Chemical Recycling: State of Play

Executive Summary

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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.

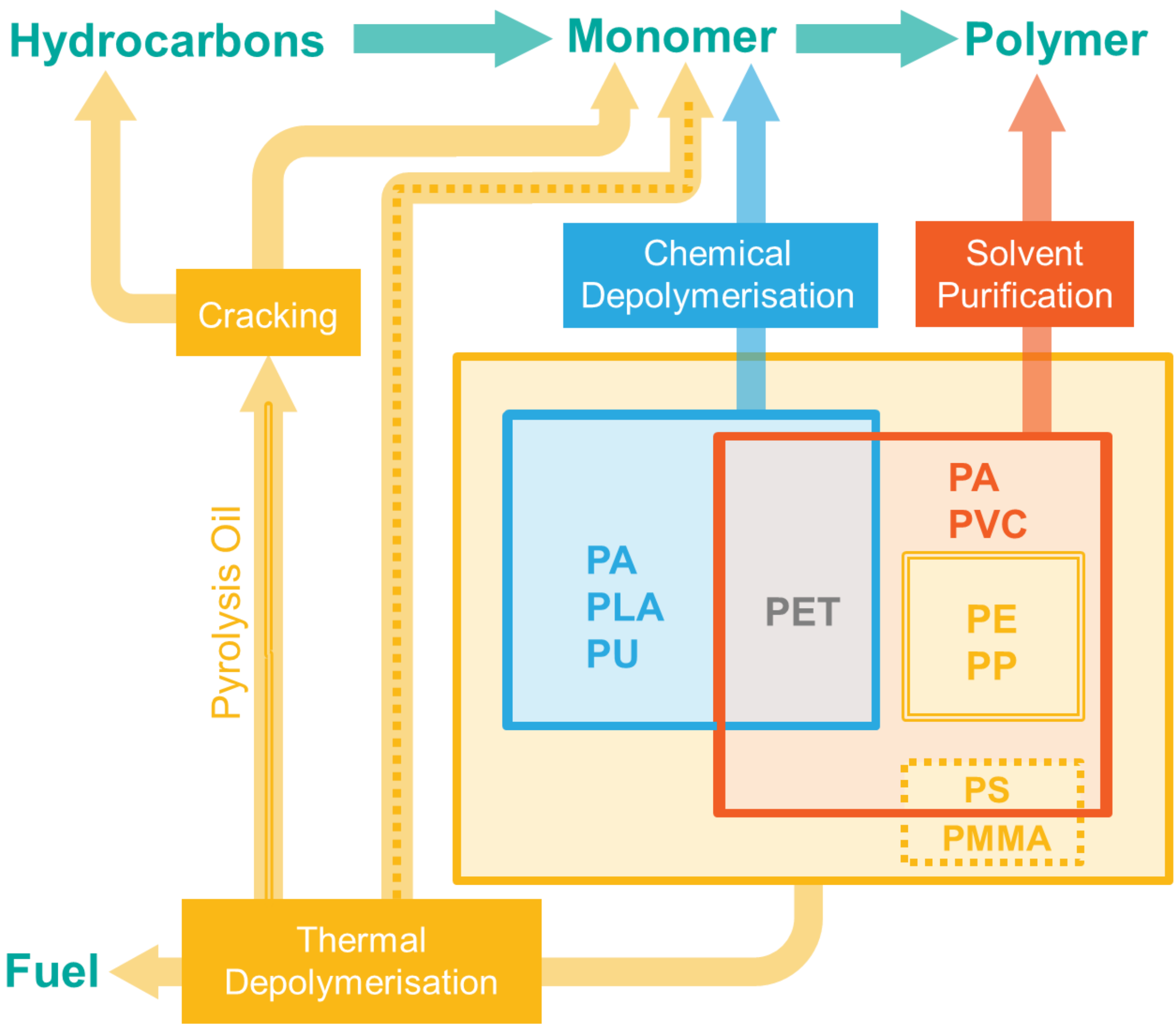
The focus of this report is to detail the technologies that have been developed, determine how mature they are and for which polymers they are aimed at. Their comparative environmental performance is also discussed against key benchmarks including waste to energy incineration (WTE), mechanical recycling 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).

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



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.