisation		Thermal Depolymerisation	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
• Has been demonstrated to separate polycotton textile blends. • Environmentally benign solvents have been tested successfully at a lab scale • Generally allows recovery of the solvent for reuse. • Demonstrated to recover non-target by-products for valorisation.	• Can currently handle only material inputs that are largely homogenous in nature. • Often requires stringent pre-sorting and or pre-treatment steps to prepare for purification. • Typically necessitates high energy requirements, in particular the post-purification drying stages. • Typically, cannot remove contaminants entirely. • Has not been demonstrated to provide food-grade outputs. • Lack of clarity regarding the solvent types and toxicities for larger scale technologies • Does not allow for limitless recycling of the material, due to thermal degradation of the chains during reprocessing to form new plastics. • Current lack of clarity regarding environmental performance. • Yet to demonstrate economic viability on a commercial scale.	• Monomer outputs can be utilised to produce plastic products of equal quality to virgin equivalents. • Demonstrated examples of systems that allow the recovery and reuse of chemical reagents such as catalysts and solvents. • High yields demonstrated for a number of technologies. • Demonstration of commercial viability for bottle and fibre inputs.	• Technologies typically require homogenous waste streams as an input, often requiring extensive pre-treatment/sorting technologies. • Lack of information concerning the quantities of chemical reagents and other supplementary materials e.g. catalysts. • Lack of clarity as to the overall energy inputs associated with the technologies, processes often requiring high energy inputs. • Lack of yield information at plant level. • General lack of understanding around the level of contamination that the technologies can handle, nor how the contaminants are dealt with following monomer purification. • Little consideration given for hazardous inputs/by-products. • Lack of verified environmental performance data for the majority of technologies.	• Technology can typically accept more heterogenous mixtures of waste as an input, but at the expense of output quality and utility (recovery as a fuel). • Can be applied to waste streams that are currently unrecyclable. • When purified, outputs can be used to manufacture plastics and other high-value chemicals, of equal quality to virgin feedstocks. • High temperatures utilised to effectively decontaminate the waste inputs.	• Requires a homogenous source of plastic waste to provide higher level (i.e. monomer) outputs. • The random nature of the depolymerisation process leads to a complex mixture of products, requiring costly purification systems to isolate usable products. • Current thermal depolymerisation outputs are skewed towards the lower cost production of fuel. • No clarity as to the recycling of by-products and reagents as part of the process. • Steam cracking of pyrolysis oil to create monomers typically results in a proportion of the input being converted to energy (recovery) to run the process. • Requires existing virgin polymer value chain to produce monomers. • No environmental performance data currently available for the majority of technology providers.

APPENDICES

A.1.0 Technical and Commercial Maturity – Technology Lists and Supplemental Information

This section provides supplemental information regarding the current known chemical recycling activities that are taking place by technology type, inputs and outputs and an assessment of the maturity based on current or projected capacities. This is split into three categories;

- **Commercial Scale** - Economically viable and established plants dealing with large volumes of waste (typically upwards of 30,000 tonnes/yr)
- **Pilot/Demonstration Scale** – A plant has been built that can receive the target wate materials in low volumes (typically <10,000 tonnes/yr). Experiments may still be underway to determine the economics of processing different feedstocks.
- **Laboratory Scale** – Studies exist that demonstrate the feasibility of a technology in the lab.

A.1.1 Solvent Purification

Table 13 shows the organisations current working with solvent purification technologies.

Table 13: Solvent Purification Technologies by Plastic Type

Target Polymer(s)	Company	Plastic Waste Stream	Maturity
Polystyrene (PS)	PolyStyreneLoop (CreaSolv technology)[135,136]	Expanded polystyrene foam used for insulation	Building demonstration plant (3,300 t/y).
	Polystyvert[137]	Post-consumer household polystyrene waste	Small-scale plant (600 t/y), technology patent pending.

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[135] (2018) *PolyStyreneLoop project*, https://circulareconomy.europa.eu/platform/en/good-practices/polystyreneloop-project-pioneer-demonstration-plant-treat-3300-tonnes-polystyrene-wasteyr-2018

[136] (2020) *PolyStyreneLoop Newsletter* https://polystyreneloop.eu/news/newsletter-in-the-loop-may-june/

[137] (2018) *Total and Polystyvert join forces on the recycling of household post-consumer polystyrene*, https://www.prnewswire.com/news-releases/total-and-polystyvert-join-forces-on-the-recycling-of-household-post-consumer-polystyrene-300641098.html

Target Polymer(s)	Company	Plastic Waste Stream	Maturity
Polyethylene Terephthalate (PET)	Worn Again[138,139,140]	Polyester/cotton textile blends In development: PET packaging	Pilot research and development facility launched processing 80kg batches; larger demonstration facility expected 2021.
Polyethylene (PE)	Unilever/Fraunhofer (CreaSolv technology)[141]	Multilayer sachets	Pilot plant (1,000 t/y), aiming for 5,000 t/y in 2020.
Low Density Polyethylene (LDPE) & Polyamide (PA)	APK (Newcycling technology)[142]	Multilayer films of the two polymers (aim will be mixed plastic waste)	Pilot plant (8,000 t/y)
Polypropylene (PP)	Proctor & Gamble (PureCycle Technology)[143,144]	Pilot: polypropylene carpet In development: All PP waste	Feedstock evaluation unit to be scaled up to a processing capacity of ~50,000 t/y by 2021, with development of a second plant being evaluated due to demand.

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[138] GreenBlue Worn Again: A Solution for PET/Cotton Blended Fabrics

[139] *Worn Again Technologies secures £7m of investment* https://www.letsrecycle.com/news/latest-news/worn-again-technologies-secures-7m-of-investment/

[140] (2020) https://www.sustainableplastics.com/news/worn-again-launches-pet-recovery-rd-pilot-facility

[141] (2018) *Our solution for recycling plastic sachets takes another step forward* https://www.unilever.com/news/news-and-features/Feature-article/2018/our-solution-for-recycling-plastic-sachets-takes-another-step-forward.html

[142] (2019) Imminent start-up of commercial solvent-based recycling facility in Germany https://www.plasteurope.com/news/APK_t241633/

[143] (2019) *PureCycle says it has recycled waste carpet into PP* https://www.plasticsnews.com/news/purecycle-says-it-has-recycled-waste-carpet-pp

[144] (2017) *PureCycle Technologies and P&G introduce technology that enables recycled plastic to be nearly-new quality* https://www.prnewswire.com/news-releases/purecycle-technologies-and-pg-introduce-technology-that-enables-recycled-plastic-to-be-nearly-new-quality-300491368.html

A.1.2 Chemical Depolymerisation

A.1.2.1 Commercial Scale Technologies

There are some current examples of chemical depolymerisation technologies that are already producing recycled plastics as a commercial product, including PET focussed companies such as Nan Ya Plastic (ECOGREEN technology), PerPETual Global Technologies and Itochu (RENU technology), and the polyamide focussed Aquafil (Econyl technology). In general, however, there is little to no supporting information as to how these processes operate.

Nan Ya Plastic's ECOGREEN technology is unusual in that it works in combination with mechanical recycling, processing PET bottle flakes through glycolysis.[145] PerPETual Global Technologies also utilises glycolysis to process approximately two million bottles a day, claiming a technology utilises *"no chemicals that are foreign or toxic"* foregoing a catalyst to avoid the issues associated with their recovery and using a *"proprietary micron level filtration to remove all contaminants"*.[146]

Itochu's RENU technology uses pre- and post-consumer textile waste as inputs for its methanolysis process. The inputs must first be screened and pre-treated to ensure they at least 93% polyester, in order to maintain quality of output. While this requires more time-intensive sorting, the company claims the resulting product has a dye-ability comparable with virgin polyester, without the constraints that most recycled polyester products in the market currently face.[147]

Aquafil's ECONYL nylon yarn regeneration is perhaps the most well documented depolymerisation technology, utilising the hydrolysis pathway for depolymerisation to produce the monomer caprolactam, which can be repolymerised into recycled nylon products. The process involves a decontamination step to selectively decompose and remove impurities, followed by washing and drying steps that afford a clean monomer product. The solvent is noted to be purified for reuse within the technology. While the technology requires high energy inputs for both depolymerisation and decontamination,

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[145] Nan Ya Plastics Corp. ECOGREEN: 100% Post-consumer Recycled Polyester, https://www.npc.com.tw/j2npc/zhtw/proddoc/%E7%92%B0%E4%BF%9D%E7%B5%B2%E7%B9%94%E5%B8%83%E7%A8%AE/ECOGREEN?docid=F000000791&pdid=F00000079

[146] https://www.perpetual-global.com/manufacturing/

[147] (2020) https://renu-project.com/wp-content/uploads/2020/02/RENU%E2%84%A2_Brochure_1908_v06_EN.pdf

it has shown commercial success due to the comparably high costs of producing virgin nylon.[148,149,150]

It is worth noting that all four of these technologies, while utilising different plastic waste inputs, use the monomer product for the manufacture of polyester yarns. Given the concerns surrounding the industry's carbon footprint and a lack of existing recycling technologies[151], the demand from big-name brands (Adidas, H&M, Gucci, Prada) for recycled fibre in the textiles industry might account for why these technologies have reached more commercial success, despite the relatively small plant capacities.[152,153,154]

A.1.2.2 Pilot Scale Technologies

Despite these commercial examples of chemical depolymerisation, the majority of technologies that have progressed from laboratory stage are yet to reach larger scale operation. A number of companies, however, have successfully demonstrated pilot plant viability, while others provide only claims that their technologies are being scaled for commercial production. However, all use PET waste streams for input.

Glycolysis

A number of pilot scale technologies utilise the glycolysis process for depolymerisation. All have demonstrated viability at pilot plant stage and are working towards commercial viability, however, the size of these plants varies considerably (e.g. CuRe Technology – 25,000 t/a; Jeplan – 80t/a). Both Garbo (CHEMPET) and CuRe Technology claim technologies that process a wide variety of inputs. For example, Garbo's CHEMPET technology utilises a 6-hour process that depolymerises a wide variety of PET waste streams including bottles, trays, films, strapping and fabrics. This is combined with a *"special purification process"* to produce clean monomer. Similarly, CuRe Technology states it "*offers a low energy recycling*" method that can work on "*any type of used polyester by removing the color and converting it into clear pellets with the same properties as virgin grade polyester*". However, there is little understanding as to how

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[148] (2014) https://www.aquafil.com/assets/uploads/EPD-FOR-ECONYL-YARN.pdf

[149] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[150] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[151] Ellen MacArther Foundation (2017) *A New Textiles Economy Full Report*, accessed 5 September 2019, https://www.ellenmacarthurfoundation.org/assets/downloads/publications/A-New-Textiles-Economy_Full-Report.pdf

[152] (2019) https://www.perpetual-global.com/perpetual-technology-brought-to-the-fore-with-recent-adidas-press-release/

[153] (2020) https://renu-project.com/hm-conscious-exclusive-2020ss%e3%81%ae%ef%bc%93%e3%82%a2%e3%82%a4%e3%83%86%e3%83%a0%e3%81%abrenu%e6%8e%a1%e7%94%a8/

[154] https://www.econyl.com/brands/brands-apparel/

these depolymerisation technologies are designed to effectively decontaminate and recycle the monomers.[155,156]

Others, however, provide a clearer understanding as to how they have been designed to transition from laboratory scale demonstration to commercial application. As previously noted, the use of catalysts and the decontamination process are often economically prohibitive, due to the associated high costs to ensure purity at high yield. Ioniqa Technologies, however, has sought to overcome these barriers to viability through the use of a highly specialised catalyst that acts as both as a rate enhancer and as a decontaminant. The catalyst, which can be recovered for reuse following purification, adsorbs additives such as pigments and dyes to remove from the reaction mixture. Jeplan's BRING technology, on the other hand, uses a separate catalyst and pigment adsorbent, combined with a selective purification process, to allow both monomer and catalyst recovery.[157,158,159]

Hydrolysis

Hydrolysis is perhaps the least developed depolymerisation process when it comes to technologies that have demonstrated viability on a larger scale. While some companies, such as Gr3n and Carbios, are in the process of scaling up to pilot plant level, others are yet to disclose any information regarding their stage of development.

Gr3n utilises a patented microwave technology as an energetic catalyser, in conjunction with a chemical catalyst and solvent. Following the initial depolymerisation, unreacted materials are filtered out. The resulting monomers go through further decontamination and purification procedures to recover clean product, as well as the recovery of the chemical catalyst and solvent for reuse.[160] The process, while requiring higher energy inputs, is balanced by the greatly reduced timescales of the reaction.[161,162] Tyton Biosciences, in contrast, utilises high pressure and temperature to ensure effective degradation of the polymer.[163] Carbios favours a biological (enzyme) catalyst to cause hydrolysis; the depolymerisation occurring at lower temperatures to minimise energy inputs.[164,165] It is interesting to note that despite the technology's viability having only

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[155] http://www.garbosrl.net/chempet/?lang=en

[156] https://curetechnology.com/how-it-works/

[157] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[158] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

[159] https://www.jeplan.co.jp/en/technology/bottle/

[160] Parravicini, M., Crippa, M., and Bertele, M.V. (2014) *Method and apparatus for the recycling of polymeric materials via depolymerization process*

[161] https://www.demeto.eu/mission

[162] http://gr3n-recycling.com/#tecnological_breakthrough

[163] Barla, F.G., Showalter, T., Su, H.-C., Jones, J., and Bobe, I. (2019) *Methods for Recycling Cotton and Polyester Fibers from Waste Textiles*

[164] BOISART, C., and MAILLE, E. (2018) *Method for recycling plastic products*

[165] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

been demonstrated at laboratory level, the pilot plant currently in development has a planned capacity of at least 50,000 t/a, larger even than those chemical depolymerisation technologies operating commercially.

As with the glycolysis technologies, there is a lack of detail regarding the subsequent purification processes required to afford clean monomer product. Within the literature, purity is noted as a general drawback of the process, due to the need for catalysts and supplementary chemicals which are difficult to subsequently separate from the monomer product. There is, in general little detail provided as to the quantities of chemical reagents used, their recovery for reuse, nor how the process deals with contaminants present in the waste stream.[166,167]

Methanolysis

While there are few technologies utilising the methanolysis process that have progressed beyond laboratory stage, there is one notable example in Loop Industries, which is already operating a pilot plant level. The technology utilises a specific type of organic solvent, as well as a chemical catalyst, to cause depolymerisation of PET. As this type of organic solvent exists more readily as a vapor, this could lead to both environmental and economic impacts with regards to recovery of the solvent and ensuring the solvent does not pollute the air. However, there is no information on how this issue is being resolved.[168,169]

Another important consideration, as previously mentioned, is the purification of the monomer products and associated by-products. This is detailed within the literature as a common issue for methanolysis due to the production of other alcohols and polymer derivatives during the reaction process.[170] While Loop Industries notes its use of purification processes that remove *"all colouring, additives, and organic and inorganic impurities"*, in there is no further detail regarding how these issues of purity are addressed to ensure a clean product. Loop Industries, in partnership with Suez, are planning to build a full commercial scale plant somewhere in Europe by 2023 with a capacity to process 4.2 million[171] beverage bottles annually (approx. 84,000 tonnes).[172]

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[166] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[167] Al-Sabagh, A.M., Yehia, F.Z., Eshaq, Gh., Rabie, A.M., and ElMetwally, A.E. (2016) Greener routes for recycling of polyethylene terephthalate, *Egyptian Journal of Petroleum*, Vol.25, No.1, pp.53–64

[168] Essaddam, H. (2017) *Polyethylene terephthalate depolymerization*

[169] https://www.cdc.gov/biomonitoring/HalogenatedSolvents_BiomonitoringSummary.html

[170] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[171] The official press release states 4.2 billion, but this would equate to 84 million tonnes per annum and is assumed to be an error.

[172] https://www.suez.com/en/news/press-releases/loop-industries-and-suez-announce-strategic-partnership-to-build-first-infinite-loop-facility-producing

A.1.2.3 Laboratory Scale Technologies

All technologies detailed so far are, for the most, part focussed on the chemical recycling of PET waste streams. However, there is a lack of depolymerisation technologies utilising other condensation polymers such as polyurethane (PU) and polylactic acid (PLA), that have progressed beyond laboratory level, with the notable exception of Aquafil's Econyl (PA) process. However, there are a few examples of those that show promise for development.

H&S Anlagentechnik has designed depolymerisation techniques for both flexible and rigid PU foams. Flexible PU foam is broken down through the hydrolysis process, utilising organic acids in the presence of a solvent and a catalyst. While hydrolysis with an acid is often not carried out due to the issues with purification, this technology is reportedly capable of recovering monomer products that are sufficiently pure, costing 25-30% less than the virgin equivalent. However, this process does require a number of pre-treatment steps to ensure the waste inputs are free of contaminants to ensure an effective recycling process. [173] A partnership is in place with chemicals manufacturer Dow to commercialise the flexible foam technology as part of their Renuva mattress recycling program—capitalising on the recent boom in PU foam-based mattresses—although this is still in development. The company is also looking to further expand its depolymerisation of rigid PU foams, utilising the glycolysis pathway.[174]

In pursuit of methods to effectively recycle PLA, the Fraunhofer Institute for Chemical Technology have worked to develop a depolymerisation method, however at present this has only been demonstrated on a laboratory scale and only with virgin PLA and post-consumer cups.[175]

A.1.2.4 Other Technologies

While the majority of technologies explored within chemical depolymerisation focus on the production of monomer products for the reintroduction into plastics manufacturing, there are emerging technologies that are looking to the production of materials as feedstocks for other products.

Applications are varied, with demonstrated examples at a laboratory scale. PET has been shown to be depolymerised into shorter chain oligomers that can be used in the production of urethane oils and other polyurethanes. Oligomer products can also be

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[173] H&S Anlagentechnik (2017) Sustainable Technologies for generating Polyols

[174] (2020) https://www.sustainableplastics.com/news/dow-polyurethanes-build-pioneering-industrial-scale-recycling-facility-orrion-chemicals

[175] (2020) https://www.plasticstoday.com/sustainability/fraunhofer-ict-introduces-upcycling-post-consumer-pla-waste

utilised as plasticisers in the formulation of PVC products, which are used to make the plastic softer and more flexible as well as improve thermal stability.[176,177]

A.1.2.5 Organisation list

Table 14 shows the organisations current working with chemical depolymerisation technologies, ordered from highest to lowest output for each material.

Table 14: Chemical Depolymerisation Technologies by Plastic Type

Company	Plastic Stream	Method	Maturity
Polyethylene Terephthalate (PET)			
Nan Ya Plastics (ECOGREEN)	PET bottle flake (from mechanical recycling)[178]	Glycolysis	Commercial plant operational, processing 216,000 t/y to produce 144,000 tonnes of recycled yarn & 20,000 tonnes staple fibre.
Itochu (RENU technology)[179, 180]	Pre- and post-consumer polyester textiles (93% polyester, no polyurethane or metal elements)	Unknown (DMT and EG products infer Methanolysis)[181]	Commercial plant operational (30,000 t/y)
CuRe Technology[182, 183]	• Coloured PET, including: ○ Carpets ○ Textiles • Food packaging	Glycolysis	Pilot plant operational (currently 20kg/hour continuous, sources state estimated capacity of 25,000 t/a)

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[176] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[177] https://www.bpf.co.uk/plastipedia/additives/Default.aspx#Plasticisers

[178] https://www.npc.com.tw/j2npc/zhtw/proddoc/%E7%92%B0%E4%BF%9D%E7%B5%B2%E7%B9%94%E5%B8%83%E7%A8%AE/ECOGREEN?docid=F000000791&pdid=F00000079

[179] (2020) https://renu-project.com/wp-content/uploads/2020/02/RENU%E2%84%A2_Brochure_1908_v06_EN.pdf

[180] (2020) https://sportstextiles.com/WSA/154687

[181] Fakirov, S.(2002) *Handbook of Thermoplastic Polyesters: Homopolymers, Copolymers, Blends and Composites*, WILEY-VCH

[182] (2019) https://packagingeurope.com/cumapol-developing-potentially-groundbreaking-polyester-recy/

[183] https://www.msp-emmen.com/sites/default/files/Cure-Polyester-leaflet.pdf

Company	Plastic Stream	Method	Maturity
Loop Industries[184,185,186]	Bottles Containers Thermoforms Fines from MRFs	Methanolysis	Pilot plant operational (20,700 t/a), working to increase capacity (40,000 t/a). Commercial plant due by 2023 (84,000 t/a)
PerPETual Global Technologies[187,188]	PET bottles Polyester textiles, PET packaging, PET film (in development)	Glycolysis	Commercial plant operational, retrofitted with technology, processes 2,000,000 bottles/day.
Ioniqa Technologies[189,190]	Bottles Fibres (in development)	Glycolysis	Pilot plant operational (10,000 t/a), plan to scale up to 50,000 t/a.
Garbo (ChemPET Technology)[191,192,193,194]	Thermoform scraps and multilayer trays Aluminium coupled films Opaque bottles Coloured PET powder Black PET trays PET/PP Strapping Non-woven fabrics Polyester & cotton textile blends	Glycolysis	Pilot plant in operation (3 t/d), with commercial scale plant due for start-up in 2020 (~100 t/d)

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[184] GreenBlue (2017) Loop Industries
[185] (2020) https://www.loopindustries.com/en/news#:~:text=The%20growing%20demand%20for%20Loop,PET%20plastic%20and%20polyester%20fiber.
[186] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges
[187] https://www.perpetual-global.com/manufacturing/
[188] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges
[189] (2019) https://ioniqa.com/ioniqa-takes-first-10-kiloton-pet-upcycling-factory-into-operation/
[190] https://ioniqa.com/applications/
[191] (2017) https://petcore-europe.org/images/news/pdf/14-chemical-recycling_wim-hoenderdaal.pdf
[192] (2019) https://www.sustainableplastics.com/news/garbo-build-large-scale-pet-chem-recycle-plant-italy
[193] http://www.garbosrl.net/chempet/?lang=en
[194] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges

Company	Plastic Stream	Method	Maturity
Jeplan (BRING Technology)[195, 196,197,198]	• Non-Opaque Bottles • Fibres	Glycolysis	Started commercial operation in 2019 (80 t/y), increasing to 400 t/y in 2020.
Gr3n (DEMETO technology)[199, 200201]	• Bottles • Food containers • Polyester textiles	Hydrolysis	Demonstration plant running (capacity not known), commissioning of full-scale pilot plant was due early 2020 (1,000-1,500 t/a).
Carbios[202,203204]	• Bottles • PET Waste (in development)	Hydrolysis	Process optimisation complete at laboratory level. Pilot plant in construction, due 2021 (estimated capacity 50,000 – 100,000 t/a).
Tyton Biosciences[205, 206]	Polyester & cotton textile blends	Hydrolysis	Aiming to begin commercial production in 2020. Maturity not known.

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[195] https://www.jeplan.co.jp/en/technology/
[196] (2020) https://bioplasticsnews.com/2020/06/07/yokogawa-jeplan-chemical-recycling/
[197] Simon, J.M., and Martin, S. (2019) El Dorado of Chemical Recycling - State of play and policy challenges
[198] Textile Exchange (2020) Preferred Fiber & Materials Market Report 2020
[199] (2019) https://www.demeto.eu/post/2019/09/03/newsletter-september-2019
[200] http://gr3n-recycling.com/#tab-id-9
[201] (2018) https://universal-sea.org/inspirations/gr3n-the-new-technology-to-tackle-the-plastic-waste-issue
[202] (2020) https://carbios.fr/en/carbios-begins-construction-on-industrial-demonstration-plant-in-final-step-to-commercializing-its-pet-recycling-technology/
[203] (2017) https://www.businesswire.com/news/home/20171011005697/en/CARBIOS-Production-Virgin-PET-Post-Consumer-Plastic-Bottles
[204] (2018) https://carbios.fr/en/carbios-achieves-a-major-milestone-in-the-optimization-of-its-biorecycling-process-of-pet-based-plastics/
[205] https://www.tytonbio.com/our-technology/
[206] (2019) https://asia.nikkei.com/Spotlight/Environment/Marubeni-teams-with-US-startup-to-recycle-fiber-for-clothing

Company	Plastic Stream	Method	Maturity
BP Infinia[207]	- Coloured & opaque bottles and trays	Unknown (TPA and EG products infer Hydrolysis)[208]	Plans for USD 25 million pilot plant ahead of commercialisation. Maturity not known.
Far Eastern New Century (ChemCycle technology)[209]	- Bottles - Textile waste	Unknown (TPA and EG products infer Hydrolysis)[210]	Working with Coca Cola and Adidas to commercialise the technology for each waste stream. Maturity not known.
Eastman (Polyester Renewal Technology)[211, 212]	PET Waste, type unknown	Methanolysis	Engineering feasibility study on commercial scale facility for development of plant by the end 2021. Maturity not known.
Polyurethane			
H&S Anlagentechnik[213,214]	Flexible Polyurethane Foam	Hydrolysis	Partnering with DOW as part of the Renuva Mattress Recycling program, new plant to be completed end 2020, with product to be available 2021. Maturity not known.

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[207] (2019) https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-new-technology-to-enable-circularity-for-unrecyclable-pet-plastic-waste.html

[208] Fakirov, S.(2002) *Handbook of Thermoplastic Polyesters: Homopolymers, Copolymers, Blends and Composites*, WILEY-VCH

[209] (2020) http://www.fenc.com/news/news_detail.aspx?lang=en&id=5228

[210] Fakirov, S.(2002) *Handbook of Thermoplastic Polyesters: Homopolymers, Copolymers, Blends and Composites*, WILEY-VCH

[211] https://www.eastman.com/Circular-Economy/Pages/Circular-Economy.aspx

[212] (2019) https://www.recyclingtoday.com/article/eastman-pet-chemical-recycling-solution/

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

[214] (2020) https://www.sustainableplastics.com/news/dow-polyurethanes-build-pioneering-industrial-scale-recycling-facility-orrion-chemicals

Company	Plastic Stream	Method	Maturity
H&S Anlagentechnik [215,216]	Rigid Polyurethane Foam	Glycolysis	Maturity not known.
Polyamide			
Aquafil (ECONYL) [217,218,219]	• Nylon textile waste ○ Fishing Nets ○ Carpet Waste • Fabric Scraps	Hydrolysis	Commercial plant operational (~40,000 t/a) Second carpet specific recycling plant operational (16,000 t/a)
Polylactic Acid			
Fraunhofer ICT [220]	*PLA cups*	Not stated	Moved to technical scale (15L) – no updates since 2015

A.1.3 Thermal Depolymerisation

A.1.3.1 Commercial Scale Technologies

Despite the myriad considerations and challenges presented by thermal depolymerisation, there are current examples of successful plants utilising the technology at a commercial level.

Regenyx, a joint venture by Agilyx and Amsty, is the only commercial example of a thermal depolymerisation process that can recover monomers. Its PolyUsable technology, which requires moderately high temperatures, relies on the slightly more reactive bonds in polystyrene, which can be preferentially broken to produce styrene monomer that can be reintroduced into the polystyrene manufacturing process. Any

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[215] https://www.hs-anlagentechnik.de/en/recycling-reactors-for-flexible-pu-foam-residues.html
[216] (2020) https://www.sustainableplastics.com/news/dow-polyurethanes-build-pioneering-industrial-scale-recycling-facility-orrion-chemicals
[217] https://www.econyl.com/assets/uploads/ECONYL_brochure_150318_EN-5.pdf
[218] (2019) https://www.econyl.com/assets/uploads/RS18_Aquafil_ENG_200819_72dpi.pdf
[219] (2019) https://www.nationalgeographic.com/science/2019/10/partner-content-prada-renylon-ljubljana-slovenia/
[220] (2020) https://www.plasticstoday.com/sustainability/fraunhofer-ict-introduces-upcycling-post-consumer-pla-waste

heavier hydrocarbon products are reintroduced into the system for further degradation to ensure waste is minimised.[221]

Plastic Energy and GreenMantra Technologies are two further pyrolysis processes that have demonstrated viability on an industrial scale. In contrast, however, these technologies target mixed waste streams composed of PP, PE and PS and, as such, lead to a heterogenous product. Plastic Energy requires an initial sort to ensure the inputs are free from heavier plastics and metals, as well as a pre-treatment to minimise the moisture content. The resulting oil from the pyrolysis process consists of heavier diesel and lighter naphtha oil fractions, as well as a gaseous component. While it is stated that the oil fractions can be utilised for plastic's production, it is unclear as the relative quantities that are produced, nor the end products that they are used for as the oil is sold to others in the petrochemical industry, as opposed to converting into chemical feedstocks at the plant. GreenMantra Technologies, on the other hand, utilises the waste input to produce, predominantly, a range of waxy hydrocarbon compounds through a catalytic pyrolysis process. These materials can be used as additives in a variety of manufacturing processes, including for PP and PE plastics, adhesives and rubber production.

A.1.3.2 Pilot Scale Technologies

There are a number of pilot scale technologies in development that are exploring alternative mechanisms for thermal depolymerisation. Pyrowave is another technology focussed solely on polystyrene, utilising both a catalyst and microwave energy to cause depolymerisation. This both lowers the temperature required for degradation and, it is claimed, ensures the process requires 10 times less energy in comparison to making virgin polystyrene. However, there is no further evidence as to how.[222,223] MMAtwo is an EU funded project under the Horizon 2020 Research and Innovation Program, targeting both pre- and post-consumer PMMA – a common substitute for glass. However, currently there is no further information provided as to the process that leads to the MMA monomer.[224]

Enval, like Pyrowave, also uses microwaves for the pyrolysis process. However, its target for depolymerisation are plastic aluminium laminates (the associated polymer is not specified), used in a variety of products including food pouches and cosmetics. The process utilises an unspecified carbon input, which absorbs the microwave energy to reach the required high temperatures of depolymerisation. The pyrolysis oil is

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[221] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[222] Doucet, J., and Laviolette, J.-P. (2018) *Catalytic microwave depolymerisation of plastic for production of monomer and waxes*

[223] (2019) Pyrowave: Closing the Loop, The Endless Regeneration of Plastics through Microwaves

[224] (2020) https://www.mmatwo.eu/wp-content/uploads/2020/05/MMAtwo_Newsletter_May-2020.pdf

subsequently sold, both as a fuel and to *"go back into the remanufacture of polymers"*, yet there is no further detail as to how. What differentiates this process from other thermal depolymerisation technologies is a focus on the recycling of not just the plastic polymer, having been designed to recover the aluminium by-product from the pyrolysis reactor.[225,226]

Other pilot technologies are focussed on more diverse waste inputs. Carboliq is a catalytic pyrolysis technology targeting mixed plastic/cellulose packaging. The process has been developed to handle significant PVC contamination and other halogen containing waste by neutralising the by-products. Producing comparatively low gaseous outputs, the resulting pyrolysis oil can be utilised for the production of both basic chemicals for polymers and fuel.[227] Recycling Technologies, in contrast, looks to residual plastic waste as a feedstock by integrating with existing mechanical recycling infrastructure and taking the non-target plastics (mostly films) that would otherwise be sent to residual waste treatment. Its resulting Plaxx oil is, it claims, not intended for fuel use but as a chemical feedstock, however, there is no supporting information. The technology is currently being tested in partnership with Citeo, Mars and Nestlé to assess its commercial application.

ReNew ELP's Cat-HTR technologies is unusual as it does not fall under the typical categorisations of pyrolysis and gasification. The process mixes water and oil with the plastic input under moderate temperature and high pressure, changing the properties of the water so that it acts as a catalyst for depolymerisation. Its presence results in the production of hydrogen, resulting in the cracking of the plastic waste and the production of a mixture of hydrocarbons. These are subsequently used for fuel enhancers or as chemical feedstocks.[228]

As noted with the commercial technologies, the same uncertainties remain as to the end-points of the materials formed following depolymerisation. There is also little specific reference to purification of the end products from contamination, nor how the impurities are subsequently dealt with.

A.1.3.3 Laboratory Scale Technologies

While yet to reach pilot scale demonstration, BioCellection and Fuenix are two further notable examples of thermal depolymerisation processes. BioCellection is unusual in that its process, like ReNew ELP, does not follow the typical pyrolysis or gasification pathways for degradation. Instead, the technology uses a thermal reaction pathway in the presence of an acid, which breaks apart polyethylene at low temperatures to

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[225] https://www.flexpack-europe.org/files/FPE/recovery/Enval.pdf

[226] (2020) https://www.letsrecycle.com/news/latest-news/enval-aiming-to-capture-mid-range-plastics/

[227] (2019) https://carboliq.com/pdf/1910_CARBOLIQ-flyer-K-2019.pdf

[228] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

produce organic acids, which can be utilised as chemical feedstocks. It has currently demonstrated the end products can be used to produce regenerated polyurethane from 50% post-consumer recycled monomers.[229,230,231]

Fuenix's Ecogy pyrolysis process, on the other hand, is designed to produce naphtha, paraffin and LPG fractions for subsequent use. The technology is being developed in conjunction with Dow to scale up for commercial application.[232,233]

A.1.3.4 Organisation list

Table 15 shows some of the organisations currently working with thermal depolymerisation technologies, ordered from highest to lowest output for each material. The list is not exhaustive due to the number of organisations using pyrolysis more generally for fuel or other waste treatment. Not every pyrolysis provider is openly promoting their technology for plastic to plastic recycling currently and this situation is constantly changing.

Table 15: Controlled thermal depolymerisation technologies by plastic type

Company	Plastic Waste Stream	Method of Depolymerisation	End Products	Maturity
Polystyrene (PS)				
Regenyx (Agilyx's PolyUsable technology)[234, 235]	Polystyrene waste	Pyrolysis	Styrene monomer	Commercial plant operational (~3,000 t/y), plan for larger facility (~15,000 t/y).

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[229] https://www.biocellection.com/tpu

[230] https://www.biocellection.com/innovation

[231] Thiounn, T., and Smith, R.C. (2020) Advances and approaches for chemical recycling of plastic waste, *Journal of Polymer Science*, Vol.58, No.10, pp.1347–1364

[232] (2019) https://corporate.dow.com/en-us/news/press-releases/dow-and-fuenix-enter-into-a-partnership-for-the-production-of-10.html

[233] (2019) https://bioenergyinternational.com/biochemicals-materials/dow-and-fuenix-enter-into-a-partnership-for-the-production-of-100-circular-plastic

[234] (2019) https://www.businesswire.com/news/home/20190430005768/en/AmSty-Agilyx-Launch-Joint-Venture-Regenyx-LLC

[235] (2018) https://advancedwastesolutions.ca/polystyrene-recycling-facility-to-be-built-in-the-u-s-a/

Company	**Plastic Waste Stream**	**Method of Depolymerisation**	**End Products**	**Maturity**
Pyrowave[236,237]	Post-consumer & post-industrial expanded and high impact polystyrene	Catalytic microwave pyrolysis	Styrene monomer	Pilot plant operational (~200 t/y)
Poly (methyl methacrylate) (PMMA)				
MMAtwo[238,239]	Pre- and post-consumer PMMA	Pyrolysis	Methyl methacrylate monomer	Pilot tests demonstrated. Capacity unknown.
Mixed Polymers				
Plastic Energy[240,241]	• LDPE, HDPE, PS and PP • Waste from MRFs and recycling facilities	Pyrolysis	For conversion into plastic, oil and fuel: • Naphtha • Diesel Used as fuel for plant: • Non condensable gases • Synthetic gas	Commercial plants operational (7,000 t/a in total) Further plants in construction/design – aim of 200,000 t/a total capacity by 2021.

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Company	Plastic Waste Stream	Method of Depolymerisation	End Products	Maturity
GreenMantra Technologies[242,243,244]	PP, PE, PS (depolymerised separately) - Virgin plastic - Plastic Jugs - Plastic bags - Other recyclable plastic	Catalytic Pyrolysis	- Diesel - Grease - Wax, utilised for polymer additives and chemicals	Commercial plant operational (5,000 t/a), plans for expanded facility (7,500 t/a)
Carboliq[245,246]	Mixed Packaging plastics (70%) and celluloses (30%)	Catalytic Pyrolysis	Basic chemicals for polymers and fuel	Pilot plant operational (2,500 t/a), producing fuel. Plans in place to double capacity by 2021.
Recycling Technologies (Plaxx)[247,248]	Mixed plastic waste	Pyrolysis	"New plastic production"	Demonstration plant operational (capacity unknown), commercial plant in development (7,000 t/a)
ReNew ELP (Cat-HTR technology)[249,250]	- Film - Pots, tubs and trays - Piping - MRF waste - Commercial waste	Catalytic hydrothermal depolymerisation	Fuel enhancers and chemicals	Commercial plant in development (20,000 t/a)

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Company	Plastic Waste Stream	Method of Depolymerisation	End Products	Maturity
	- Hospital waste			
BioCellection[251, 252,253]	PE Films, bags and packaging	Thermal oxidative decomposition	Dicarboxylic acids (chemical feedstocks)	Reactor level demonstration (2kg/day), increasing capacity in development (500kg/day)
Not Specified				
Enval[254,255]	Plastic aluminium laminates such as toothpaste, cosmetics, food pouches	Microwave Pyrolysis	Fuel and feedstock for speciality chemicals	Commercial scale demonstration (2,000 t/a)
Fuenix (Ecogy technology)[256, 257]	Unclear (plastic waste)	Pyrolysis	- Naphtha - Paraffin - LPG	Maturity not known. Partnering with DOW to scale up the technology.

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