Disclaimers

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Introduction

Plastic is incredibly useful. To name a few reasons why: it's versatile, lightweight, waterproof and cheap. Each year, we produce an amount of plastic roughly equivalent to the mass of two-thirds of the world's population. Much of this quickly ends up as waste, with most not currently recycled and, unfortunately, ~3% entering the ocean. Following TV programmes such as the BBC's Blue Planet II, marine plastic has become one of the most high-profile environmental issues of our time. Recycling more plastic cannot solve this problem, but it can help.

In this report, we provide a brief introduction to the plastics recycling sector and estimate its potential for growth. Our focus is on feedstock recycling, a non-traditional method of recycling that works by converting standard plastics back into the oil from which they are derived. Our main findings are:

- The UK could *today* support ~90 small-scale feedstock recycling plants (processing ~8500 tonnes/year) simply by diverting plastic that is currently collected for recycling and then shipped abroad. This is one of the main ways the UK could help address the marine plastic problem.
- This figure goes up to 150 if we are more ambitious about the amount of plastic we collect; feedstock recycling can handle more types of plastic than traditional methods, including mixed plastic.
- Across the pond, the US could today support ~260 medium-scale feedstock recycling plants (25,000 tonnes/year), resulting in 38,500 jobs and $9.9 billion in US economic output.
- With a slight following wind, by 2030 50% of plastic worldwide could be reused or recycled, creating a profit-pool growth of as much as $60 billion for the petrochemicals and plastics sector.
- By 2050, nearly 60% of plastic demand could be covered by production based on previously used plastic. To cover this demand, feedstock recycling would need to expand at an impressive CAGR (Compound Annual Growth Rate) of 17%.

Note we use the terms 'plastic' and 'plastics' interchangeably in this report.

Background

What is a Plastic?

The term plastic comes from the Greek word 'plastikos' which means 'able to be shaped or moulded'. It is used to label a wide range of materials with this property, typically formed from organic polymers - carbon-containing molecules made up of chains of linked, repeating subunits known as monomers. Monomers are chiefly produced from petrochemicals; that is, from chemicals derived from oil and natural gas (~6% of crude oil is processed to produce plastic [1]). As an example, the most common plastic, polythene, is formed from chains of the monomer ethene, see **Figure 1a**, below.

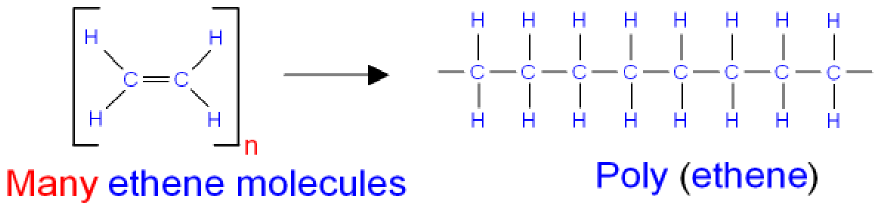


Figure 1a – Formation of the common plastic polythene from the monomer ethene.

Like polythene, all standard plastics contain hydrogen and carbon; their chemical make-up is similar to the hydrocarbons from which they are derived. Certain plastics also contain other elements such as oxygen and chlorine, which can complicate the recycling process. For example, single-use drinks bottles are generally made from polyethylene terephthalate (PET) which contains oxygen; polyvinyl chloride (PVC), used for plastic piping, contains chlorine. Plastics also contain additives – colourants, plasticisers, stabilisers, fillers and reinforcements. These affect the overall chemical composition, properties and ease of recycling of the plastic.

[1] https://ourworldindata.org/faq-on-plastics#how-much-oil-do-we-use-to-make-plastic

What are the Types of Plastic?

There are many types of plastic and a few different ways of categorising them.

For our purposes, one of the most useful distinctions is between thermoplastics and thermosets. The primary physical difference is that thermoplastics can be remelted back into a liquid, whereas thermosets cannot. This is due to cross-links between the polymer chains, see **Figure 1b**, below. In general, this means that thermosets cannot be recycled as plastics - though they can be ground up and reused this way - whereas thermoplastics can. Most plastics - about 92% [2] - are thermoplastics.

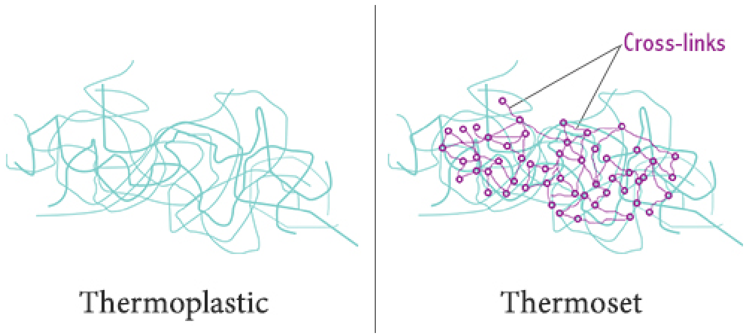


Figure 1b – Difference between thermoplastics and thermosets.

Another relevant way of classifying plastics is by their resin code, which identifies the type of polymer used in the plastic, see **Figure 1c**, over page. You will find these symbols on many plastic products. There is no hard and fast rule about the recyclability back into plastic of the different resin codes, but, in general, 1 and 2 are recyclable; 3 and 5 sometimes recyclable; 4, 6 and 7 usually not recyclable. As we will see later, these rules apply to traditional plastic recycling methods. Newer recycling methods *can* deal with some of these so-called unrecyclable plastics.

[2] https://plastics.americanchemistry.com/How-Plastics-Are-Made/

Symbol	Polymer	Common Uses	Properties	Recyclable?
1 PETE	Polyethylene terephthalate	Plastic bottles (water, soft drinks, cooking oil)	Clear, strong and lightweight	Yes; widely recycled
2 HDPE	High-density polyethylene	Milk containers, cleaning agents, shampoo bottles, bleach bottles	Stiff and hardwearing; hard to breakdown in sunlight	Yes; widely recycled
3 PVC	Polyvinyl chloride	Plastic piping, vinyl flooring, cabling insulation, roof sheeting	Can be rigid or soft via plasticizers; used in construction, healthcare, electronics	Often not recyclable due to chemical properties; check local recycling
4 LDPE	Low-density polyethylene	Plastic bags, food wrapping (e.g. bread, fruit, vegetables)	Lightweight, low-cost, versatile; fails under mechanical and thermal stress	No; failure under stress makes it hard to recycle
5 PP	Polypropylene	Bottle lids, food tubs, furniture, houseware, medical, rope, automobile parts	Tough and resistant; effective barrier against water and chemicals	Often not recyclable; available in some locations; check local recycling
6 PS	Polystyrene	Food takeway containers, plastic cutlery, egg tray	Lightweight; structurally weak; easily dispersed	No; rarely recycled but check local recycling
7 OTHER	Other plastics (e.g. acrylic, polycarbonate, polyactic fibres)	Water cooler bottles, baby cups, fiberglass	Diverse in nature with various properties	No; diversity of materials risks contamination of recycling

Figure 1c – Summary of plastic polymer groups. [3]

Why Recycle Plastic?

Environmental Perspective

From an environmental perspective, the arguments in favour of recycling plastic are reasonably clear cut.

If not recycled, and if disposal is not manged correctly, plastic has the potential to end up in the environment – on the land, in our waterways and oceans - ruining the beauty of nature, and potentially impacting habitats and wildlife. Once there, decomposition can take centuries [4]. The decomposition rates of common items in a marine environment are given in **Figure 2**, below. It is estimated that around 3% of global annual plastic waste enters the oceans [5] (~9 million tonnes, 2015). The marine plastic problem is discussed further in the box on the next page.

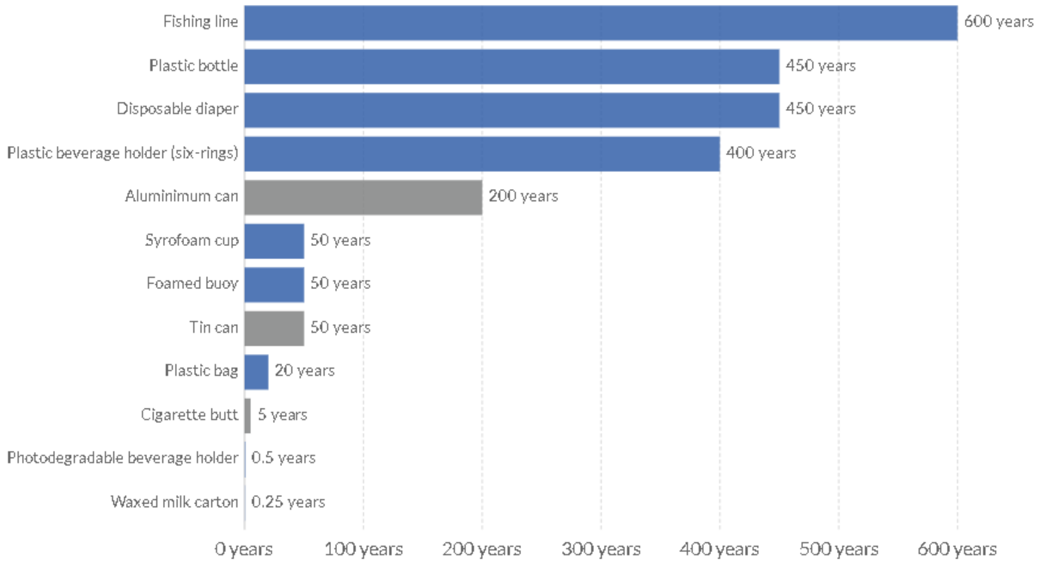


Figure 2 – Decomposition rates of marine debris items [4].

[3] https://ourworldindata.org/faq-on-plastics#are-all-types-of-plastic-equally-easy-to-recycle

[4] https://ourworldindata.org/faq-on-plastics#how-long-does-it-take-plastics-to-break-down

[5] https://ourworldindata.org/plastic-pollution#empirical-view

The Marine Plastic Problem **(~3% of plastic waste enters oceans)**

Where does marine plastic come from? [6]

Roughly 70-80% from land-based sources. 20-30% from marine sources such as fishing fleets (nets, lines, ropes, etc).

Of greatest importance is the quantity of mismanaged waste generated by coastal populations. This is most likely to end up in the ocean. Mismanaged waste is the sum of inadequately managed waste - that which is not formally managed, such as disposal in dumps or open, uncontrolled landfills - and littered waste. Most mismanaged waste originates in lower income regions of the world, with the East Asia and Pacific region the worst offender (60% of total mismanaged waste).

What effects does marine plastic have on wildlife? [7]

We are still learning. There are three pathways by which plastic can affect wildlife: entanglement, ingestion and interactions (e.g. collision, obstruction, abrasion). Entanglement has been reported for 344 species to date. Ingestion has been reported for 233 species. Ingestion can have multiple health impacts including reduced stomach capacity (so the organism does not eat enough), obstructed or perforated gut, ulcerative lesions or gastric rupture. This can ultimately lead to death. Negative biochemical responses have also been observed in the lab. The effects of microplastics – plastic with particle sizes <5 mm – are not completely clear, though may impact some organisms.

Will increasing the plastic recycling rate solve this problem?

Given the causes mentioned above, no, not on its own, but it should help. For example, with an established plastic recycling industry in higher-income countries, less plastic will be exported to lower-income countries for 'processing', where the likelihood of the plastic entering the ocean is far greater.

Recycling versus Landfill and Incineration

If not recycled, and if disposal is managed correctly, plastic will ultimately end up in landfill or being incinerated.

In landfill, plastic just lies there, taking up space, its financial and high energy value lost to society. Buried plastic can take even longer to break down than suggested by **Figure 2,** on the previous page.

Incinerating plastic releases CO_2 into the atmosphere, one of the main drivers of climate change. If the plastic is simply incinerated, rather than being processed in an Energy from Waste facility - which recovers some of the energy content of the plastic - this is clearly bad for the environment. However, if Energy from Waste is used, whether this is a net positive to the environment depends on the efficiency of the incineration process and the mix of energy sources it is replacing. [8]

Incinerating plastic also has the potential to release toxic gases into the environment, such as dioxins. This is only likely to be an issue in lower income countries where environmental regulation is less strict.

Recycling plastic is seen to be environmentally beneficial as it theoretically displaces the need for primary plastics production. One-for-one displacement saves energy and CO_2 by avoiding the processes of oil refining and polymerisation of monomers (assuming a traditional recycling method). These are estimated to account for over 95% of the total energy consumed in plastics production [9]. It also avoids the depletion of fossil fuels, which are a limited resource, and the harm to the environment caused by the extraction of those fossil fuels.

In summary, from an environmental point of view, recycling is almost always the best option. This is backed by a 2016 meta-study which showed that, in most studies analysed, recycling plastic has both the lowest global warming potential and total energy use versus landfill and incineration alternatives [10].

[6] https://ourworldindata.org/plastic-pollution#share-of-global-total-mismanaged-plastic-waste-by-country and https://ourworldindata.org/plastic-pollution#ocean-plastic-sources-land-vs-marine
[7] https://ourworldindata.org/plastic-pollution#impacts-on-wildlife

[8] https://pubs.rsc.org/en/content/articlelanding/2009/ee/b908135f#!divAbstract

[9] http://www.wrap.org.uk/sites/files/wrap/Plastics_Market_Situation_Report.pdf
[10] https://aip.scitation.org/doi/pdf/10.1063/1.4965581

Economics Perspective

The fundamental economics argument in favour of recycling overlaps with the above environmental arguments. Creating the virgin polymers used to make new plastics is a hugely expensive process in terms of capital investment, commodity and energy use and carbon footprint (which may have its own cost). Recycling plastic has the potential to reduce these costs significantly by bypassing some of the steps involved, see **Figure 3**, below. We explain the recycling types shown in **Figure 3** in the later section 'Plastic Recycling Types'.

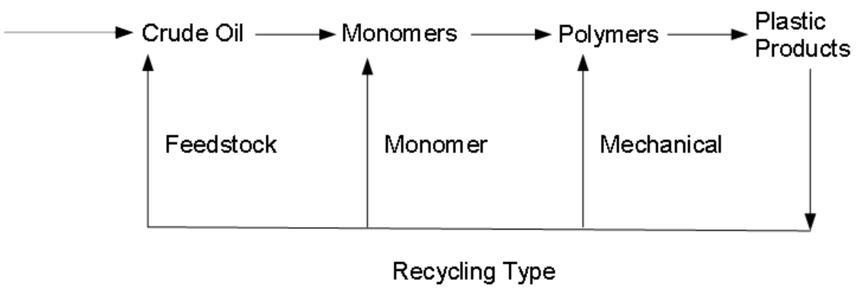


Figure 3 - Simplified diagram of the plastics production process and associated types of recycling.

In contrast to virtually all other mainstream materials, plastic has an undeveloped recycling market. For example, in the UK we recover 71.3% of metal, 79% of paper and cardboard, 68% of glass and just 46% of plastic packaging (2017) [11]. The reasons for this include:

- The beneficial attributes of plastic – cheap and light – make transport expensive, impairing the economics.
- As we have seen, there are many types of plastic. Traditional plastic recycling – shown as 'Mechanical' in **Figure 3** – requires that plastics are sorted by type prior to recycling. This is technically challenging and costly.
- Traditional recycling *can* only recycle certain types of plastic and, for technical and economic reasons, *does* currently recycle only a subset of those.
- Traditional recycling tends to lower the quality of the plastic, meaning the recycled plastic is less useful and valuable. This also limits the number of times you can recycle before disposal becomes necessary.
- With high costs, traditional recycling is vulnerable to movements in the oil price, this being the main determinant of the virgin plastic price against which recycled plastic must compete.

As we will cover in later sections, non-traditional recycling methods – shown as 'Feedstock' and 'Monomer' in **Figure 3** - can potentially overcome some of these limitations, paving the way for considerable growth in the sector. This growth will be aided by:

- Governments attempting to increase domestic recycling rates and the use of recycled plastic, both in response to the marine plastic problem, and as part of a wider shift to sustainability and circularity.
- For the same reasons, the entire 'plastics value chain' – from oil companies, through petrochemicals, plastics and consumer goods companies – being pushed by both governmental and consumer pressure into producing and using more recycled plastic.
- Waste management organisations responding to this demand for recycled plastic, as well as looking for an alternative to domestic disposal by landfill or incineration, or shipping plastic abroad for recycling, all of which have financial and environmental costs.

[11] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/784263/UK_Statistics_on_Waste_statistical_notice_March_2019_rev_FINAL.pdf

Alternative: Use Less Plastic

Given the coverage in the media, you might be forgiven for thinking that plastic is 'evil' and that, therefore, we should simply stop using it. The problem is that – putting aside the marine plastic problem – plastics are often both greener and more economic than alternatives (and there may be no clear alternative). When compared to alternatives in typical applications they can: reduce energy costs by up to 40%, waste by 75 - 80%, emissions by 70% and reduce water pollution by up to 90% [12]. So, while the elimination of some single-use plastic is inevitable, there is unlikely to be a mass migration away from plastic.

Alternative: Use Bio-based or Biodegradable Plastic

Biodegradable/degradable plastic breaks down at a faster rate than conventional plastic. This type of plastic may not be able to be recycled as it can render the recycled polymer untrustworthy for long-term use. In addition, the UN concluded that: "the adoption of plastic products labelled as 'biodegradable' will not bring about a significant decrease either in the quantity of plastic entering the ocean or the risk of physical and chemical impacts on the marine environment, on the balance of current scientific evidence." [13]

Bio-based plastic is based on hydrocarbons derived from renewable resources such as wood, vegetable oils, sugar and starch, rather than fossil fuels. These resources have to be grown – so there are land use concerns – and not all bio-based polymers are fully compatible with their standard equivalents in the recycling process (such as polylactic acid which is often made from corn starch). Further, being bio-based does not imply that a plastic is biodegradable.

Both incompatible bio-based and biodegradable plastics need to be separated from standard recyclable plastics during the waste management process. This can be difficult and expensive, particularly so given their low concentrations; these plastics currently make up only a few percent of all plastics.

[12] https://www.bpf.co.uk/plastipedia/polymers/polymer-bio-based-degradables.aspx
[13] https://europa.eu/capacity4dev/unep/document/biodegradable-plastics-and-marine-litter-misconceptions-concerns-and-impacts-marine-environ

Plastics Production and Waste

Production of plastic has grown consistently over the last seventy years and it shows no sign of slowing down, see **Figure 4**, below.

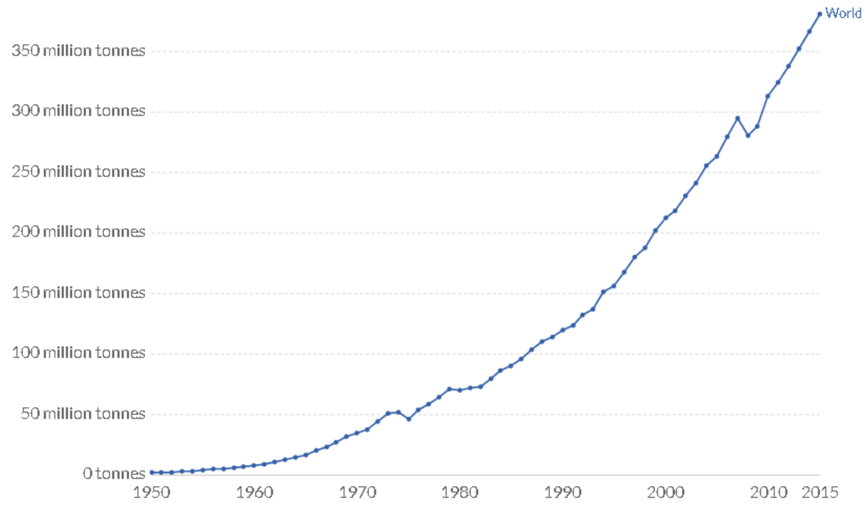


Figure 4 – Global plastics production [14].

In 1950, the world produced only 2 million tonnes of plastic a year. In 2015, production was 381 million tonnes; around three-quarters ended up as waste [14]. Due to its short 'in-use' lifetime – typically around 6 months or less – packaging is the dominant generator of plastic waste by sector, responsible for almost half of the global total, see **Figure 5**, on the next page. **Figure 6**, also on the next page, shows that some of the most commonly used polymers are currently not recycled, or less commonly recycled.

[14] http://advances.sciencemag.org/content/3/7/e1700782.full

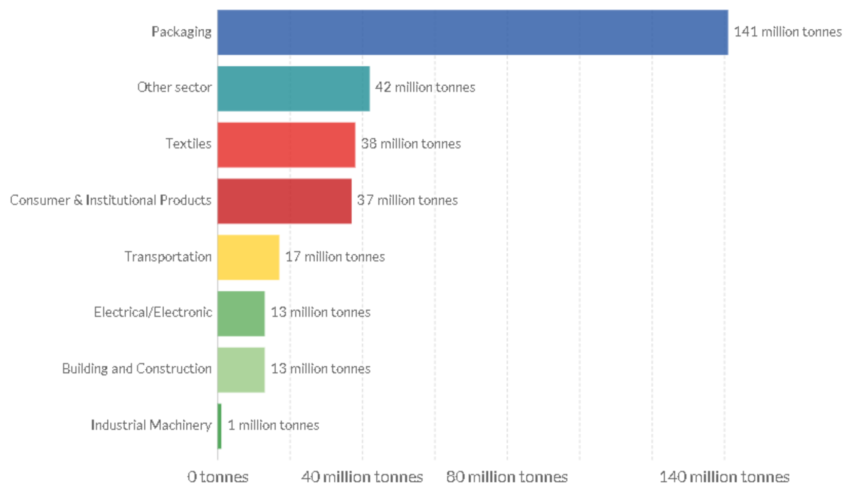


Figure 5 – Plastic waste generation by industrial sector, 2015 [14].

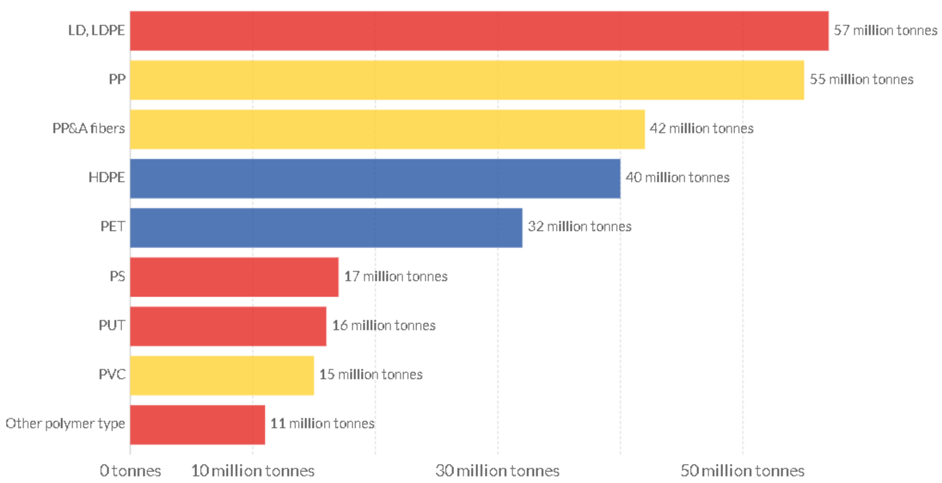


Figure 6 –Plastic waste generation by polymer, 2015 [14]. Blue indicates commonly recycled, yellow – less commonly, red – usually not recycled. Polymer types are as follows: LDPE (Low-density polyethylene); HDPE (High-density polyethylene); PP (Polypropylene); PS (Polystyrene); PVC (Polyvinyl chloride); PET (Polyethylene terephthalate); PUT (Polyurethanes); and PP&A fibres (Polyphthalamide fibres).

Global Fate of Plastic

Figure 7, below, shows the fate of plastic globally in 2016. Only ~12% of plastic was recycled, with 25% incinerated, 40% ending up in landfill and 19% being disposed of in an unmanaged fashion (with a higher probability of ending up in the ocean) [15]. Clearly, there is considerable room to improve this picture.

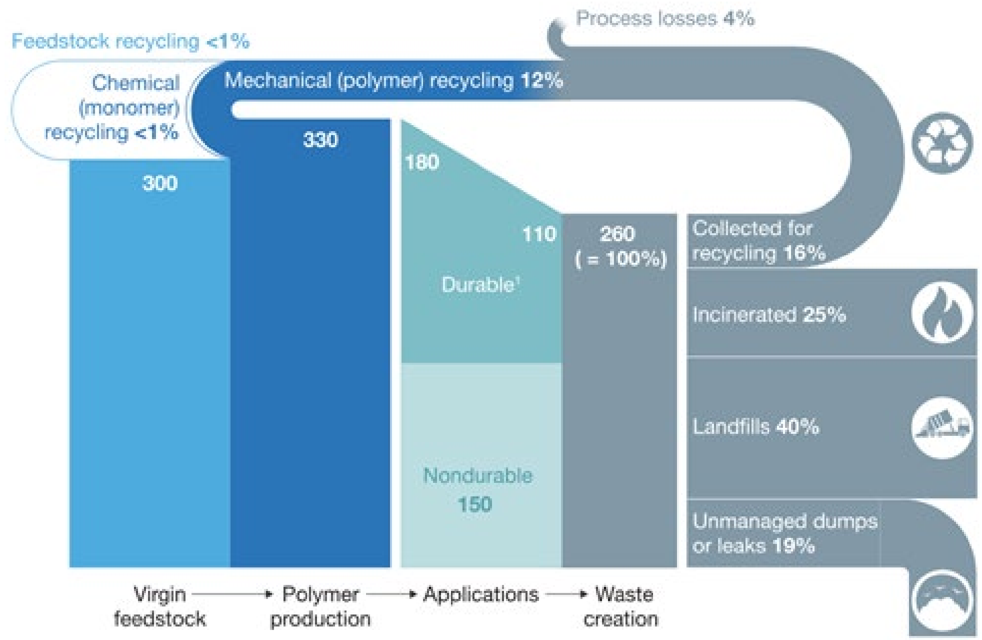


Figure 7 – Global plastic flows, millions of metric tons per annum, 2016. [15]

[15] https://www.mckinsey.com/industries/chemicals/our-insights/no-time-to-waste-what-plastics-recycling-could-offer

UK Fate of Plastic

Figure 8, below, shows the approximate fate of plastic in the UK, 2016. Only ~27% of plastic was recycled - domestically or exported for recycling - with ~40% incinerated and ~23% ending up in landfill [16].

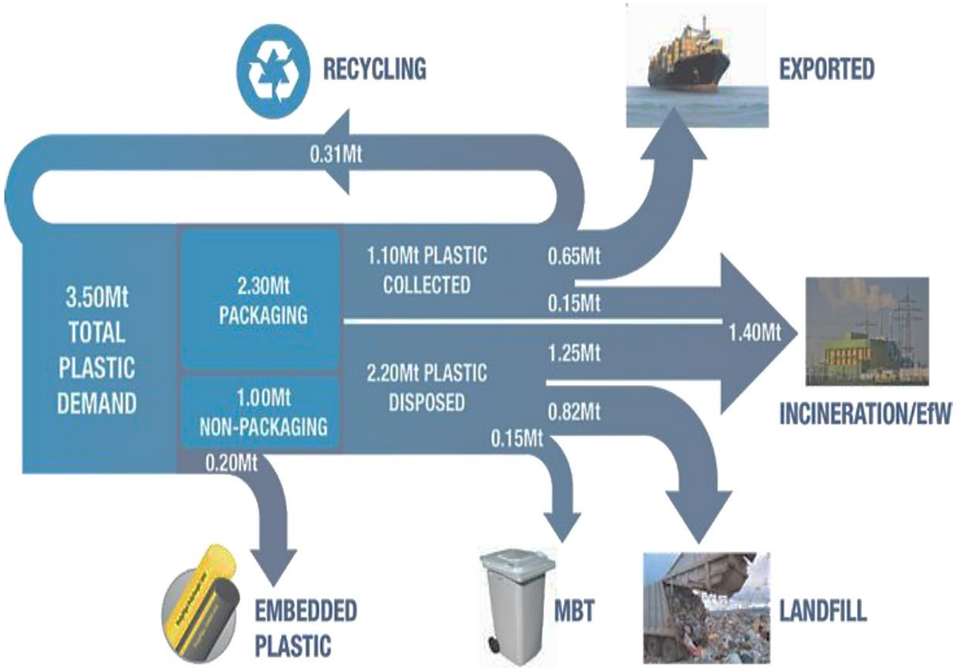


Figure 8 – UK plastic waste flows, millions of metric tonnes per annum, 2016 [16]. MBT - Mechanical Biological Treatment. EfW – Energy from Waste.

Note that, of the plastic collected in 2016, ~59% was exported to other countries, a large fraction to China. However, in early 2018, China effectively banned all plastic waste imports. This ban led to a major bottleneck in the British market and exposed years of underinvestment in domestic recycling facilities. With China off-limits for plastic waste exporters, neighbouring markets such as Malaysia, Thailand and Vietnam have found themselves overrun with UK waste. There is little oversight of what happens to this waste, and in such countries, there is a higher chance of plastic ending up in rivers and oceans, rather than being recycled. British waste has recently been found dumped at illegal sites in Malaysia [17].

This new export regime will not last long. Thailand has announced a plan to ban plastic waste imports by 2021 [18], while Malaysia, Vietnam and others are also considering actions. As we explain next, the UK government acknowledges that the export system is flawed and is looking to reform it. With both sides unhappy, export volumes are likely to fall, providing a considerable opportunity for domestic recycling to scale-up.

UK Waste Policy

Much of UK waste policy stems from the EU (e.g. Waste Framework Directive, Circular Economy Package, Plastics Strategy and proposed Directive). After Brexit, the UK is expected to retain or strengthen the ambitions of this EU policy, including target recycling rates for household waste, packaging and plastic packaging, all of which strengthen over time.

The UK has made progress towards existing targets using a combination of policies such as the landfill tax, a 5p plastic bag charge, and various producer responsibility schemes, including one for packaging. In the packaging producer responsibility scheme, producers of packaging are obligated to meet a share of the government's annual recycling targets. Producers purchase packaging waste recovery notes (PRNs) from accredited reprocessors (or packaging waste export

[16] Created by Recycling Technologies Ltd. Original sources quoted as Plastics Spatial Flow 2016, Valpak & WRAP | Plastics – the facts 2014/2015, PlasticsEurope.
[17] https://unearthed.greenpeace.org/2018/10/21/uk-household-plastics-found-in-illegal-dumps-in-malaysia/
[18] https://www.businessgreen.com/bg/news-analysis/3064938/a-load-of-rubbish-uk-plastics-recycling-industry-under-fire

recovery notes, PERNs, from accredited exporters), as evidence that they have met their obligations. See **Figure 9**, below.

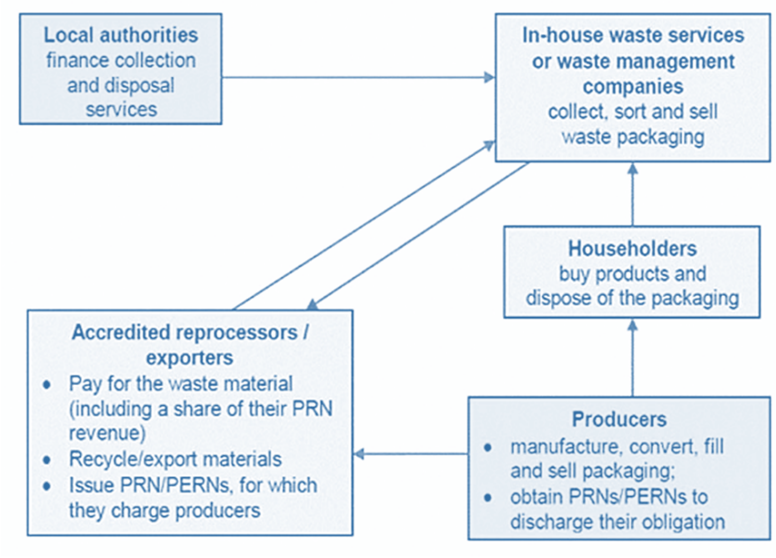


Figure 9 – UK packaging producer responsibility scheme.

This scheme is a market-based subsidy for the recycling sector, though it is not perhaps all it is cracked up to be. As well as oversight and related environmental concerns, covered earlier, the export part of the packaging producer responsibility scheme is suspected of "widespread abuse and fraud", with exporters allegedly faking waste shipments for extra cash and dodging rules designed to ensure quality recyclate [19]. There is also no evidence that the scheme has encouraged companies to minimise the use of packaging or make it easier to recycle, as was its original intention [20].

[19] https://www.theguardian.com/environment/2018/oct/18/uk-recycling-industry-under-investigation-for-and-corruption

[20] https://www.nao.org.uk/report/the-packaging-recycling-obligations/

Waste Strategy

The government recently released its Waste Strategy for England [21], which outlines longer-term strategic ambitions and near-term actions. Unsurprisingly, measures to deal with plastic waste are a major constituent. As part of these, reform of the packaging producer responsibility scheme is listed as an ”immediate priority”, targeted to be operational by 2023. This reform aims to ensure that export of packaging waste is done in an “environmentally responsible way and that there is a level playing field between accredited domestic reprocessors and exporters”. It also aims to ensure or incentivise (abridged):

- A reduction in the use of unnecessary and difficult to recycle packaging.
- An increase in the production of recyclable packaging and packaging being recycled back into the same or similar products.
- Adoption of mandatory labelling on packaging and improved communication, making it easier for consumers to know what packaging they can recycle. This will be funded by producers.
- Collection of a nationally agreed set of packaging materials for recycling, adoption of minimum standards and delivery of a good quality recyclate.
- Producers fund the full costs of the management of the packaging at the end of its life (including collection and recycling); they currently pay less than a tenth of this.

Also outlined in the Waste Strategy is the introduction of a new tax on plastic packaging, scheduled for April 2022. This tax will apply to all packaging containing less than 30% recycled plastic, its aim being to “encourage manufacturers to produce more sustainable packaging and in turn create greater demand for recycled material”.

Overall, this strategy, together with overlapping initiatives from industry, such as the UK Plastics Pact – see the box below - should provide a supportive environment for the plastics recycling sector.

[21] https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england

The UK Plastics Pact

The UK Plastics Pact is a collaborative initiative to create a circular system that keeps plastic in the economy and out of the natural environment. Led by the charity WRAP and set up in partnership with the Ellen MacArthur Foundation, its members cover the entire plastics value chain. Its ambitious targets to 2025 for plastic packaging are:

- 100% to be reusable, recyclable or compostable.
- 70% to be effectively recycled.
- 30% average recycled content across all plastic packaging.
- Action taken to eliminate problematic or unnecessary single-use plastic packaging items.

A roadmap to achieving these targets has been published [22].

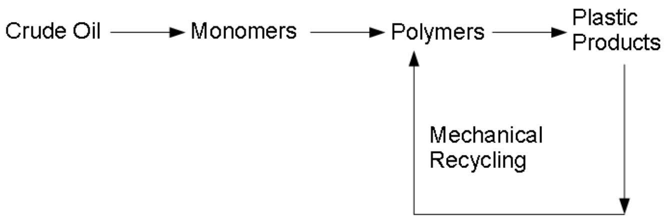
[22] http://www.wrap.org.uk/content/the-uk-plastics-pact-roadmap-2025

Plastic Recycling Methods

There are two main types of plastic recycling - mechanical and chemical.

Plastic has traditionally been recycled using mechanical methods, though investment interest is increasingly focussed on chemical methods, given their potential to expand the sector. The fundamental difference is that mechanical recycling leaves polymer chains intact (more or less), whereas chemical recycling breaks polymer chains into shorter molecules. Mechanical recycling therefore is only used to create new plastic products, often of a lower quality. Chemical recycling is a more complicated process, but it can be used to produce equivalent quality plastics and/or a range of other oil-based products. In theory, there is no limit to the number of times you can chemically recycle a plastic; you head back to a chemically-perfect plastic each time.

Mechanical Recycling



The process of mechanical recycling takes thermoplastic as it input and physically processes it back into pellets (or similar) from which new plastic products can be made. The main steps - which typically start out in the public sector and end up in the private sector - are:

- Collection of recyclable waste. Often, plastic is mixed in with other recyclable materials such as paper and glass.
- Separation of plastics from other recyclables at a Material Recovery Facility (MRF).
- Separation of plastics by polymer and colour. This may take place at a specialist Plastics Recovery Facility (PRF).
- Cleaning and resizing of the separated plastic.
- Melting and then commonly extruding the melted plastic into pellets.
- Manufacturing new products using these pellets.

Separation by polymer is necessary because when mixed plastics are melted together, they tend to phase-separate like oil and water and set in layers. The boundaries between these layers cause structural weakness in the resulting material, limiting its usefulness. Separation by colour is desirable to produce a consistent looking recycled plastic, though separation is currently limited by the sorting technology – it does not easily recognise black plastic.

Separation by polymer is complicated by products being a mix of polymers or mix of plastic and other materials. Plastic film is particularly problematic, both in separating it from other '2D' materials like paper, and by polymer. A further complicating issue is the existence of multi-layer films, consisting of several different polymers and sometimes non-plastic as well. Where film recovery is undertaken it is usually with the object of cleaning up other streams for recycling. The strategies used for these clean-up operations can result in low-quality plastic film streams not suitable for mechanical recycling.

To summarise, perfect separation into plastic/non-plastic and further by polymer and colour is not possible. These issues, combined with others, such as the thermal degradation of polymers that occurs during the recycling process, mean that mechanically recycled plastic is often of lower quality and value than the original plastic; this is termed "downcycling". In practice, this means that most mechanically recycled plastic is recycled only once or twice before being disposed of in landfill or by incineration [23].

[23] https://ourworldindata.org/faq-on-plastics#how-many-times-can-plastic-be-recycled

Mechanical recycling can be a challenging business. On the input side, the quality, consistency and availability of recyclate coming through from collection and sorting - which there is little control over - can greatly impact the feedstock cost. On the output side, companies are dependent on spot markets for selling their product, which can result in sharp fluctuations in revenue, while also being easily substituted for virgin material. Prices for recycled polymers and plastic products tend to follow those for their virgin equivalents, which, given that they are derived from oil, are in turn broadly correlated with changes in the oil price (and for PET, type 1 plastic, also cotton prices).

Despite these issues, mechanical recycling is already established as a sizeable business in many of the world's developed economies. Contrary to commonly held assumptions that waste management is simply a cost burden, mechanical recycling is already profitable, albeit often in selective applications or markets. As we noted earlier, not all polymers *can* be mechanically recycled and only PET and HDPE *are* widely recycled.

UK Recycling Capacity

The vast majority of UK's current recycling capacity is based on mechanical recycling. **Figure 10**, below, shows the UK's total recycling capacity, 2016.

Households, Businesses → MRF → PRF → Reprocessing

	Plastic Capacity (tonnes/year)
Material Recovery Facilities (MRF)	1,200,000
Plastic Recovery Facilities (PRF)	522,000
Reprocessing	600,000

Figure 10 – UK's sorting and reprocessing capacity (2016) [9].

As **Figure 8**, 3 pages back, showed, packaging accounts for ~60% of all plastic arisings in the UK. Publicly available figures show there are 58 companies currently accredited to reprocess plastic packaging in the UK, a mix of the large waste management companies (e.g. Biffa, Veolia, Viridor) and others. In addition, 84 are accredited to export plastic packaging. [24]

Figure 11, below, shows how well the UK is doing recycling the main categories of packaging in 2018. Clearly, there is considerable room for improvement, both with plastic bottles - happily recyclable using mechanical recycling - and more so with pots, tubs and trays and film, perhaps more suited to chemical recycling, described next.

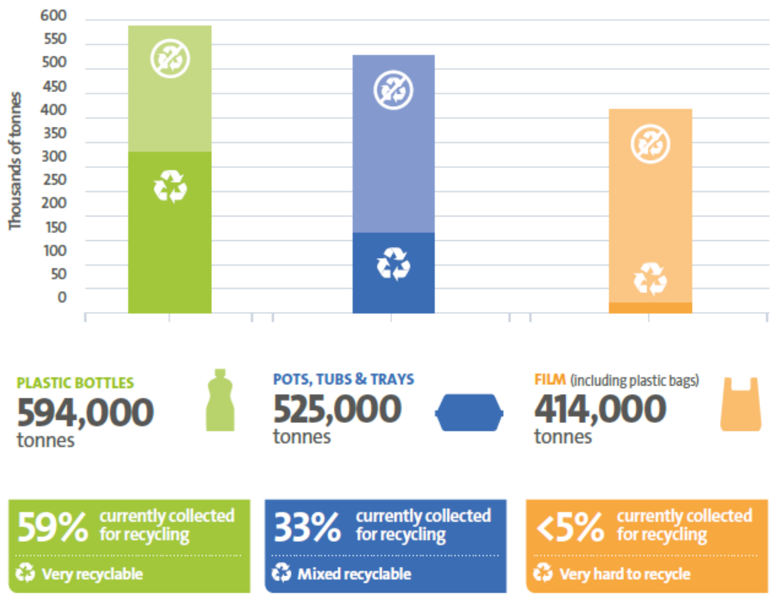


Figure 11 – UK recycling tonnages (2018) [25].

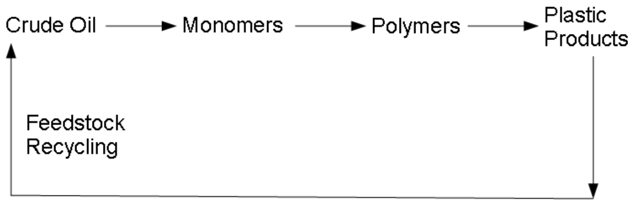
[24] https://npwd.environment-agency.gov.uk/

[25] https://www.veolia.co.uk/sites/g/files/dvc1681/files/document/2018/09/Veolia%20UK%20_%20Plan%20for%20plastics%20report.pdf

Chemical Recycling

As noted above, mechanical recycling has its limitations. There are several complementary chemical recycling methods commercially operational or emerging onto the market. There are two main types: monomer and feedstock recycling, the latter of which is more broadly applicable. In all cases, the chemistry of the plastic is being altered, hence the term 'chemical recycling'.

Feedstock Recycling



Although there is some overlap with mechanical recycling – the two can process some of the same types of plastic – feedstock recycling is promoted as a way of dealing with plastic that you cannot or do not mechanically recycle, with mixed plastic being the most significant example. Feedstock recycling *can* deal with mixed plastic. An ideal use, therefore, is for a small-scale feedstock recycling facility to be co-located at a Plastics Recovery Facility (PRF), where plastic is sorted for recycling. See **Figure 12**, right, for an example of this setup. All local plastic is brought to this facility, where plastic suitable for mechanical processing is first separated out. The remaining mixed Residual Plastic Waste (RPW) provides suitable input for feedstock recycling. This combined setup maximises recovery of plastic and avoids unnecessary transportation costs.

Feedstock recycling works by breaking plastic down into a synthetic oil. This oil is a mixture of short chain hydrocarbons, similar to the mixtures of hydrocarbons found in crude oil. After processing, fractions of this synthetic oil may be used as feedstock in the production of new plastics – hence the name 'feedstock recycling' - or to create a range of other oil-based products. This process skips out less of the plastics production chain than mechanical (or monomer recycling, described later), but the more mainstream and diversified nature of the offtake markets mean feedstock recycling is potentially more resilient to changes in market conditions, though many of the challenges are similar, with a more direct dependence on the oil price. We cover the economics of feedstock recycling in more detail later.

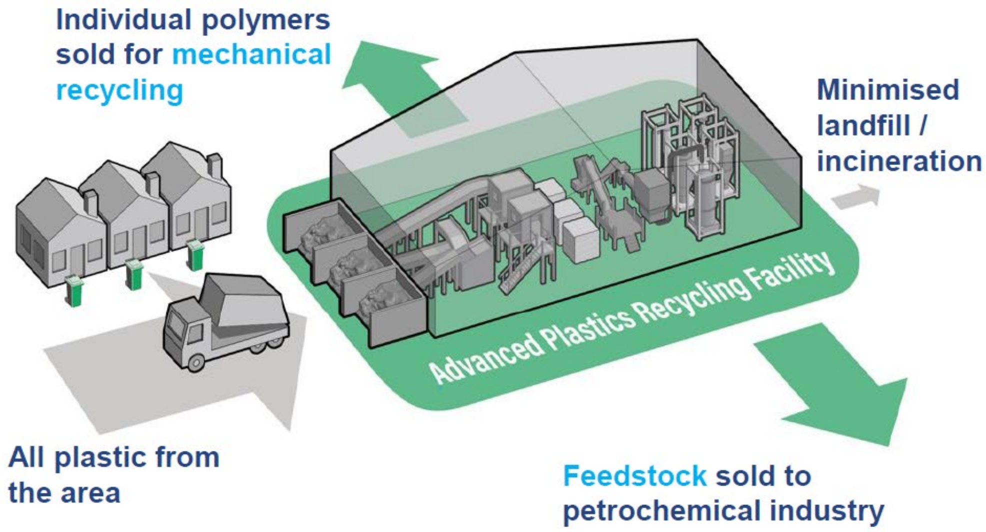


Figure 12 – Design for a plastics recycling facility that caters for both mechanical and feedstock recycling. Source: Recycling Technologies Ltd.

Feedstock Recycling: Pyrolysis

Pyrolysis is the most common form of feedstock recycling; the term 'thermal depolymerisation' is broader in meaning but also used. Most companies recycling mixed plastics - commonly types 2,4,5 and 6 - use some form of pyrolysis, even if this may not be immediately obvious from marketing materials.

Pyrolysis works by heating plastics to moderate temperatures (~400–600°C) in the absence of oxygen. After collection and separation of feedstock from non-plastics, as per mechanical recycling, the main steps are:

- Pre-treatment – to process the feedstock so that it can be fed into the pyrolysis unit (sorting, cleaning, sizing, drying). May be performed off-site.
    - To ensure the quality of the oil output, the feedstock needs consistently low levels of certain contaminants, such as those that contain oxygen (PET, type 1 plastic, cellulose (from paper labels) and other biomass).
    - To reduce the production of corrosive acids, the amount of PVC (polyvinyl chloride, type 3 plastic) in the feedstock is also limited.
- Pyrolysis – heating the feedstock, to convert it from solid to vapour and gas.
- Condensation – to recover the vapours from the pyrolysis unit as an unrefined oil product.
- Acid removal – chiefly to remove hydrogen chloride produced by conversion of PVC.
- Purification – to convert the unrefined oil into a material ready for sale. May be performed off-site.

Pyrolysis converts plastic into the desired synthetic oil, as well as gas and solid char by-products, the relative proportions of which depend upon the method of pyrolysis and the operating conditions of the pyrolysis reactor. To maximize oil production, 'fast pyrolysis' is used. Typical yields are shown in **Figure 13**, below.

Output	Gross conversion	Net conversion
Char	2 to 13% wt	2 to 13% wt
Liquid	77 to 90% wt	67 to 80% wt
Gas	8 to 10% wt	0% wt

Figure 13 – Typical outputs from a pyrolysis process [26]. % Wt = percentage by weight. Net figures include self-consumption.

The unrefined synthetic oil may be:

- Used in part (up to ~10%) to provide energy to the process.
- Sold unrefined as a heating fuel, or
- Sold for refining in a conventional oil refinery, or
- Refined onsite, to produce a range of higher-value oil products for sale.

The refining process is likely to lead to a further yield loss (beyond **Figure 13**), estimated at ~10%, as well as incurring costs.

The gas, a mixture of carbon monoxide, hydrogen and methane, known as syngas, is often used, like part of the oil, to heat the feedstock to the required operating temperature. Any excess can be sold. The solid char, a mixture of carbon and materials not decomposed during pyrolysis, is usually inert and suitable for disposal in landfill, or may be used as a fuel, or have some other use.

Figure 14, below, shows a generic pyrolysis process.

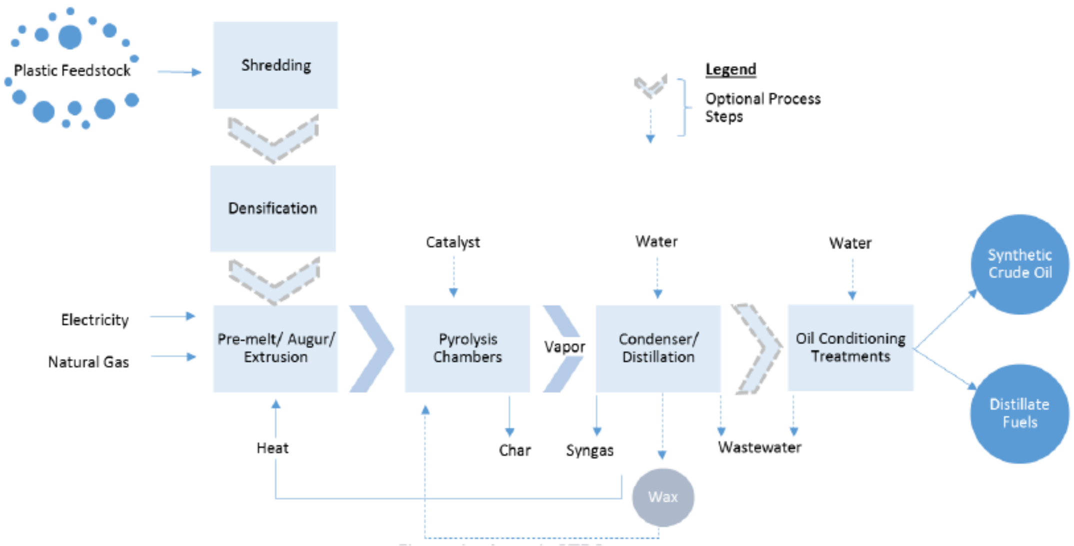


Figure 14 – A generic pyrolysis / catalytic depolymerisation process [27]. Oil conditioning covers fractionation, distillation, hydrogenation and water treatments.

[26] https://www.zerowastescotland.org.uk/sites/default/files/Plastics%20to%20Oil%20Report.pdf

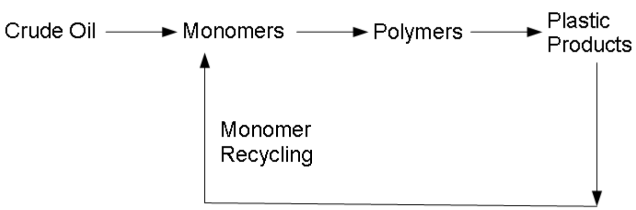
[27] https://www.oceanrecov.org/assets/files/Valuing_Plastic/2015-PTF-Project-Developers-Guide.pdf

Pyrolysis is a relatively low-cost, high-yielding technology, already operational at commercial scale. It is, however, typically limited to a maximum throughput for one pyrolysis unit of ~1-2 tonnes/hour, thought this rate is similar to the output of a typical European waste management facility; units can be used in parallel, if necessary. Manufacturers tout being modular, scalable and mass-producible. It is worth noting that pyrolysis is not limited to plastic-only feedstock, though this is one of the most suitable feedstocks.

Feedstock Recycling: Catalytic Depolymerisation

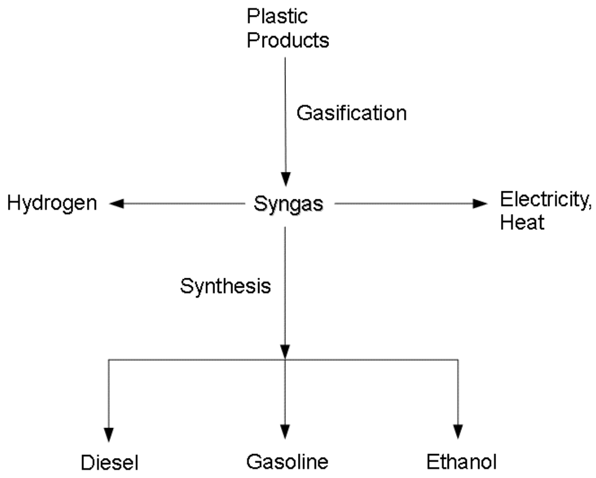
With the addition of a catalyst, which reduces the necessary operating temperature of the process, pyrolysis is renamed 'catalytic depolymerisation'. Catalytic depolymerisation tends to produce a more refined oil output than pyrolysis, however, the catalyst is typically consumed during the process. Some processes introduce hydrogen to overcome this problem, lengthening the life of the catalyst. Other processes use a carrier oil to assist with the mixing and dispersion of the molten plastic and catalyst.

Monomer Recycling



Monomer recycling involves the breakdown of polymers directly into their constituent monomers. This is a neater form of circularity than feedstock recycling, skipping out more of the production chain. It is, however, a niche method, only applicable to certain types of polymers; for example, polyesters (notably PET, type 1 plastic) and polyamides (e.g. nylons). Examples of monomer recycling processes applicable to PET include hydrolysis, acidolysis, glycolysis and alcoholysis. Monomer recycling is likely to form a small, but important, part of the recycling picture moving forward, as we cover later.

Gasification



Although unlikely to be used as a plastic-to-plastic recycling method, gasification can be used for plastics-to-energy and, like feedstock recycling, for plastics-to-fuel, so it is worth covering briefly.

Gasification is a partial oxidation process that involves much higher temperatures than pyrolysis (900-1400°C) and breaks the polymer chains more completely, largely converting them to syngas, mentioned as a by-product of pyrolysis. Liquid and solid by-products also result. The solid char is oxidised in situ to provide heat to the process. The liquid tars must be completely removed from the syngas, else they impede later processing; this is a relatively new process for feedstocks like plastic. Typical yields are shown in **Figure 15**, below.

Output	Proportion of total output
Syngas	93% wt
Tars	6% wt
Char	1% wt

Figure 15 – Reported outputs from a waste gasification process [26].

Although gasification is an established technology for the conversion of coal and petroleum coke into syngas, its use for the conversion of waste has been mostly limited to applications that use the syngas directly for production of some combination of heat, steam, electricity and hydrogen. To use gasification as a plastics-to-fuel process takes an additional step in which the small molecules in the syngas are stuck together, or synthesised, to produce the desired end-product. Because you are starting from scratch, it is easier to head directly for a fuel, rather than going all the way back to a crude oil (and contamination of feedstock is less of an issue than with pyrolysis). There are several possible synthesis techniques, including:

- Fischer-Tropsch conversion of syngas to diesel products (and wax).
- Catalytic conversion of syngas to methanol, then methanol to gasoline.
- Biological conversion of syngas to ethanol.

These two stage plastics-to-fuel processes involving gasification are more complex and offer significantly lower yields than pyrolysis or catalytic depolymerisation (though there is no need for further refining), see **Figure 16**, below, and would likely need to operate at significant scale to be economical.

	Pyrolysis	**Catalytic depolymerisation**	**Gasification and F–T synthesis**	**Gasification and methanol-to-gasoline synthesis**	**Gasification and bioconversion to ethanol**
Output					
Oil product	Plastic-derived Crude	Diesel/gasoline mixture	Synthetic diesel (+ cracked wax)	Synthetic gasoline	Synthetic ethanol
Quantity of product (kg/h)	680	616	228 (374)*	336	584
Power (MW)	8.5	7.4	3.0 (4.9)*	4.5	4.8
Output as percentage of input					
By mass	68%	62%	23% (37%)*	34%	58%
By energy	87%	76%	31% (50%)*	46%	49%

*Figures in parentheses include the mass and energy values from the waxes also produced by the F–T process.

Figure 16 - Comparison of representative plastics-to-fuel methods. Assumes input of 1000 kg/hour of feedstock and 9.8 MW of power [26].

Pioneer Companies

Below is a non-comprehensive list of companies that are pioneering non-traditional methods of processing plastic waste and are headquartered or operating in the UK. Please use the given weblinks for further detail.

- Plastoil Global

  Low temperature pyrolysis of plastic and used oils. Outputs oil.

- Enval

  Microwave induced pyrolysis of plastic aluminium laminates. Outputs oil and aluminium foil.

- ReNew ELP

  Catalytic depolymerisation of plastic, using supercritical water as the 'agent of change.' Outputs oil fractions: naphtha, diesel, vacuum gas oil, wax.

- Recycling Technologies

  Fluidised bed thermal depolymerisation of plastic. Outputs oil cut into four fractions.

- Plastic Energy

  Pyrolysis of plastic. Outputs oil fractions: naphtha and diesel.

- Powerhouse Energy

  Gasification of plastic, tyres and other waste streams. Outputs can include syngas, electricity, heat and hydrogen.

Feedstock Recycling Plant Economics

Revenue

A feedstock recycling plant makes money by:

- Charging gate fees for receiving and processing feedstock (likely to vary greatly by region).
- Selling oil end-product(s).

Gate Fees

In countries with a high landfill tax, such as the UK, a feedstock recycling plant is likely to be able to charge a gate fee for receiving and processing certain plastic waste streams, such as Residual Plastic Waste (RPW). This fee will vary with the quality of the feedstock, defined by its composition and by how much further pre-processing is necessary before recycling can proceed (sort, clean, resize, dry). This also impinges on the suitability of the feedstock, given the site's ability to pre-process feedstock onsite (which in turn impacts capital and operational costs).

Suitable feedstock may originate from municipal, agricultural, commercial or industrial sources, and be sourced directly from the generator or from a recycling facility (MRF, PRF). Post-industrial plastics, which are generally more homogenous and have lower contamination rates, bypass municipal recycling programs and are sold directly into recycling markets. As suggested earlier, to reduce transportation costs, the feedstock source should be close to, or ideally co-located with, the plant (e.g. see **Figure 12**).

For RPW, the gate fee will need to be competitive with local landfill, Energy from Waste (EfW) and export options, taking transportation costs into account, to provide the necessary incentive to divert from those sources,. Residual plastic has a high energy content, which is more valuable to EfW plants than mixed refuse, so the gate fee will need to reflect this. Indicative UK gate fees for RPW from 350 PPM sources range from £50-£80/tonne.

In countries without a landfill tax, all other things being equal, gate fees for RPW will necessarily be lower or negative, implying the need to buy feedstock. Gate fees are not the main source of revenue, so operators may be perfectly happy to do this. Alternatively, feedstock suppliers may be willing to consider revenue sharing in exchange for low or no cost feedstock supply.

In all cases, securing a feedstock agreement with one or more suppliers, which defines all relevant parameters of feedstock delivery (quantity, quality, price etc.), is a fundamental part of developing a viable plant.

Selling End-Products

The main source of revenue for a feedstock recycling plant comes from the sale of oil end-product(s). The value of this revenue is determined by the amount of feedstock processed by the plant, the feedstock-to-oil yield and the price obtained for the oil end-product(s). In turn, the amount of feedstock processed by the plant is determined by its design capacity and operational factors such as the availability of feedstock, while the feedstock-to-oil yield is determined by:

- The recycling method and technology used.
- The mix of plastics in the feedstock. Certain plastics produce much higher yields, with yields ranging from 30-80%.
- The moisture level of the feedstock. A higher moisture level reduces the yield for the same weight of wet input (and energy is spent drying it).
- The contamination level of the feedstock, including non-target plastics and non-plastics. Non-plastic contaminants include dirt, metals, paper and wood. Contaminant levels are directly correlated with char production rates (and certain contaminants may cause oil quality problems as highlighted earlier). A high char production rate reduces the feedstock-to-oil yield and increases char management costs.

One of the fundamental decisions impacting the operation and economics of a feedstock recycling plant is whether synthetic crude oil is the principal or intermediary output. As mentioned earlier, synthetic crude oil can *either* be sold to a refinery for further processing *or* can be fractionated onsite into distillates that can be marketed directly to end users, blenders or distributors. Distillates may be classified as fuel blendstocks, which require further mixing before use, or drop-in fuels, which can be used as-is. **Figure 17**, below, shows some potential end-products and who might buy them; there are standards that define these products. Wax is another potentially saleable end-product. To reduce transportation costs, offtake companies should be as local as possible, bearing in mind the potentially conflicting and overriding desire to have the plant close to the feedstock source.

Oil Output	End Users
	Un-distilled
Light Sweet Synthetic Crude	Refinery
	Heavy Distillates
Residual Fuel Oils (No. 5 and No. 6)	Shipping/Aviation Industries
	Middle Distillates
No. 2 Fuel Oil	Heating Oil Companies
No. 2 Diesel Fuel	Oil Blender, Oil Broker, Oil Distributor, Direct to End User for use in Energy Generation Equipment
Kerosene	Aviation (jet fuel)
	Light Distillates
Gasoline	Retail Transportation Fuel, Chemical Industries, Refineries, Fuel Blenders/Brokers
Naphtha	Chemical Industries, Refineries, Fuel Blenders/Brokers

Figure 17 – Potential oil end-products and end users [27].

Unlike fossil fuel derived crude oil, which is a well-known commodity with fairly predictable characteristics, synthetic oils and distillates from plastic are relatively new. Oil quality can vary weekly due to fluctuations in feedstock composition, which leads to unpredictability for buyers. This may require ongoing testing to provide reassurance. Furthermore, small quantities produced compared with the size of refineries may make it less easy to place into the market. For offtake agreements to be secured it may be necessary to identify companies that assign value to local, waste-derived oil products, often with a low or ultra-low sulphur content (a desirable property). Such offtake agreements, as well as their feedstock equivalents, are core to plant viability and to availability of financing.

Assuming compatibility, oil end-products should command the same market prices as their fossil fuel derived equivalents, with more refined products, closer to drop-in status, fetching higher prices. For example, 350 PPM sources quote figures from< £0.30/litre for a relatively unrefined (and non-standard) product, through £0.40/litre for a naphtha substitute, up to £0.60/litre for a drop-in fuel.

By-products of the feedstock recycling process - char, possibly syngas - may also generate revenue, if markets exist, and if not used completely onsite. In the absence of available markets, transportation and disposal becomes necessary.

Other Revenue

A feedstock recycling plant may, now or in the future, be able to receive certain region-specific subsidies, for example:

A subsidy for processing plastic/plastic packaging. The UK has an existing subsidy for plastic packaging – the PRN system, see the above section 'UK Waste Policy' – but it is believed that feedstock recycling is not currently eligible. Business models 350 PPM has seen do not include this.

A subsidy for the production of transport fuels from plastic. In the UK, although not currently eligible for the RTFO, the Renewable Transport Fuel Obligation, the government is "considering the potential of fuels made from waste feedstocks of fossil origin that cannot be reused or recycled, sometimes known as recycled carbon fuels" [21].

Costs

Capital and O&M (Operation and Maintenance) costs for a feedstock recycling plant are likely to vary considerably by plant. Factors affecting capital costs include:

- The business model under which the plant is developed. Several business models are possible with varying levels of participation from the technology supplier, including: Design Build Own Operate (DBOO), joint venture, equipment sales and service and a licensing arrangement.
- The technology type and supplier.
- The extent to which feedstock pre-processing and oil post-processing is performed onsite. As mentioned earlier, these decisions have wider impacts, and may also affect the regulatory structure under which the plant must operate.
- The size of the plant – processing capacity and land footprint. Typical capacities range from 10-60 tonnes/day.
- Local site development costs.

O&M costs include the following, some of which will not apply in all cases:

- Feedstock purchase and transportation, electricity, natural gas (for startup purposes), water (for condensing syngas, conditioning oil), catalyst, hydrogen, oil additives.
- Transportation of end-products, disposal of char, disposal of catalyst, wastewater management.
- Lease or debt servicing, trailing royalties on oil sold.
- Salaries, business rates, insurance, rent and other standard business expenses.
- Maintenance.

For further information on plant economics and the process of plant development, please see footnotes [26] and [27].

Feedstock Recycling Market Potential

Current Market Potential

Although there are a growing number of commercially operational feedstock recycling plants around the world, the current market potential is massively larger than this implemented capacity (we can safely ignore implemented capacity here).

One 350 PPM industry source estimates the UK market could support ~150 plants, each processing ~8500 tonnes/year of mixed plastic. This is more than the amount of plastic currently collected for recycling, so implies higher collection rates. This is not an unreasonable assumption as widespread use of feedstock recycling would allow for a wider range of plastics to be collected for recycling. However, if we simply convert the amount of plastic currently collected in the UK, but not recycled domestically – this will mostly be mixed and low-grade plastic - this equates to ~90 plants.

The American Chemistry Council has made equivalent estimates for the US market. They concluded that the US could potentially support 260 new chemical recycling plants, each processing 25,000 tonnes/year of mixed plastic (considerably larger plants than our UK calculations). Further, they found that these plants could result in 38,500 jobs and $9.9 billion in US economic output. [28]

Future Market Potential

As preceding sections have highlighted, it is perfectly rational to be optimistic about the future of the plastics recycling sector - and feedstock recycling in particular - both in the UK and worldwide. To summarise:

Plastics production in on a long-term upwards trend. Although there may be a slight reduction in plastic demand as certain single-use plastics are phased out, there is no reason to believe this renders the trend obsolete. Fitting a polynomial trendline to **Figure 4** suggests plastics production will roughly triple from 2015 to 2050, to ~1.1 billion tonnes/year, see **Figure 18**, below. Most estimates 350 PPM has seen are in this ballpark.

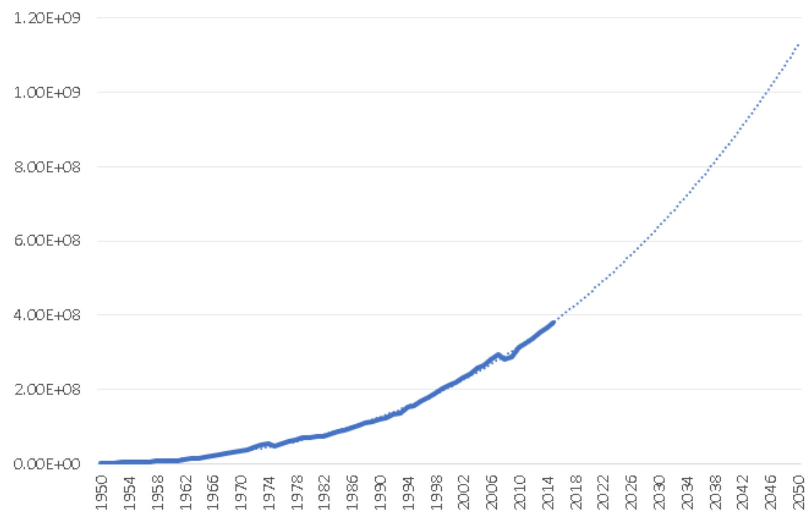


Figure 18 – World plastics production forecast (tonnes).

Given this production forecast, waste, waste collection and recycling volumes should all naturally increase, even without increased recycling rates. However, it is reasonable to believe that domestic recycling rates will increase, especially in developed countries like the UK:

- With plastic exports likely to reduce, there will be a requirement for more plastic to be recycled locally.
    - For the UK, a total ban of plastic packaging exports would need a trebling of the UK's recycling capacity, according to Policy Connect. A cross partly group of politicians are calling for such a ban, to be implemented by 2030. [29]

[28] https://plastics.americanchemistry.com/Economic-Impact-of-Advanced-Plastics-Recycling-and-Recovery-Facilities-in-the-United-States.pdf

[29] https://www.businessgreen.com/bg/news/3070850/government-must-aim-for-net-zero-plastic-waste-exports-by-2030-say-researchers

- Commercial and governmental pressures are likely to force increased use of recycled plastic.
- Feedstock recycling can recycle more plastic from what is currently collected. It also allows for more to be collected in the future, allowing even more to be recycled.

The above is not a comprehensive list. For example, there are also likely to be developments both in designing new plastics for recyclability and in improving recycling technologies.

2050 Market Potential

Plastic recycling bridges two significant industries - waste management and petrochemicals and plastics - and has the potential to create significant new opportunities for both.

To end this report, we look at how management consultants McKinsey & Company have quantified this potential for the global petrochemicals and plastics industry. They have modelled an optimistic but perfectly plausible scenario involving:

- A multi-stakeholder push to boost recycling.
- Regulatory measures to encourage recycling.
- Consistent progress on recycling technologies.
- A $75-a-barrel oil price.

Their results are shown in **Figure 19**, right. The headline is that by 2030, 50% of plastic worldwide could be reused or recycled - a fourfold increase over what is achieved today. If this were to happen, plastic reuse and recycling could generate profit-pool growth of as much as $60 billion for the petrochemicals and plastics sector, representing nearly two-thirds of its possible profit-pool growth 2016-2030.

Extrapolating out to 2050, McKinsey & Company suggest nearly 60 percent of plastic demand could be covered by production based on previously used plastic. This production would be covered by traditional mechanical recycling growing at a CAGR (Compound Annual Growth Rate) from 2016-2050 of 7%. This is solid growth, but the equivalent forecast for feedstock recycling is 17% and for monomer recycling is 18% CAGR (starting and ending at a much smaller market share). This is impressive growth and clear reason to be excited about the sector.

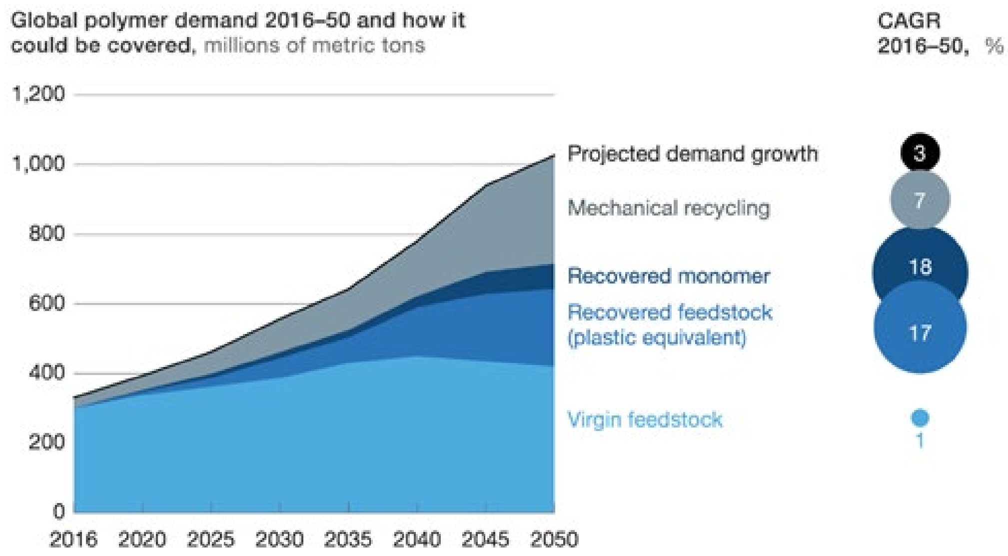


Figure 19 – Global polymer demand 2016-50 and how it could be covered. [30]

[30] https://www.mckinsey.com/industries/chemicals/our-insights/how-plastics-waste-recycling-could-transform-the-chemical-industry