



## Non-Mechanical Recycling of Plastics

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# Executive summary

A high-level market study has been carried out into non-mechanical recycling technologies. There are several companies developing alternatives to conventional mechanical recycling, to allow for greater recycling rates and to achieve higher quality outputs.

Non-mechanical recycling, often referred to as “Chemical Recycling”, can be broadly grouped into the following categories:

- 1: **Pyrolysis** – This is the thermal breakdown of material without oxygen, resulting in a range of hydrocarbon products including wax, oil and gas. The gas is often burnt to provide energy to the process, whereas the oil and wax can be sold.
- 2: **Gasification** – This is the partial combustion of material to produce carbon monoxide (CO) and hydrogen (H<sub>2</sub>), which is a mixture known as SynGas. This gas can be burnt for energy or used in the production of new hydrocarbons.
- 3: **Chemical depolymerisation** – The use of chemicals to break down a polymer into its monomers or intermediate units
- 4: **Dissolution** – Polymers are dissolved in a selected solvent so the polymer can be separated from any contamination before being precipitated back out and re-used as a polymer. Dissolution does not affect the chemical composition of the polymer.

There are already commercial scale facilities carrying out pyrolysis of waste plastic, but to produce a fuel that is then burnt. The change in the industry is now some companies are looking to take pyrolysis oil and convert it back to polymer. This could enable the pyrolysis technologies to be classed as recycling.

The huge advantage of the non-mechanical recycling technologies may not only be the recycling of “non-recyclable” materials, but the ability to produce high grade, food contact, colour and additive free recycled polymer from post-consumer household waste.

Care must be taken when considering non-mechanical technologies as “recycling”. The process can only be considered recycling if a product is made that can be used as a secondary raw material. In the case of chemical depolymerisation and solvent dissolution, high yields of new polymer can be achieved. Through pyrolysis however, current processes will achieve low yields of secondary raw materials providing the naphtha is converted into new polymer. Yields of new polymer may be less than 10%. This issue of yield is vital when considering an effective recycling rate of 70%.

The need and desire for recycled content in packaging is growing, and this may mean there is no longer the economic barrier that chemical recycling once had. However, the environmental impact of the processes is not well defined at this time, and there could be a danger of creating higher environmental impacts for the sake of achieving recycling targets.

Non-mechanical recycling technologies will most likely be needed to reach the 70% effective recycling rate and 30% recycled content targets. Mechanical recycling will still play a vital role and more capacity will still be required.

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## 1.0 Introduction

Axion has been commissioned by WRAP to carry out a high-level market study into non-mechanical recycling technologies. This is to help progress The UK Plastics Pact roadmap, as non-mechanical technologies may be vital in achieving not only the 70% effective recycling rate but also enabling the average 30% recycled content of packaging.

A combination of desk-based studies and interviews has been used to determine the landscape for non-mechanical recycling technologies.

## 2.0 Overview of non-mechanical recycling technologies

The various non-mechanical recycling technologies described in this report can be grouped into four main categories:

- 1: Pyrolysis (also being referred to as “feedstock” recycling)
- 2: Gasification
- 3: Chemical depolymerisation
- 4: Dissolution.

Any commercial scale facility is also likely to need conventional technology, such as Near Infrared (NIR sorting), screening and wet or dry cleaning to ensure suitable quality material is fed into the non-mechanical recycling process.

### 2.1 Pyrolysis

Pyrolysis is the thermal degradation of organic materials at temperatures between 400 and 1,000 °C in the absence of oxygen. This results in the devolatilisation and decomposition of the feedstock, however the absence of oxygen means that no combustion occurs; instead, the heat energy breaks the chemical bonds of the more complex molecules to shorter, simpler products. Where the feedstock is plastic, particularly polyolefins, this results in the production of short chain hydrocarbons, similar to those found in crude oil.

Pyrolysis produces three products: gas, liquid and solid char. The relative proportions of which depend upon the method of pyrolysis and the operating conditions of the pyrolysis reactor, chiefly the rate of heating, the operating temperature, and residence time within the pyrolysis reactor.

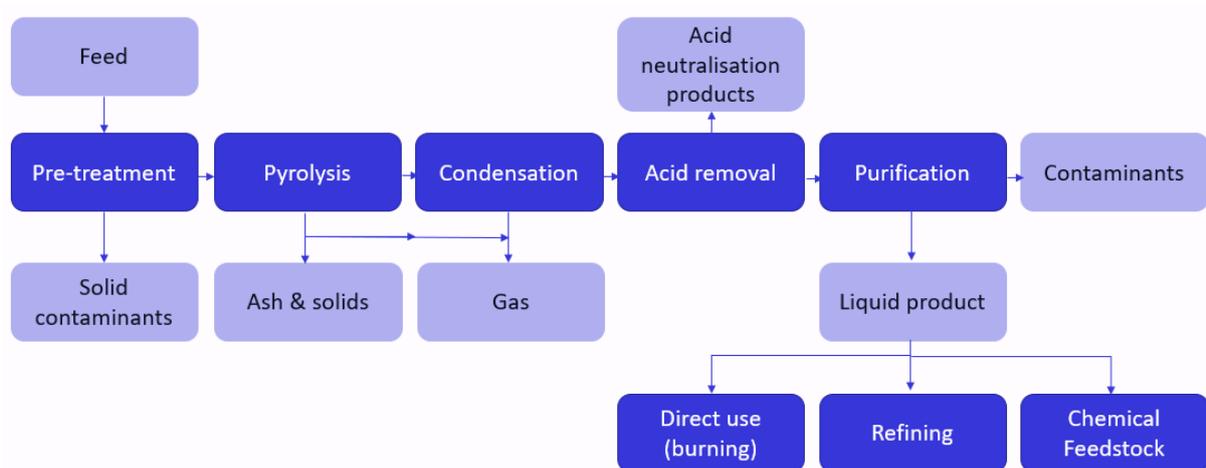
A typical pyrolysis process consists of the following steps:

- Pre-treatment to process the feedstock so that it can be fed into the pyrolysis unit – typically mechanical separation to remove contaminants and size reduction to increase conversion rate.
- Pyrolysis to convert the feedstock from solid to vapour and gas.
- Condensation to recover the vapours from the pyrolysis unit as an unrefined oil product.
- Acid removal to remove, e.g., hydrogen chloride produced by conversion of PVC.
- Purification to convert the unrefined oil into a material ready for sale.

The suitability of the product for these end markets is dependent on the level of contaminants, e.g. chlorine, sulphur and sodium.

An illustration of a typical pyrolysis process is shown in figure 1.

Figure 1 Process flow diagram for a typical pyrolysis process



In terms of waste plastic, pyrolysis works best with polyolefins such as polypropylene and polyethylene. Polystyrene (aromatic rings) is less desired, while levels of PET (oxygen and aromatic rings) and PVC (Chlorine) must be strictly controlled to minimise operating costs and maximise product yield and value.

## 2.2 Gasification

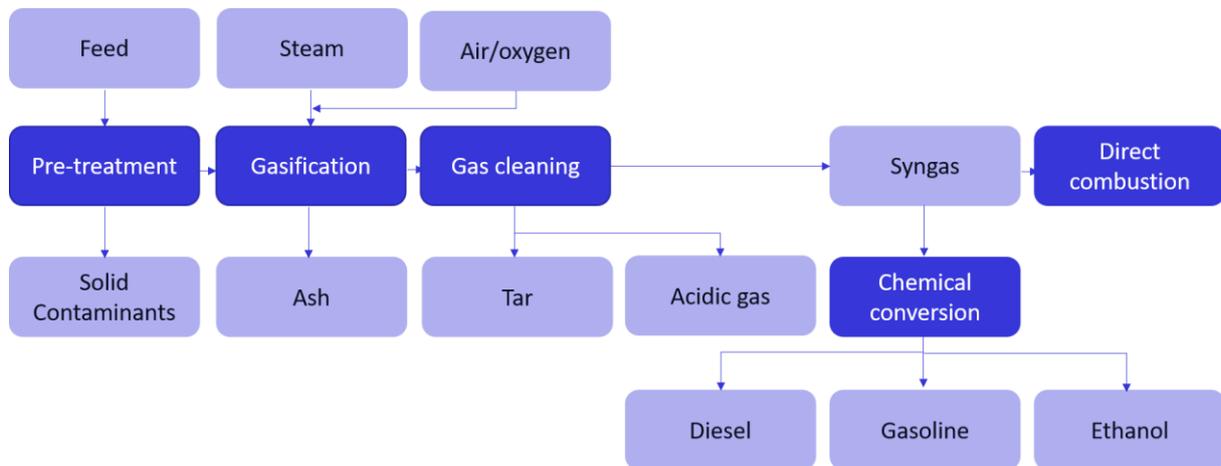
Gasification is a partial oxidation process whereby feedstock and an oxidising agent (air, oxygen, steam or a combination) are fed into a chamber operating at between 900 and 1,400 °C. This results in the total decomposition of the feedstock into a mixture of gases 'Syngas' including carbon monoxide, carbon dioxide, hydrogen, water and methane. The decomposition reaction also produces a carbon char, which is oxidised in-situ thereby providing the heat required to achieve the high operating temperature. Incomplete oxidation also leads to the formation of tars, which need to be removed from the syngas as they foul catalyst surfaces used for subsequent processing into oil products. The relative quantities of carbon monoxide, hydrogen and methane are determined by the composition of the feedstock and the operating temperature of the gasification reactor.

A typical gasification process consists of the following steps:

- Pre-treatment similar to that in the pyrolysis process.
- Gasification to convert the feed material into a crude syngas and separate the inert ash.
- Gas cleaning to remove entrained tar and other contaminants such hydrogen chloride.

This will produce a clean syngas that can either be combusted as-is or converted using a number of technologies into diesel, methanol-to-gasoline, or bioproduction of ethanol. An illustration of a typical gasification process is shown in Figure 2.

Figure 2 Process flow diagram for a typical gasification process



Gasification is less limited by heating rate than pyrolysis, as heat can be supplied by the oxygen, air and steam. Hydrogen deficiency is also not an issue and the presence of oxygen-containing compounds such as PET can be tolerated. However, the process does suffer from problems with inert material, which must be removed with the ash. Similarly, the presence of chlorine (PVC) and sulphur will produce undesirable gases such as hydrogen chloride and sulphur oxides, with the amount of gas cleaning required depending heavily on the levels on these contaminants.

### 2.3 Chemical depolymerisation

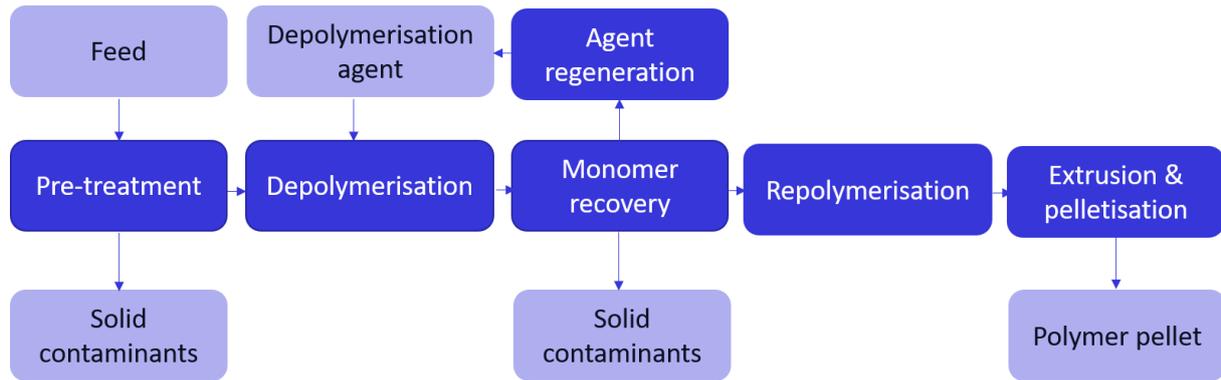
Chemical depolymerisation aims to reverse the polymerisation process to produce the monomers that can be isolated and repolymerised to produce more polymer. As an example, PET can be broken down to its monomers Purified Terephthalic Acid (PTA) and monoethylene glycol (MEG); these can reform better quality PET. Chemical depolymerisation technologies identified in this report all focus on PET.

A typical chemical depolymerisation process consists of the following steps:

- Pre-treatment to remove any contamination and organic material.
- Depolymerisation to break the polymer bonds and form monomers, typically using an agent (e.g. catalyst, reactant) to promote the reaction.
- Monomer recovery to separate the monomers from any unreacted and inert material. This is done using crystallisation.
- Repolymerisation to reform the polymer from the recovered monomers.
- Extrusion and pelletisation to create new polymer products.

An illustration of a typical depolymerisation process is shown in Figure 3.

**Figure 3** Process flow diagram for a typical depolymerisation process



For PET, the depolymerisation agent is either water or monoethylene glycol (MEG). If water is used, then the PET is broken down to monoethylene glycol (MEG) and Purified Terephthalic Acid (PTA). MEG and PTA are the precursor to the PET monomer and so can be combined to make Bis(2 Hydroxyethyl) terephthalate (BHET) which is the PET monomer. BHET can then be polymerised into PET.

If using MEG to break down the PET, this breaks it back down to the BHET directly, which can then be crystallised and the polymerised back into PET.

In theory, the depolymerisation process is more tolerant to contaminants than pyrolysis and gasification as the depolymerisation agent should selectively attack only the target polymer, leaving all other materials intact. However, it is possible that the depolymerisation agent may be inhibited by certain contamination or react with some unforeseen contaminant.

This method is less effective for polymers such as polypropylene and polyethylene as all bonds along the polymer backbone are chemically similar; in contrast, the carbon-oxygen bonds on the backbone of PET or PLA can be more easily targeted.

## 2.4 Dissolution

This process uses a solvent to selectively dissolve the target polymer. The polymer can then be separated from the undissolved solid materials, precipitated and extruded.

As the polymer bonds are not chemically broken during the dissolution process, repolymerisation is not required, as in chemical depolymerisation.

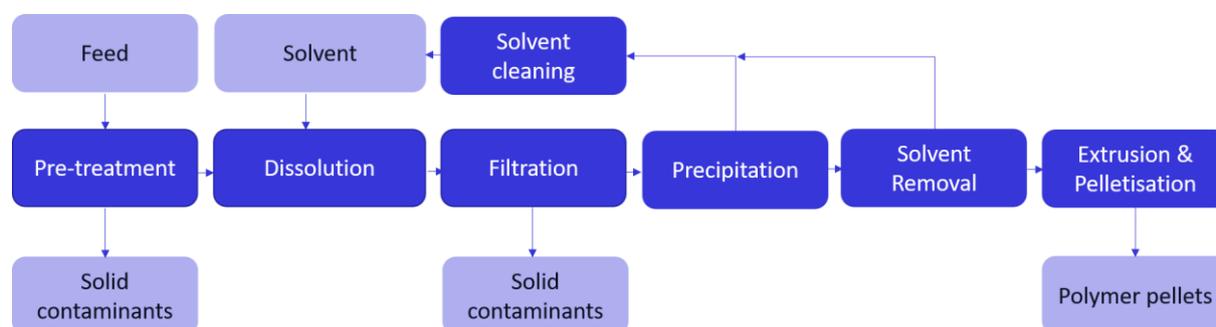
A typical dissolution process consists of the following steps:

- Pre-treatment.
- Dissolution to extract the target polymer into the solvent, often at elevated temperatures (100-200 °C).
- Filtration to separate undissolved solid materials.
- Precipitation to liberate the dissolved polymer from the solvent, typically carried out at temperatures lower than during dissolution.
- Solvent removal through e.g. drying or vacuum, to recover solvent from the precipitated polymer.

- Extrusion and pelletisation to create new polymer products.

An illustration of a typical dissolution process is shown in Figure 4.

**Figure 4** Process flow diagram for a typical dissolution process



As with chemical depolymerisation, the solvent and dissolution conditions can be specifically chosen to selectively target one type of polymer so the presence of contamination should in theory not be an issue; however, in the same way, certain contaminants may be problematic.

Key to solvent-based processes is the ability to recover and reuse the solvent; if a process cannot do this efficiently the cost of fresh solvent can determine the economic viability. This is particularly important for processes that use exotic and expensive solvents, such as ionic liquids. At the same time, it is essential to minimise the amount of solvent remaining in the polymer, so that this does not affect the product quality.

### 3.0 Environmental impact

Each of the four processes discussed in this report have environmental impacts that must be considered alongside the potential benefits that they bring. Chief of these is the energy required for each process; breaking the chemical bonds in pyrolysis and gasification processes is very energy intensive and requires high temperatures, even when aided by a catalyst. Many processes will use part of the produced oil or syngas to provide the required heat energy. To a lesser extent, chemical depolymerisation and dissolution are often carried out at elevated temperatures (>80 °C).

The processes also produce various wastes and by-products; almost every process, unless it stipulates strict standards on infeed quality will require pre-sorting before the plastic packaging can be fed into the main process. This will generate waste materials, some of which may have value (e.g. metals) but most of which will be uneconomical to recycle and will therefore likely be disposed of to landfill or energy from waste.

Similarly, during the main process, additional wastes will be generated – the ash from pyrolysis and the gasification processes may be hazardous due to the concentration of heavy metals within them, while the unreacted or undissolved solids from the depolymerisation and dissolution processes will also require disposal and similarly, may contain hazardous or toxic residues.

Pyrolysis and gasification processes can also produce toxic vapours such as hydrogen chloride; these can be treated before emission to the atmosphere but this requires further reactants (with the associated environmental impact of their manufacture), energy and the products from this treatment (e.g. salts from acid neutralisation) will require disposal.

Chemical depopulation and dissolution processes may use exotic reactants and solvents (such as ionic liquids), the production of which may have large environmental impact.

Whether or not the impact, across any or all Life Cycle Analysis (LCA) categories of non-mechanical recycling is in fact higher than producing virgin polymer from crude oil is unknown at this stage. It is a real possibility that from an LCA perspective, an approach of making packaging from virgin polymer and mechanically recycling waste polymers into both packaging and non-packaging applications has a lower impact than non-mechanical recycling.

LCA is limited as it often does not consider the impact plastics have when they enter the environment (e.g. through littering).

#### **4.0 Definition of recycling for non-mechanical processes**

An area that currently lacks clarity is whether non-mechanical technologies can be considered “recycling”. Axion has been in contact with the Environment Agency to discuss the matter of Packaging Recovery Notes (PRNs). To become accredited to issue PRNs, a recycler must do one of the following:

- Produce a material with the same properties and functions as the packaging waste material it processed; and that material must be used instead of a raw material from a natural source.
- or
- Demonstrate that its process results in a beneficial output that does not need further reprocessing, i.e. it must pass an end of waste test.

For solvent recycling and the depolymerisation then re-polymerisation of PET, it is highly likely these should be considered recycling, as a polymer is made from the input material, with high yields achieved.

For pyrolysis, classing these as recycling is more challenging, and further discussion would be needed in the industry. Since the process produces gas which is burnt to provide energy to the process, this fraction could not be considered recycling.

If the oil or gas output is then supplied to a refiner who produces a polymer from the material, then it is likely that this should be considered recycling, though the yield of the refining process must also be taken into account.

Finally, pyrolysis can also produce a wax (notably in the case of Recycling Technologies). This is not converted into a polymer product, however it can be used in the production of wax based products. This is an area for clarification.

Without producing new polymer, the outputs should be considered recovery, and there is effectively little benefit over incineration of the plastic.

## 5.0 Summary of technologies

Each technology is addressing a different issue to help improve recycling rates and qualities. Table 5 gives a summary of some of the key aspects of each technology category. Gasification has not been included as this is not being actively developed.

**Table 1** Summary of technologies

	<b>Pyrolysis</b>	<b>Chemical depolymerisation</b>	<b>Solvent dissolution</b>	<b>Gasification</b>
<b>Suitable feed</b>	Most suitable feed is PP and PE, with a focus on film waste due to the difficulties in mechanically recycling this material.	Developed for PET. Would be suitable for all PET, including coloured and trays.	Developed for PP and for multilayer films with PE.	Developed for PE and PP.
<b>Product</b>	Wax, oil and gas.	PET monomers.	Recovered PP or PE resin.	'SynGas', including carbon monoxide, carbon dioxide, hydrogen, water & methane
<b>Environmental concerns</b>	Some of the polymer is turned to gas which is often burnt to provide energy to the process. This is essentially incineration of the plastic, and so CO <sub>2</sub> is released.	Potentially a high energy demand.	Potentially a high energy demand and the use of solvents which can be damaging to the environment if not managed correctly.	Can be energy intensive to reach the desired temperatures. 'SynGas' is processed into fuels such as diesel, gasoline and ethanol, this is then combusted - essentially the incineration of plastics and the release of CO <sub>2</sub> .
<b>Recycling classification</b>	If used in a new product the wax could be considered recycling. The oil would have to be supplied to a refinery to be converted into a new polymer before being considered recycled, and the low yield must be taken into account. If burnt, the gas cannot be considered recycled.	Providing the monomers are used in the production of PET (no other alternative) then this should be considered recycling.	The recovered PP and PE can be considered recycled, although some materials (e.g. PET) in the laminates made be disposed of as waste.	Any burning of products cannot be classed as recycling.
<b>Cost</b>	Not well defined. If gas can be used to provide power, then cost should be relatively low.	Depending on the technology could be high. Some use ionic liquids which are costly.	Can be very high depending on the solvent and solvent loss. Solvent recovery is key.	Not well defined, though if the 'SynGas' product is used to power the reactor then costs can be kept down.

## 6.0 Integration into existing waste management

The different non-mechanical recycling technologies can be broadly split into solutions for polyolefins (HDPE, LDPE and PP) and PET. In order for these technologies to be useful and yield high quality output, sorting is still required and these non-mechanical recycling technologies are unlikely to be a “catch all” solution to all the “non-recyclable” packaging waste.

Solvent recycling and PET depolymerisation can achieve high yields (>90%) of recovered polymer, however the pyrolysis/gasification technologies will achieve a much lower conversion to polymer, in the region of 30 – 40%.

The future will therefore be a mixture of mechanical and non mechanical recycling technologies.

### 6.1 PET recycling

Arguably the most advanced non-mechanical recycling processes are focused on PET. The reason for this is twofold:

- 1: Mechanically recycling PET to maintain IV without discolouration and ensuring the material is food grade is very challenging – this is why many PET bottles are recycled into lower grade thermoforms or fibre.
- 2: The market for PET is predominantly in packaging, so it is vital to make a high quality, food grade recycle.

There is therefore a clear need to recycle PET thermoforms and coloured PET into a virgin quality, high IV, clear polymer that cannot be met by mechanical recycling.

The opportunity therefore lies in using non-mechanical recycling to recycle this less desirable PET fraction. The PackFlow 2025 report suggests that 61% of PET packaging placed on the market is bottles and 27% is PTTs. Without a solution for the PTTs, achieving 70% effective recycling is impossible.

### 6.2 Rigid polyolefin recycling

The mechanical recycling of rigid High Density Polyethylene (HDPE) bottles is very well developed in the UK, with two plants able to produce food grade rHDPE for supply into the dairy industry. Importantly, the Material Recovery Facilities (MRFs) have been set up in the UK to recover both natural and coloured HDPE. HDPE packaging can also be sorted and cleaned with relative ease as the packaging tends to be thick walled.

There is therefore little to no need to non-mechanically recycle rigid HDPE, as neither input quality nor output quality are of significant concern. Coloured HDPE is not used (typically) in food applications so food grade coloured rHDPE is not critical.

Polypropylene (PP) is highly recyclable, but the UK lacks much of the necessary infrastructure to separate it from kerbside collected material before exporting. As a result, much of the PP is baled with PET, PS and other PTTs as a “mixed plastic”. There

are facilities in the UK to recycle PP, but MRFs must be updated to ensure PP is recovered on its own.

The demand for black rPP is currently so high that attempting to produce food grade rPP is not economically viable. However, with a growing desire to incorporate recycled content into food packaging, the only way this will be practically possible is through non-mechanical recycling.

For PP, the three options are dissolution, pyrolysis and gasification. Of these, only dissolution will achieve high yields, and as it is relatively easy to recover a high purity rigid PP material flow, this is likely to be a better option than pyrolysis or gasification. The opportunity for polyolefin rigids is therefore in using dissolution to create a food grade rPP, however with the strong demand for non-food rPP there is less urgency than for PET.

### 6.3 Polyolefin film recycling

Post-consumer film waste is predominantly polyolefin based, with some PET and aluminium foil laminates. In the UK there is very limited collection of these materials.

The melt flow characteristics of PE cannot be modified, which means that film must be recycled back into film, or into composite items like decking. Film is a very demanding application, and the level of contamination and odour that remains when recycling LDPE films means it isn't always possible to recycle back into film. There is therefore no real market for small format PE films.

PP films in theory have a wider end market, as the melt flow of PP can be more easily modified, and thus supply it into less demanding injection moulding applications where the contamination is not an issue. However, the economics of doing so may be challenging and there is no stand alone post-consumer PP washing and extrusion plant in Europe.

There are therefore several options for polyolefin film:

- Separate >A4 size PE films for mechanical recycling.
- Combine the PE and PP small format films to recycle into injection moulded items as the PE on its own could not be mechanically recycled into injection moulded items.
- Recover the PP films and mechanically recycle these into injection moulded items, while sending the PE films to a pyrolysis or gasification process.
- Send all small format films to a gasification/pyrolysis process.

The downside of using the gasification or pyrolysis processes are the potential yields on new polymer is low. As a result, mechanical recycling should be considered first, with pyrolysis and gasification used for material that may otherwise have no market as a recyclate or would be uneconomical to recycle.

#### 6.4 Recycling of “non-recyclable” material

The quantity of “non-recyclable” packaging placed on the market is very low, with the main one being multilayer laminates, making up approximately 20% of flexible packaging.

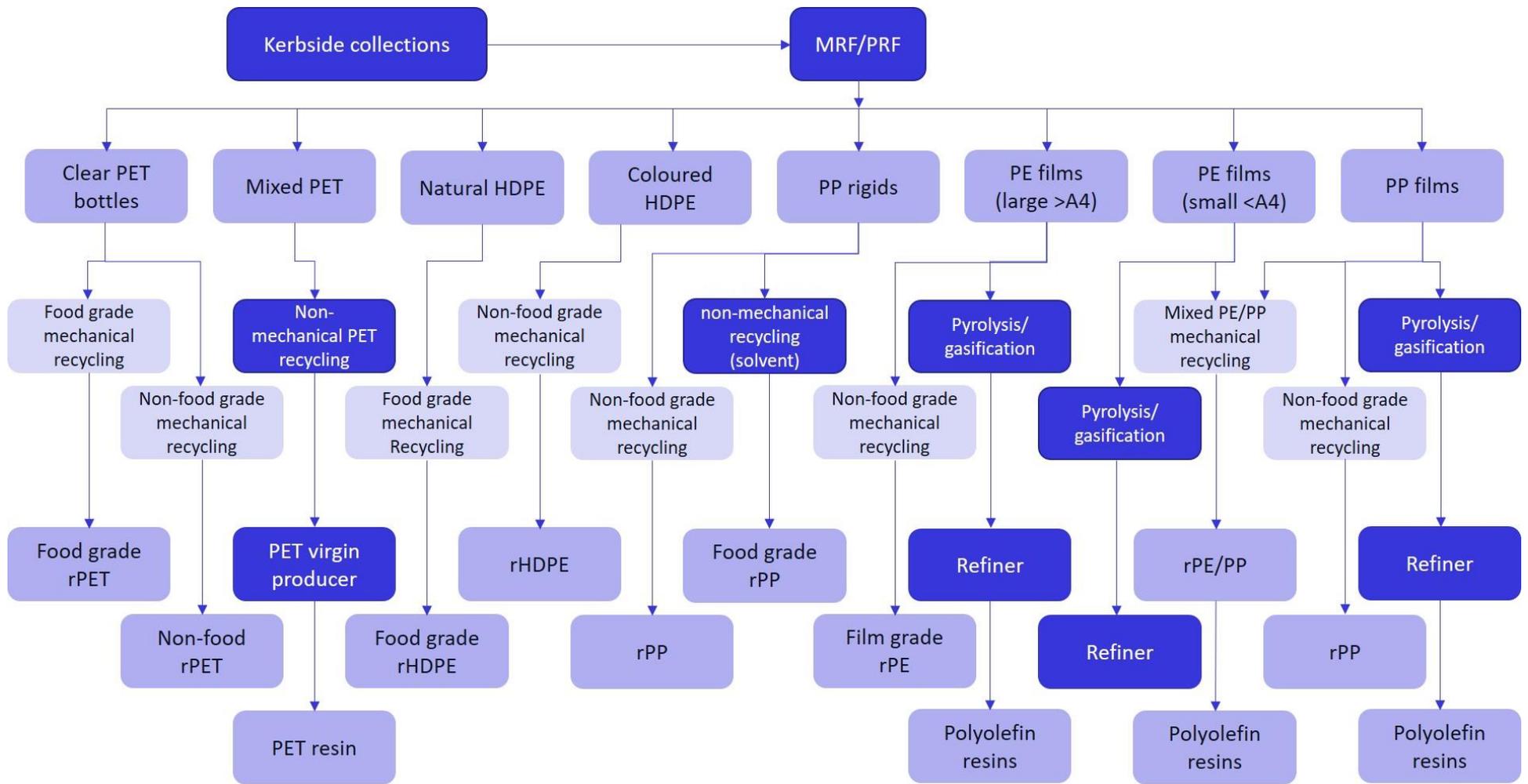
The multilayer laminates are often made with a combination of PET and PE or PP, and sometimes with aluminium. Pyrolysis is not suitable for PET, and so the option would be to use a dissolution process or delamination process.

The difficulty is creating a sufficiently concentrated “laminates” waste stream. It is not impossible, but focusing on these waste streams while so much progress is needed on other, more easily managed streams is unlikely to be viable in the UK. These technologies are more likely to be successful in developing countries where large quantities of multilayer sachets are used.

Non-mechanical recycling technologies must have a specific, high purity infeed to produce high purity output that can be made into new products. The focus should therefore be on high quality outputs, and how the non-mechanical technologies can achieve this where mechanical methods fail.

#### 6.5 Overview

Figure 6 shows how non-mechanical recycling could be used in the UK, with modifications to collection and sorting capabilities, to achieve higher rates of recycling. This diagram does not consider yields and by-products of the pyrolysis process and it must be noted potentially only a small proportion of plastic may be converted into a new polymer.



## 7.0 Key barriers

The challenge that all these technologies will face is sourcing a suitable feedstock at a suitable price/gate fee. In order for these technologies to be successful, there needs to be a real understanding of what material is available, and how much sorting and cleaning is required.

The non-mechanical recycling process will more likely replace the extrusion stage of a typical mechanical recycling process. This is to say the material will need sorting and some form of cleaning, be it dry cleaning or wet washing.

The other barrier is the lack of material that is collected at the kerbside in the UK. The UK must increase collection of pots, tubs ,trays and more importantly films in order to generate a feedstock.

An economic barrier will still persist, as mechanical recycling will likely always be cheaper. This could change with the need for recycled content in packaging. Non-mechanical recycling will be the only feasible way to achieve food grade PP and recycled content in primary film packaging. It will also likely be needed to recycle PET PTTs back into clear food packaging.

More clarity is needed to understand whether recycled polymer will have a higher price than virgin if the quality is equivalent, as this could create the economic driver non-mechanical recycling has previously been unable to achieve.

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