Municipal Collection and Sorting Mechanisms

Lifecycle pathway for recycled plastics

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This report focuses on many of the processes plastic goes through from the point a consumer decides to recycle it until it is available for reuse in an IEM or AM facility. This includes the pre-sorting by consumers, kerbside collection, and the sorting mechanisms at different stages in the plastic waste recycling system.

Date December 2022

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Deliverable WPLT 1.2 Municipal collection and sorting mechanisms

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Interreg North-West Europe TRANSFORM-CE

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List of Abbreviations/Acronyms

AM	Additive Manufacturing
C&I	Commerce and Industry
CE	Circular Economy
HDPE	High Density Polyethylene
HWRS	Household Waste Recycling Centre
EfW	Energy from Waste
EPRS	Extended Producer Responsibility Schemes
GHG	Greenhouse Gasses
IEM	Intrusion Extrusion Moulding
Kt	kilo tonnes, 1000 tonnes
LDPE	Low Density Polyethylene
MIR	Mid-range Infra-red
MRF	Material Recovery Facility
MSW	Municipal Solid Waste
Mt/a	Million Tonnes per annum
NGOs	Non-Governmental Organisations
NWE	Northwest Europe
PAYT	pay-as-you-throw
PET	Polyethylene Terephthalate
PMC	Plastic, Metal and Drinks cartons (Belgium)
PMD	Plastic, Metal and Drinks cartons (The Netherlands)
PP	Polypropylene
PRF	Plastic Recovery Facilities
PPF	Plastic processing facility
PTT	Pots, Tubs and Trays
RDF	Refuse Derived Fuel
RCV	Refuse collection vehicle
SPI	Society of Plastics Industry
SUP	Single Use Plastic
WfH	Waste from Households

1. Executive summary

This report is the second in a series of three reports that look at the lifecycle of plastic waste from when the consumer discards it until it becomes a new product. It focuses on municipal collection and sorting mechanisms, particularly for flexible single use packaging waste. However, before the plastic waste can be collected at the kerbside, the consumer must make choices about why, what, how and where to recycle. This report explores consumer attitudes to recycling and what public authorities and governments can do, by way of intervention policies, to increase the capture rate of plastic waste. It was found that consumers find it difficult to recycle according to the local rules, which causes contaminants to be mixed in with clean plastics. To reduce contamination, it was recommended that collection waste trucks should be of the kerb-sort type.

Unfortunately, there is a lack of harmonisation of municipal collection methods, across all partner counties. The different colours of bins or bags used for each type of recyclant are not only different in each partner county but in many cases, they are different for different collection authorities in the same city. It is recommended that a uniform colour coding of bins and bags should be implemented across the whole of Europe.

It was found that very little of the low-grade plastic films are allowed to be placed in the recycling system, and that which inadvertently makes it in, is remover and sent to landfill or is incinerated to make energy. Recently, in some areas across Europe, new or modified waste recycling facilities have included the ability to capture single use plastic films and recycle them into new plastic pellets. However overall, the capture rate is very low. The opportunity therefore arises for this low-grade, and not yet widely recycled, thin film plastics to be captured for use in intrusion extrusion moulding (IEM) technology to make new durable plastic products.

It was also found that the technology used to sort the plastic waste from other waste is generally the same in most waste sorting facilities. However, depending on the focus of the facility, the type of technology used, and the layout of the plant differ. One problem identified for thin film recyclant is the lack of an offtake market. Due to this, most waste handling facilities are not designed to sort this type of material, and when it gets the machinery, it can become clogged up. Technology is continually advancing, and it is recommended that the sorting mechanisms will be enhanced with a big capital investment in new technologies, that are designed to include the ability to sort thin film plastics. This will increase the availability of low-grade plastic recyclant.

To produce the filaments used in additive manufacturing (AM), high-grade recycled plastic is required. The volume of plastic required for the AM industry is not very large as its use is still a niche application. Most single use plastics recycled today are for food grade use, as this has the most value. Therefore, the municipal sorting of plastic does not focus on capturing single use plastics that are useable for AM. As the AM industry grows this will have to change. It is therefore recommended to put into place sorting mechanisms for plastic that can be used for the AM industry.

It is concluded that the capture rate of single used plastic films must be increased to feed the IEM market. To focus the minds of consumers and to decrease contaminating, it is recommended that a new bag or bin be used to capture the thin film plastics in a single waste stream. As IEM can use mixed dirty low-grade plastics, the sorting stages for IEM are much less than ordinary recycled plastics. Very little changes to the present collection and sorting mechanisms are required to increase the amount of plastic needed for the AM industry. All that is needed, is a focus on collecting and sorting high quality non-food grade plastics besides PET.

2. Introduction

2.1 Background to this project

Single use plastic (SUP) causes enormous pollution in our environment. Each year 8 Mt of SUP leaks into our oceans ending up as microplastics affecting our ecosystems. Northwest Europe (NWE) generates the biggest source of SUP (40% of Europe). The EU generates 27 Mt per year of waste plastic, of which 31% is recycled, 41% is sent for energy from waste (EfW) and 27% is landfilled. This is a loss of valuable resources to the European economy. The challenge is to reduce this 68% loss of processed plastic, by diverting it using alternative recycling options. However, uptake for recycled content in new plastic products is low. In 2016 EU plastic production was 60 Mt and only 8 Mt were collected for recycling. The EU is reliant on imports of virgin plastic and there is a huge opportunity to revalue and use, low and high grade recycled SUP as an alternative to virgin plastic. The EU has set an ambitious 2025 recycling target of 65% for packaging materials, (which includes SUP,) with an increase to 70% by 2030. Existing lack of infrastructure capacity and viable links to secondary material markets across NEW, forces pre-segregated and mixed waste plastics into landfill and or is consumed as energy-from-waste (EfW). This approach is not resource efficient, will not enable EU recycling targets to be achieved, and clearly does not promote a circular economy (CE) approach. There are real environmental and resource security issues, but currently NWE lacks the economic incentives to solve them.

The plastic import ban to China (2018) meant the closure of a huge market for the export of European plastics for recycling. With this reduction in the offtake market, this created a reduction in the export demand for the waste plastics, while at the same time the supply of waste plastics continues to go up. In response, EU plastic is being stockpiled and higher levels of SUP are now being sent to energy from waste (EfW) plants and landfill. This is an economic loss to the EU and reinforces the wasteful linear economic model of 'use once and discard' (Ellen MacArthur Foundation, 2022). The EU Packaging Waste Directive and Extended Producer Responsibility (EPR) policy, aims to reduce plastic production and make manufacturers more responsible for the waste they produce. Therefore, there is urgency for NWE to develop its own plastic recycling economy, to reduce reliance on import markets for virgin plastics, to repurpose, to revalue existing SUP waste and to upcycle, while at the same time diverting valuable plastic away from EfW and landfill.

Since it is technologically feasible to segregate, re-engineer and repurpose SUP, the TRANSFORM-CE project uses all types of SUP from a single waste stream. It focuses on the repurposing of post-consumer plastic packaging waste that is within the municipal waste system. NWE is a region of mixed economy, with variable levels of wealth and employment. Its consumers produce significant quantities of plastic waste in part due to affluent and urban lifestyles. The region contains some of the largest urban conurbations in Europe. Several are sufficient to provide consistent and large feedstocks for remanufacturing of SUP. The TRANSFORM-CE uses all types of SUP for two innovative technologies. The low valued plastics such as foils i.e., thin packaging films, are moulded into products using intrusion-extrusion moulding (IEM). The higher valued plastics i.e., pre-sorted drinks and cleaning bottles, and food trays/containers, are processed into filaments to be used to make additive manufactured (AM) products. AM provides opportunity for integration into complex products, while IEM provides opportunity for simpler single unit designs

The goal for this project is to divert 308.25 t of post-consumer municipal SUP waste over 3 years, which is an estimated reduction in CO_2 equivalents of 478 tonnes, (based LCA natureline Save Plastics of 1.3 kg net CO_2 reduction per kg plastic diverted), to become feedstock for both AM and IEM. Long-term uptake through scaling up of the technology with industry investment has the potential to divert approximately 16,000 t in 10 years using the manufacturing facilities within this project. Further increases are possible as the TRANSFORM-CE business model is taken up across NWE by the business community.

The very low amounts of recyclant ending up in new products has been identified as being due to, technical unknowns, lack of investment via government, and waste companies not capturing low-grade plastics for recycling. This results in a non-secure supply chain for recycled plastic feedstocks. Therefore, this project identified three risks that exit to the successful uptake of recycled plastic by manufacturing businesses. This report focuses on Risk 2 and 3. Risk 2 identifies the lack of technology uptake throughout the recycling process including technology like AM and IEM that can use the recyclant in new products. Risk 3 is the lack of market uptake for the recycled material, this includes businesses worried that consumers will not want to buy products made from recycled plastics.

This report is the second in a series of three reports. It looks at the long-term prospects of providing a steady stream of quality recycled plastic in viable volumes for the AM and IEM markets. In the previous report in this series, Long-Term 1.1, one of the factors that affected the quantity of SUP available for AM and IEM was the quality of plastic in the recycling system. It was shown that the quality is dependent on the actions of the consumer in the sorting and recycling of their plastic waste before it starts its recycling journey into the municipal waste management system. To reduce misthrow, that introduces contaminants into the recyclant, it is important to understand the attitudes and motives of consumers towards recycling in the proper manor. This means consumers' willingness to follow the guidelines prescribed by their municipality.

The capture rate is the amount of plastic entering the recycling system as a proportion of the amount that is put onto the market for consumption. This report will then look at what affects the capture rate of consumed plastics by focusing on the ways consumers and materials recovery facilities (MRF) handle the plastics. It will look at the collection mechanisms and then the sorting mechanisms at both the MRF and the plastic recovery facility (PRF) stages in the recycling process. Reports from work package T1 deliverables 1.2, 2.1 and 2.3 are used as inputs to this report, its output will inform work package T3, the Navigation Tool for the Plastic Circular Economy.

Having a waste management system that can provide adequate plastic recyclant, will mitigate part of Risk 3. However, not having a secure long-term supply of clean feedstocks to turn into recycled plastic, will result in lack of adoption of recycled plastics in the design and manufacturing processes for new products. This report aims to identify mechanisms that will improve the collection (capture rate) and sorting (reducing the rejection rate) of plastic waste. The treatment options and the resources used for the plastic waste will be the focus of the third report in this series.

This report is split into three sections, representing three of the stages of the recycling process. The first section looks at the mechanisms carried out by the consumer/ householder when they dispose of the packaging plastics after use. It looks at householders' perspectives on recycling, including attitudes to sorting. It looks at the capture rate and what rewards and penalties policy makers can use to increase the capture rate and the quality of the waste. The second stage of the recycling process is carried out by the municipality. Waste management companies, some are private contractors other municipality owned, collect the waste and take it to the materials recovery facility (MRF). This section looks at the existing collection mechanisms and how they affect the quality of the waste. Where possible improvements to the existing collection system are identified. The third section discusses the sorting mechanisms for the plastic. Some of the sorting is carried out as part of the collection mechanisms, the rest is carried out in the MRF and PRF. Improvements to the whole system will be recommended for public stakeholders to take up.

This report will focus on waste streams emerging through the municipal system. It will not look at the commercial waste management sector that operates in parallel to the municipal waste system.

2.2 Defining recycling

A question could be asked, if a consumer puts waste plastic in a recycle bin can we truly say that recycling has taken place? Furthermore, at what stage during the lifecycle of a piece of plastic can the label recycled be used? This research sees the answer to these questions in the definition of a circular economic model. For a piece of plastic to be truly recycled it should have become part of a new product that itself will be used, discarded, and reused again in a future product. In a true circular economy, when a piece of plastic cannot be used again, it must undergo a chemical depolymerisation prosses and starts again as recycled virgin input material to used again. This means that in a true circular economy no plastic is landfilled or burnt.

It is very interesting to note who uses the term 'recycled', how it is used and defined. Waste plastic goes through many stages from being deposited in a collection bin, until the end of its life. Geiger et al (2019), define recycling as individuals' waste collection intentions and behaviour to allow materials to be re-used, This implies that recycling is the action or process of converting waste into reusable material. SUEZ (2021, p. 7) identify 'collected for recycling' and 'recycled', as two distinct targets within the waste management system.

Some consumers may define recycling as the action of putting waste into the recycle bin and the municipality takes it away. Material recovery facilities may define the plastic as being recycled if a pallet of plastic leaves their facility to go to a processing plant. Some defined it as been recycled if it gets used in a waste for energy plant rather than if it goes into landfill. This means, if for whatever reason the plastic ends up being sent to landfill by a MRF the consumer may still consider that the plastic has been recycled by them, but the MRF does not. The reprocessing plant will consider that the plastic has been recycled if they sell new plastic pellets that are sent to a factory that uses the pellets in new products. However, especially in the UK, the industry as well as UK government statistics, have considered the plastic recycled if it has been exported to a facility overseas (RECOUP, 2020, p. 13). It is important to note that, in the past, the majority of quality household packaging plastic was exported to the Far East. However now, due to import bans, there is a need for Europe to bring recycling plastics inhouse.

A lot of the plastic which was sent to the Asian market, that in Europe was accounted for as recycled, ended up burned in waste-for-energy plants, was burnt in open fires, or become environmental pollutants clogging up waterways, rivers and making its way into the oceans. It has been found that hundreds of containers of plastic waste sent from Australia to Malaysia were sent to unlicenced companies who were causing ecological damage. The Malaysian government minister stated that she had closed down 150 illegal recycling companies between July 2018 and the time of her interview (60 Minutes Australia, 2019). The same was true about plastic from the UK sent to Poland and Turkey. See Figure 1for imports to Malaysia for part of 2018.

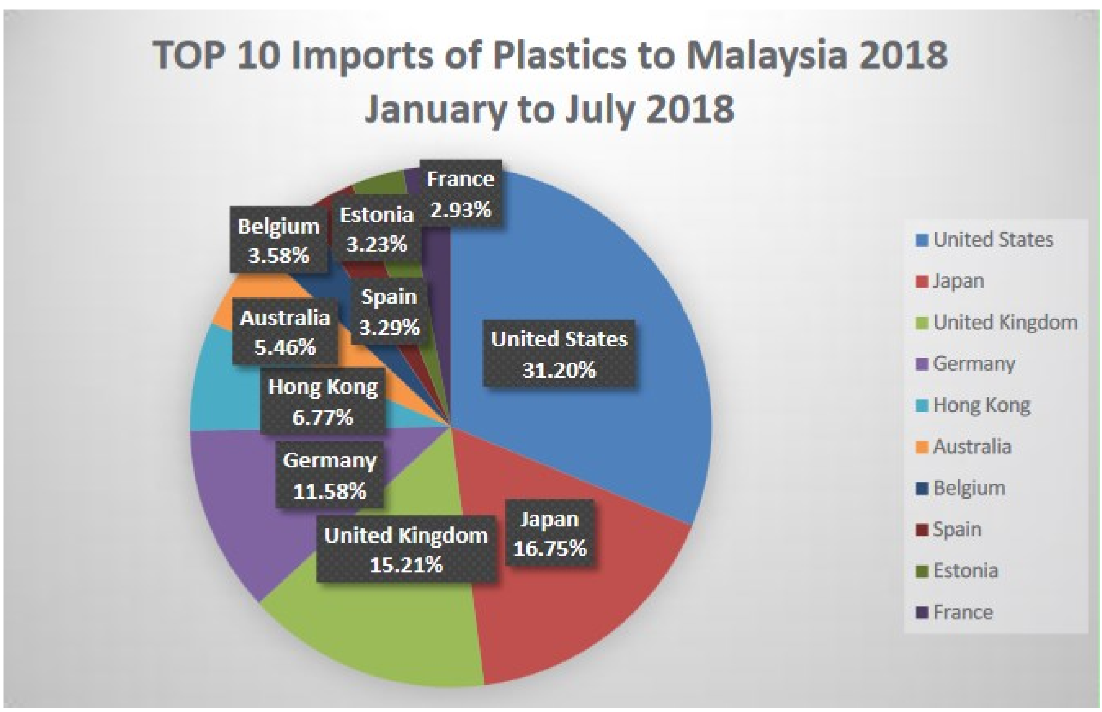

Figure 1Main plastic waste exporting countries to Malaysia – From "The Recycling myth" report, 2018.

A report from Zero Waste Europe (https://bit.ly/2MTyItW) provides figures about intra- and extra-EU imports and exports of plastic waste for the year 2015 (before some Asian countries banned imports). The EU collectively exported 40% of the plastics collected for recycling in 2015, corresponding to 12% of the entire post-consumer plastic waste, reaching approximately 3 Mt. For the same year, intra EU trade was 2.3 Mt and extra EU imports around 0.4 Mt. More than 50% of plastic waste exported from EU is polyethylene, (Buchhorn, 2022).

Therefore, claiming that plastic has been recycled without the full knowledge that it has been reused as defined by circular economy definition, could be an erroneous designation for the plastic. In the literature and in government statistics, the closing of the loop i.e., the reusing of the used plastic, has not been the ultimate definition of what recycled means when used outside a circular economy definition. Therefore, for the circular economy model defined within this report, the term 'recycled' will follow the definition found in the Circular Economy Act from Germany (Bundestag, 2012), as follows "*waste is reprocessed into products, materials or substances either for the original purpose or for other purposes*". This implies that to be truly classified as having been recycled, the recycled plastic must be used again as a plastic product or if depolymerised and the polymers used again, and not end up in landfill or as waste for energy.

2.3 The lifecycle of plastic

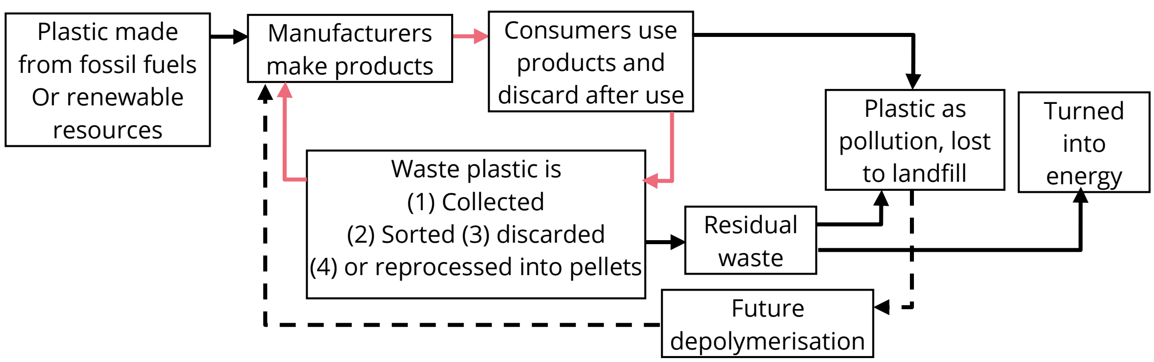

Figure 2 The Basic stages in the lifecycle of plastic incorporating the circular economy model

2.3.1 Types of plastic polymers

There are six basic types of plastic polymers, plus many other small and niche types that form the seven types of plastics as described by the Plastic Industry Association, see Appendix 1 for the list. For many practical reasons, plastic products are not made with pure primary polymers but are mixed with other chemicals. These include additives that are, stabilizers, colorants, plasticizers, fillers and reinforcing fibres, ultraviolet absorbers, antioxidants as well as processing aids including lubricants and flow promoters, (Shamsuyeva & Endres, 2021). As well as these additives within single polymer plastic films, there are multi-layer plastic films that could also include aluminium, for example like in a crips bag. These manufacturing processes add complexity to the types of plastics entering the waste system and the volumes of any bespoke complex plastic products.

2.3.2 Used in packaging

When these multi-layer plastics are used in food packaging, they need to be closed and are printed with some signage. Furthermore, in many instances paper stickers are attached to the plastic films or they are attached to paper and act as a window, this is in contrast rather to the whole packaging being made of single polymer plastic. This adds different types of adhesives to the plastic and lots of different types of inks. Therefore, plastic foils are complex waste, that without their use as feedstock for IEM, pose a great difficulty as to how they can be recycled. Across the partner regions of this project, foils are collected in Belgium, the Netherlands and in Germany, however they are rarely recycled and mainly end up in landfill or are burned to produce energy.

Many ordinary products are made up of parts each of which is made from a different polymer. For example, many drinks and detergent bottles are made of a PET bottle, an HDPE lid, and a multilayer (sometimes only PP or paper) printed and glues label. Thus, simple single polymers become part of a complex multi-polymer product. One of the recommendations from the first report of this series (LT1.1), was to reduce this complexity by harmonising the composition polymer makeup of plastic packaging products. However, in reality there are technical, design, and engineering reasons why products are made from complex and different polymer types and contain different additives.

2.3.3 Discarded after use

Once used, most plastic packaging has no use to the consumer and is discarded. Consumers should only discard plastic in an appropriate recycle bin. However, this is not what always happens. The plastic waste ends up in street residual waste bins, on the streets, in rivers and ultimate into the oceans as pollutants. Some of this is directly due to, consumer behaviour, to mishandling of the waste within the waste handling system, or to industrial accidental spillage.

2.3.4 The plastic waste recycling system.

The waste is collected, sorted and then processed into pellets to be reused in new products. However, a large proportion of the plastics, especially plastic films end up in landfill or is burnt in a EfW plants.

Landfill should not be seen as an appropriate end of life for the plastics. With enhanced landfill mining technics, (Canopoli et al., 2018; Cappucci et al., 2020) using chemical depolymerisation prosses (Zhang et al., 2021), the waste plastic could be turned back into recycled virgin polymers to be used again. Therefore, landfill can be looked at as a very bad storage mechanism for plastic, until it becomes economic to recycle the plastic, hence the arow closing he circular economic model for landfill plastics, see Section 2.3 above.

2.4 The flow of the plastic through the recycling system

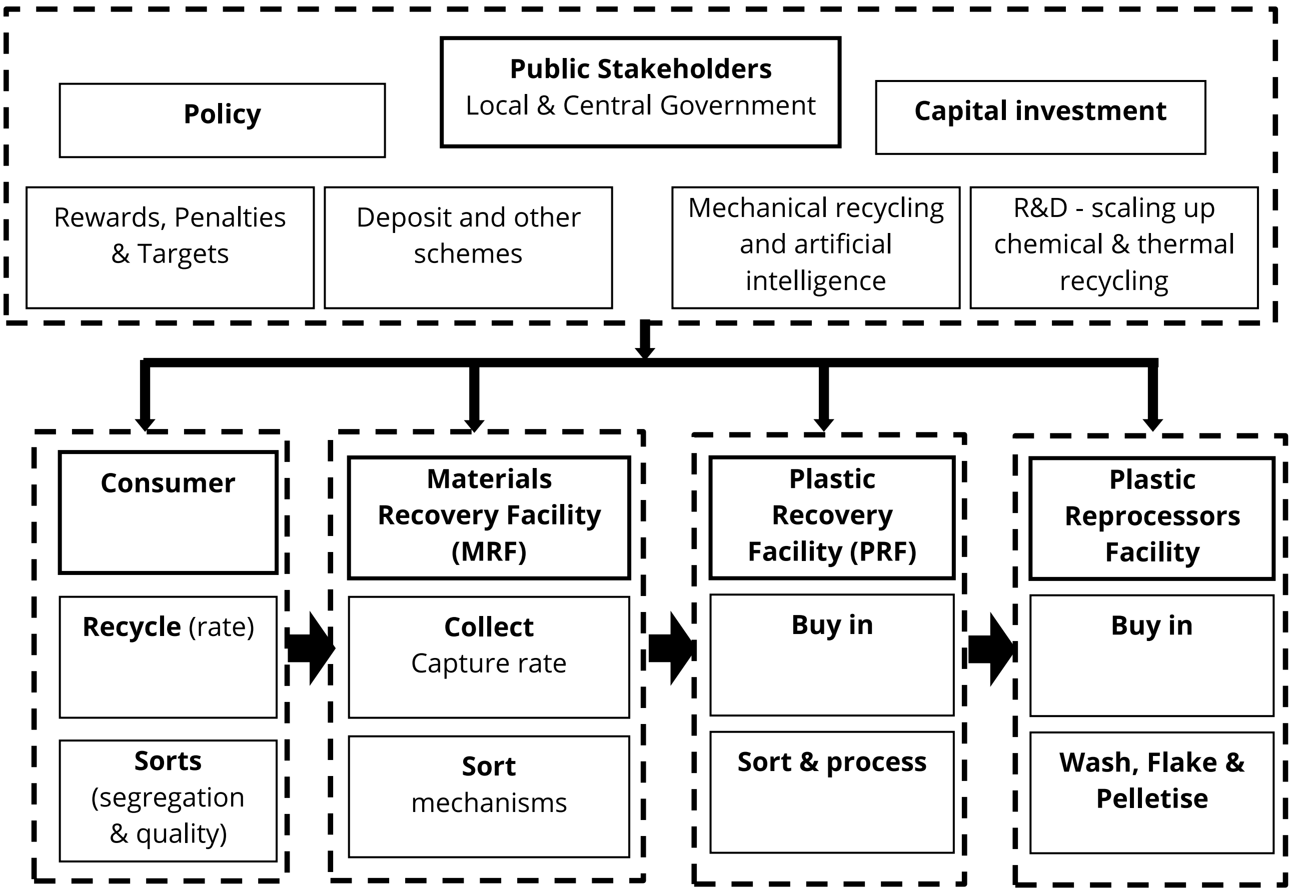

Figure 3 Interconnections between stakeholders in the plastic waste recycling system

The first stakeholder in the plastic waste system are the consumers. They buy products that produce plastic waste either before use from the transport packaging or after use when the package or the product itself is no longer required. Consumers are the beginning of the plastic waste system. They are the primarily initiator of recycling. Their attitudes to carrying out recycling in an optimal manor, are pivotal to the capture rate for waste plastic.

The waste plastic is inputted to a materials recovery facility (MRF), where the first stage of sorting takes place. The type of sorting mechanisms used will depend on the route the waste took to get into the MRF. At the MRF the plastic is sorted from all other waste fractions into saleable bales of plastic. Some bales are high quality which is usually mainly PET and become the input to a PRF. , Other bales of low-quality mixed plastics are designated for fuel to energy facilities. (Burning the plastic to generate fuel saves the high landfill costs.) From the MRF the plastic can go straight to a reprocessor, or it is sent to a plastic recovery facility (PRF). Some large MRFs include the processes of a PRF. At the PRF facility, the plastic is further sorted into polymer types and misthrow is removed. The plastic can be sorted into different colours and washed. Finally, at the reprocessor the waste is cleaned and turned into pellets that can go directly into new products. In many countries the MRF, PRF and the reprocessor are different companies. However, a large MRF may contain the process that take place in in the PRF and the reprocessor.

Taking the UK as an example, there are 110 MRFs that have the ability to sort household plastic packaging from other material streams. These have a total capacity to sort up to 1.9 Mt of packaging plastic per year. This is from both household and commercial waste. It is estimated that the total actual throughput is about 51% of the total capacity. Further to these, are seven Plastic Recovery Facilities that have an operational sorting capacity of 350 kt. (RECOUP, 2020). The RECOUP report identified 16 reprocessors that provide 230 kt of washed plastic flakes, out of their estimated operational capacity of 440 kt per year. This means that there is a significant capacity to increase the amount of plastic that can be processed in the UK with the current facilities, and with more investment, the capacity can grow. It should be noted that this capacity is for rigid and soft plastics but not for the low-grade thin films that can be used in IEM.

As of 2020, the amount of food grade plastic pellet produced from recycling was 65 kt (RECOUP, 2020, p. 7). This implies that the use of PET from bottles in AM, rather than bottle to bottle recycling, would be upcycling. This is because, at this time in the UK a high proportion of PET bottle plastic does not get recycled into food grade recyclant as it does not reach the stringent food safety standards. Therefore, until full recycling of all PET bottles into food grade plastic, the use of PET from bottles for AM should be classified as upcycling rather than downcycling. This means, by diverting the plastic from landfill or EfW, because it is below standard for food use, and making products using AM, the plastic can be said to have been upcycled.

IEM can use low quality plastics to upcycle them into durable long-lasting products. Both AM and IEM manufacturing close the loop in the circular economy model by using plastic that would not otherwise be reused. The typical low-quality plastics that are used in IEM are thin films food packaging. For example, snack bags or films used to seal food containers. While the volume of such packaging plastics is large enough to feed a growing IEM industry these is a problem with the collection and sorting of thin film plastics especially in the UK, as explained by RECOUP.

"*There are significant shortfalls in reprocessing capacity in the UK, and there are very specific operational and technical challenges around reprocessing plastic film, non-bottle PET and food grade packaging, particularly Polypropylene. There are challenging commercial conditions and fine profit margins in the reprocessing sector, indeed if profits are delivered at all. This is where financial investment is needed to build technology solutions and an operational business case for this sector not only to be commercially viable, but to thrive*", (RECOUP, 2020, p. 6). RECOUP state that in the UK there isn't currently the technical advancement or operational infrastructure to recycle household plastic films.

"*The 395,000 tonnes of household plastic film packaging that is placed on the market in the UK poses a significant challenge. There are a number of practical barriers which prevent film being compatible with many existing UK collection and MRF systems. It can contaminate established plastic bottle bales and paper lines, and clog sorting equipment.*", (RECOUP, 2020, p. 24). In the UK, while there are small quantities of plastic films being reprocessed, it is not consistently available in adequate quantities to feed a growing IEM market. During the workshop carried out as part of the T1 work package, one of the managers for a municipality explained that the reason why capital investments have not gone into MRFs so that they can handle thin plastic films, was the lack of market demand for the recyclant. This reinforces the reason for this TRANCEFORM-CE project. It is to research the capabilities of the IEM industry to be able to upcycle thin plastic films. By showing that it is possible, this can catalyse the recycling industry to change their collection and sorting systems to provide volumes of thin film plastic packaging to the IEM industry, thus creating a circular economy for single use thin plastic films.

3. Waste Disposal

Waste disposal is the beginning of the recycling system, and initially depends on consumer behaviour and attitudes for a correct disposal of waste plastics. The TRANSFORM-CE project identifies the sorting behaviours of consumers as being a focal point for successfully increasing capture rates of quality plastic packaging recyclant. This is mirrored by previous research. It was noted by Nemat et al. (2020) that in the literature there is less focus on waste sorting than on other parts of the waste management system, and this term is usually studied in parallel or included with so-called recycling behaviour, e.g., (Ordoñez et al., 2015; Strydom, 2018). There are only a limited number of studies that focus only on waste separation and sorting of packaging waste, e.g., (Langley et al., 2011; Williams et al., 2018).

3.1 Consumption of plastic packaging in partner countries

To assess the capture rate within the waste disposal system, there is a need to know what the potential volume of plastic available for recycling is. The consumption data was compiled within work package T1 and is from deliverable 1.2. (For polymer types see Appendix 1 below)

Table 1: Plastic consumption for packaging in kt in Germany (Conversio Market & Strategy GmbH, 2020), the Netherlands (Snijder & Nusselder, 2019), Belgium (essencia, 2019) and the UK (Valpak, 2020)

Plastic consumption for packaging in kt

	Germany	Netherlands	Belgium	UK	total
LDPE	966	183	212	637	1,998
HDPE	679	81	90	415	1,264
PP	696	86	94	563	1,440
PET	585	136	99	502	1,321
other	295	37	54	174	560
total	3,220	523	549	2,290	6,582

In total, about 6.6 Mt of plastic packaging are put into the market in the four TRANSFORM-CE partner countries every year. With 2 Mt/a, LDPE is the most important polymer for packaging, followed by PP (1,4 Mt/a), PET (1,3 Mt/a) and HDPE (1,3 Mt/a). All other polymers used for packaging add up to 0.6 Mt/a.

For the UK, RECOUP (2020, p. 9) breakdown the statistics into the uses of the plastic rather than by polymer types. The polymer types have been added by this report. From the RECOUP statistics, over 1.532 million tonnes of household plastic packaging are used in the UK each year (average per year) – products sold by retailers and food service providers in plastic packaging to consumers. This broadly consists of (in tonnes):

634,000 of plastic bottles – 332,000 (52%) drinks bottles and 302,000 (48%) non-drinks bottles; (usually PET)
301,000 of plastic pots, tubs and trays, (usually PET, HDPE)
395,000 of plastic film; (usually PP and complex mixtures) and,
202,000 of other plastic packaging such as caps, lids, toothpaste tubes, chocolate/sweet wrappers, egg boxes, blister packs, etc. (made from all types of polymers)

3.2 Capture rate

The capture rate is the amount of plastic entering the recycling system as a proportion of the amount that is put onto the market for consumption. For the EU27+3 as a whole the capture rate for 2019 has been calculated as amount collected 29.5 Mt divided by the amount consumed of 53.6 Mt which is 55% (Plastics Europe, 2020). Accurate values for the capture rates of plastics in general and for packaging in particular, have been hard to get for the partner countries. However, some generalised numbers are available. In Germany, the amount of plastic packaging undergoing a material recycling process, as a proportion of the amount that is put onto the market for consumption, was approximately 58 % in 2019, (verpackungsregister, 2020). For Belgium the data for 2019 was 46 % (ivcie, 2020). In the Netherlands the capture of plastic is via the PMD+ stream, and was calculate do be about 71% (Afvalfonds_Verpakkingen, 2020). The data for collection of plastic packaging in the UK is broken down by WRAP (2022) as follows; bottles 61%, PTT 36%, and films 8% . This gives a UK total capture rate of 41%. The capture rate should not be confused with the recycle rate which is only for recyclant and not the plastic that is landfilled or sent to WfE plants. The throughput rate is another measure which is the ratio between what goes into a MRF, PRF or a repossessing plant, and what comes out, his measure the amount of recyclant that comes out. (The opposite number is the rejection rate which is how much is not recycled see Section 5.4.4 below)

Waste plastics can be slit up into high value, medium value and very low value. The high value plastics are food grade clear and blue PET bottles. When they are part of a source separated collection scheme, they are of very high quality and can be used as direct feedstock for making new bottles. This is what is classified as food grade plastic. Since these are of high value, municipalities all over NWE target these in their collection and sorting systems. The capture rate for PET bottles can vary from 61% in the UK, that does not yet have a deposit return system, to up to 94% for Germany which operates a deposit returns system, of which 90% can be used for bottle-to-bottle manufacturing. Even in a country like the UK, PET bottles are targeted by all municipalities as this is a high value stream.

Medium value waste plastic is HDPE, which is the plastic used in drinks bottle lids and other food packaging. In many parts of NWE PET pots, tubs and trays (PTT) are also classified as of lower economic value and are not collected for recycling. For example, only 81% of municipalities in the UK collect PTT. PTT and HDPE are prone to contamination from foodstuff and are sent to residual waste due to their small size and consumers presuming it is not worth recycling. This is one of the reasons for the new EU rule regarding tethered bottle caps, (European Commission, 2019). Furthermore, due to contamination, instigated by consumers, a large amount of food grade plastic can only be recycled into non-food grade pellets.

The lowest grade plastics are the plastic films that may contain different layers of polymer types and include contaminates like inks and paper labels. At this time across NWE, flexible plastic films have very low economic value and are technically difficult to sort. This type of plastic is not widely collected for recycling but is put into the residual waste stream or is collected (in Germany in yellow bag or bin) and sent to waste to energy facilities. For example, in the UK only 16% of municipalities collect plastic film which results in a capture rate of approximately 5%. It is not known how much of this 5% ends up in EfW facilities or is put into the circular economy. The reason given, by waste management professionals in a TRANSFORM-CE workshop for not collecting low grade plastics was because it is uneconomic. This concurred with a recent survey carried out by RECOUPE (2019), which identified the need for commercially viable market as the main reason why low-grade plastics like films are not being collected for recycling. The TRANSFORM-CE project has a goal to change this and has identified that IEM can upcycle this lowest value plastic waste into durable and long-lasting products. The intention of this project is to prove this concept and to show that there is a market for plastic films to be collected sorted and upcycled instead of being put into the residual waste and sent to EfW facilities.

3.2.1 Sorting recyclables at source

Consumers are responsible for performing primary waste separation at home, including identifying and distinguishing plastic recyclables from the rest of the waste, properly preparing them for collection, sorting them, and afterwards putting them into the appropriate waste bins. In some places there is also the opportunity to take them to the nearby municipal collection centre. Hence, sorting of waste by consumers contributes to the entire recycling process being more efficiency and cost-effective (Miranda Carreño & Blanco Suárez, 2010) than separation and sorting at a material recovery facility, where all of the waste is initially mixed, and the quality and quantity of the sorted fractions are low (Rousta & Dahlén, 2015). Therefore, separating and sorting the different waste fractions is essential for effective recycling, and accordingly, is viewed in some countries, as a respected responsibility of households towards a sustainable waste management system (Bernstad, 2014; Zain et al., 2012). As explained above, the capture rate will depend on the actions of consumers and their willingness to recycle properly. Getting the correct plastic into the correct bin or bag is the first step for a successful recycling system.

3.3 Drivers of consumer attitudes to recycling

The optimum outcome would be if householders recycled 100% of their waste without making any mistakes. However, this is not the case. To understand why this is happening there is a need to understand householders' attitudes to recycling. This section looks at data gathered from the literature, the next section looks at data gathered via a consumer survey.

3.3.1 Personal drivers to recycle

Nainggolan et al. (2019) identified five motivating factors from the literature. These are 1) the extent to which the respondent believes that the scheme is meaningful, i.e. reduces important negative environmental impacts; 2) the extent to which the respondent believes that the recycling is effective, i.e. that the recycled material will re-enter into new product cycles; 3) the effort required to sort; 4) any additional nuisance of using the various sorting schemes; 5) the importance of existing facilities and other factors including habits, self-image and social influence for the motivations to sort. Therefore, personal knowledge and beliefs about the need to recycle and socioeconomic factors are important drivers of consumers attitudes to recycling.

The 'feel good factor' or the 'feel guilty' factor have been established as key predictors of pro-environmental behaviour (Gatersleben & Steg, 2012). The more people anticipate positive emotions after engaging in a specific behaviour, such as recycling, the more likely they are to re-engage in this behaviour (Taufik et al., 2016). Similarly, anticipated negative emotions may inhibit the recycling behaviour (Carrus et al., 2008; Elgaaied, 2012). Hence, householders are more willing to recycle when their recycling behaviour elicits more positive feelings than negative feelings. Overall, the more positive one's attitudes are towards recycling, the more he or she is likely to engage in this behaviour (Geiger et al., 2019; Oskamp et al., 1991).

Nemat et al. (2020, p. 2) found that although consumers want to sort, they can neglect to do so due to lack of time or the need for excessive effort, i.e., perceived inconvenience (Rousta & Ekström, 2013), and uncertainty (Henriksson et al., 2010) . Householders put convenience and ease of decision making high in their decision-making process. Inconvenience associated with sorting soft plastic food packaging arises from the lack of functionality of the packets. The functionality has been identified as , difficulty to empty, clean, fold and separate the packaging, and perceived inconvenience when sorting, is a key factor that leads to miss-sorted plastic waste, as highlighted by Nemat et al (2020). Therefore, easy to empty, easy to clean, easy to reseal, easy to compact/fold, easy to separate, recycling symbols and packaging, are features that can be perceived as providing additional value and convenience (Langley et al., 2011; Wever et al., 2010). Improving these features can support proper recycling and sorting (Plumb et al., 2012; Wikström et al., 2016) and helps towards increasing the capture rate for plastic packaging. The perceived low value of soft plastics arises from their inexpensive feel and low durability, as highlighted by different aspects, such as their form, texture, colour, size, and lack of reusability. From this reason, soft, flat, and small plastic packaging are more likely to be miss-sorted, than other types of packaging.

These behaviours are personal to the consumer, however there are also affects outside themselves that effect their recycling behaviours.

3.3.2 Socioeconomic effects on recycling behaviours

The amount to which an individual is worried about the environment is reflected in their environmental attitudes (Steg et al., 2011). Attitudes depend on the awareness of the consequences, expected costs, and benefits of recycling (Ajzen, 1991). Overall, the more positive one's attitudes towards recycling is, the more he or she is likely to engage in this behaviour (Geiger et al., 2019; Oskamp et al., 1991). In general, the stronger a householder's environmental attitudes are, the more likely he or she will engage in recycling behaviour. Similarly, it has been highlighted that environmental awareness and gender are factors affecting consumers' choices concerning sustainable packaging during product purchase and recycling, (Martinho et al., 2015).

The housing condition, conceptualized as the house type in which a person lives, has been found to affect the feasibility of recycling, which in turn influences the likelihood of recycling (Geiger et al., 2019). More specifically, two crucial factors, related with ownership (i.e., own vs. rental house), and type of house (i.e. single-family house, apartment or detached houses) were highlighted in prior research. Individuals living in a single-family house recycle more than individuals living in a rented apartment (Oskamp et al., 1991). Furthermore, individuals living in single-family house were associated with higher recycling rates than individuals living in apartments (Hage et al., 2009). Similarly, ownership of a recycling bin at home (Robertson & Walkington, 2009) has been shown to increase recycling behaviour. This is why, across NWE, municipalities have brought the recycling to peoples' house by providing them with different dedicated recycling bins or bags, and have instigated dedicated kerbside collection mechanisms just for recyclables.

For those that do not have a dedicated recycling home collection services, availability of recycling facilities near their home (D'Amato et al., 2016), or if they live a short distances to a recycling facility, increases the likelihood that they will recycle (Hage et al., 2009). These factors are related to 'perceived convenience', and are relevant especially in multi-family houses (Hage et al., 2009), and lead to higher collection rates.

3.4 UK household perspectives on recycling

Information about what consumers of different ages and genders think about recycling, especially packaging plastics, was only found for the UK and came in a report produced by RECOUP (2022), a UK NGO. The data in this subsection comes from this report. The data came from UK consumers who answered the Pledge2Recycle online survey (https://www.pledge2recycle.co.uk/).

3.4.1 confusion

Respondents were confused about what can and cannot be recycled, for example if non-drinks bottles were recyclable, and the following was found.

"*The more **complicated an item of packaging** is the less intuitive it is for citizens to know what to do with the pack. This resulting confusion therefore creates barriers to recycling. Even with the simplest form of plastic packaging, (the drinks bottle), citizens are still unsure how to prepare the bottle and consequently potential recyclate is being lost. Less than half of responses claimed to empty, rinse, and replace the lid before recycling*". (RECOUP, 2022) in general RECOUP found that attitudes remained stagnant over time, with pre-cleaning and preparation of the pack remaining a barrier. The easier it is to recycle the more likely it is that consumers will follow through.

Furthermore, due to these consumer mind frames, there appears that contaminants are being introduced at the kerbside due to respondents putting non-targeted recyclant, such as toothpaste tubes, films, and carrier bags, into plastic recycle bin. Interestingly, 16% of respondents said they recycle toothpaste tubes every time, even though the vast majority of toothpaste tubes are unable to be recycled and therefore should not be placed in a kerbside bin for collection. It is a concern that non-target plastics are being placed in kerbside recycling. (RECOUP, 2022, p. 25)

3.4.2 The age and gender factors – under and over 45 years old

The age and gender of the respondents told a lot about the difference in attitudes towards recycling and about the level of knowledge or confusion about what can and cannot be recycled.

The Pledge2Recycle survey used 4 categories of bottles, (1) drinking, (2) shampoo and conditioner, (3) cleaning products, and (4) sauce, It was found that the respondent group over 45 years were more confident about which categories of plastic bottle were recyclable compared to those 44 years old and younger, (RECOUP, 2022, p. 10). Older respondents were slightly more likely to say they recycle every time, with 96% of 45 and over, compared to 92% of 44 and under. Younger adults (18-24) were more likely than average to say they recycle when it is convenient (9%). The responses indicate that the older age groups (45+) are more likely to try to recycle plastics packaging every time. The younger respondents were more likely to say they never recycle plastic packaging. (RECOUP, 2022, p. 27)

Females were slightly more likely than males to say they recycle every time (96% vs 93%), (RECOUP, 2022, p. 11). The data from the survey showed that for many of the categories, male respondents were less likely than females to recycle.

With regards to drinking bottles, 95% stated that they recycle every time. There was confusion as to what to do with the lid of the bottle, some respondents kept it on the bottle , some recycled it but off the bottle, while some put the lid in general waste. (RECOUP, 2022, p. 14). There was also confusion whether bottles need emptying and rinsing. Recoup explain that across the UK different guidelines are provided. The RECOUP UK Household Plastics Collection Survey 2021 found that "*only 28% of Local Authorities advise to leave lids on bottles, with 18% actually saying to remove lids. Also, only 73% say to empty/rinse bottles before recycling. Many Local Authorities do not provide any guidance at all with 41% providing no instruction on lids, and 27% not instructing residents to empty and rinse*." The problem with lids is that they are small compared to the bottle.

In a MRF they can end up falling through the screens and contaminating the glass waste fraction, falling below the conveyor belt and even possibly clogging up the belt mechanism causing the whole system to be shutdown.

"*As of April 2021, 87% of Local Authorities in the UK collect Pots, Tubs, and Trays (PTT) at kerbside, and responses are heavily influenced by whether respondents are able to place the items in kerbside bins for recycling. In Wales, where 100% of Local Authorities collect PTT at kerbside, a higher level of respondents saying they recycle every time, and much smaller percentages saying they are confused about the item's recyclability. In areas where Local Authorities do not collect at kerbside, we see higher levels of confusion.*", (RECOUP, 2022, p. 15). An interesting finding of the survey was that all age groups recycled about 72% of clean transparent fruit and veg trays. This may imply that they see no difference between those and clean drinks bottles. This is where confusion arises if one municipality recycles these trays and another does not, (RECOUP, 2022, p. 19).

Only 13% of Local Authorities in the UK accept films and flexibles at kerbside as of April 2021, which naturally influences the responses here. Front of store schemes do not seem to be an immediate second choice for those who cannot recycle at kerbside, as the number of respondents choosing this option is relatively low. What is uncertain is where the 16% who recycle every time are taking their material and if indeed this reflects some unintentional contamination kerbside. Male respondents seem to be less aware of opportunities to recycle films and flexibles, as proportionally, they are less likely to say they use local store collection schemes or would recycle if they knew how. Male respondents are more likely to state they never recycle, or they don't because of lack of kerbside collection. (RECOUP, 2022, p. 20).

Just over a third of respondents said they use local store collection schemes to recycle plastic carrier bags. The high proportion of respondents using local store collection schemes could be because they have been offered and established for a lot longer than the wider film schemes, so more respondents are aware of the option to do this. (RECOUP, 2022, p. 21)

Just over a third of respondents said they don't recycle snacks and crisp wrappers, and pet food pouches due to lack of kerbside collection. Uptake of local store collection schemes when it comes to snack and crisp wrappers is only minimal, with respondents more likely to never recycle. However, 9% said they would recycle if they knew how, suggesting education could help to boost uptake. (RECOUP, 2022, p. 23).

What can policy makers do to advance changes that will increase the capture rate for plastic packaging?

3.5 Extraneous intervention strategies to increase the capture rate

Further to the workshop carried out in work package T1, a literature review carried out in work package T1.2.3 identified that a variety of intervention strategies have been highlighted by prior research, for example, Iyer & Kashyap (2007) and Schultz et al. (1995), to apply a wide array of behaviour-change techniques to promote household recycling. These intervention strategies are based on different types of persuasive strategies and can be classified in six distinct types, namely (1) prompts and information, (2) feedback, (3) commitment, (4) behaviour modelling, (5) environmental alterations, and (6) incentives (i.e., rewards and penalties) (Varotto & Spagnolli, 2017). Below is an expansion of these interventions with the recommendations that came out of deliverable T1.2.3.

3.5.1 Providing visual cues and written information

This intervention strategy focuses on providing (factual or persuasive) information on recycling in order to foster recycling behaviour. Such information can be written (Schultz et al., 1995; Varotto & Spagnolli, 2017) or delivered face-to-face, for instance through informative letters, fliers and brochures that promote recycling and explain how and why to commit to recycling actions or a recycling program. In addition, other informational materials such as signs or posters can be placed close to recycling bins in public areas to prompt the correct discarding of recyclable materials and describe the benefits and importance of recycling (Moreland & Melsop, 2014; Schultz, 2011). Lately, such prompts have been facilitated using the Internet (Eberl et al., 2009; Mee, 2005). This intervention mainly focuses on eliminating lack of information, which is recognized as one of the main barriers to participation in recycling programs and quality of recycling (Alexander et al., 2009; Perrin & Barton, 2001). These prior findings lead to the following recommendation:

Recommendation 1: Policy makers and community leaders should invest in prompts and informational campaigns in order to disseminate information that can augment householder's recycling behaviour and improve the quality of the materials recycled.

Knowledge, however, is not sufficient to drive recycling behaviours. Consumers may not understand or may lack the cognitive resources or the motivation to access the information received (Varotto & Spagnolli, 2017), as it may be too ambiguous, or too general or not useful (Refsgaard & Magnussen, 2009). Furthermore, if the recycling services are difficult to use, inappropriate or badly organized, such prompts may not lead to increased recycling behaviour (Pocock et al., 2008). Prompts can lead to changes in recycling behaviour when lack of knowledge is the main barrier to action, or when householders are motivated to recycle but do not know exactly how to do it (Schultz, 2002).

3.5.2 Providing feedback

Providing feedback about municipal targets on recycling, CO_2 emissions, and economics of recycling, will help to change householders recycling behaviours. However, to provide individual feedback about recycling behaviours implies constant monitoring of personal behaviours (Katzev & Mishima, 1992), something that many householders are not comfortable with.

Recommendation 2: Feedback about publicly available recycling information may help to increase the capture rate and the quality of the waste.

3.5.3 Getting commitments from householders

Once a commitment is made in regard to recycling behaviours, people tend to modify their attitudes to be consistent with the committed behaviours. Therefore, commitment involves an automatic tendency to change attitudes (Cialdini et al., 1991; Deng et al., 2022).

Recommendation 3: Householders' recycling behaviour can be improved by the implementation of commitment interventions and campaigns that are coordinated by public bodies.

3.5.4 Social Modelling

This intervention is about using role models in the community. The effectiveness of this type of intervention rests on the fact that people learn through observation of the behaviour of others, by imitating this behaviour especially when it is relevant, easily understandable and permits the individual to reach meaningful and positive outcomes (Varotto & Spagnolli, 2017).

Recommendation 4: Householders' recycling behaviour can be improved by the use of social modelling interventions, potentially implemented through recruiting distinguished community members.

3.5.5 Environmental alterations

The effectiveness of the 'environmental alterations' intervention strategy is based on the fact that households are more likely to recycle if the amount of physical and mental effort required to recycle is minimized (Schultz et al., 1995; Varotto & Spagnolli, 2017). This intervention consists of making recycling more convenient and easier to perform by modifying the physical environment. Therefore, to increase capture rate of plastics, municipalities should provide a more comprehensive and focused waste collection system.

Recommendation 5: Householders' recycling behaviour can be improved by an optimized network of adequately designed recycling facilities (e.g. a special recycling bin for plastic films or soft plastics that are not now recycled by many municipalities).

3.5.6 Keeping the public informed on recycling goals

Informing the public can take place through traditional means (e.g. newspapers, TV), through official web sites or social media, through providing tailored feedback on householders' personal mobile devices or on ambient displays (Froehlich et al., 2010; Paulos & Jenkins, 2006; Reif et al., 2010; Thieme et al., 2012; Yalvaç et al., 2014). Feedback on individual/household performance may improve a recycler's perceived self-efficacy, or his or her belief in one's ability to engage in or improve his/her recycling behaviour (Abrahamse & Steg, 2013). Therefore, the following recommendation is given:

Recommendation 6: Policymakers and local authorities should invest in providing feedback to households, either through traditional or new channels, to foster their recycling behaviour.

The data seems unequivocal that the capture rate for plastic is very low due to socioeconomic effects and to the personal attitudes of consumers. So, what can policy makers do to directly incentivise consumers to increase plastic recycling?

3.6 How can direct reward recognition and penalties influence capture rates?

Previous researchers acknowledged that householders are usually reluctant to join recycling programs because they need to sacrifice time and effort to prepare, sort, store, and transport their old belongings (Li et al., 2021; Ramayah et al., 2012). For this reason, householders often need to be incentivised to commit to recycling behaviours.

The topic of rewards and penalties was discussed in a workshop that was carried out as part of work package T1 where representatives of municipal waste management systems came together. It was a virtual workshop with representatives from all four TRANSFORM-CE partner regions. Below are the outcomes from the discussion.

The use of reward recognition is aimed to increase both the quantity and quality of plastic waste captured. As encapsulated by the UK breakout room, citizens may not be very receptive to the idea of changing their habitual practices if the reward is considered too low. Similarly, the UK government is against the idea of penalising people, so penalties are unlikely to be given out. However, if a plastics tax were to be introduced, it can both help and hinder capture rates in the UK. Initially, it will create opportunities for alternative materials to be used such as biodegradables, but will lead to imports due to not creating enough recycled plastics to meet demand. Likewise, companies may attempt to avoid the plastic tax by using alternative materials, however, these may not necessarily be sustainable or circular. Furthermore, adding to the point of governments being hesitant towards penalties, Dutch politicians are against the idea of tracking bins – known as 'spies in bins'. Technically, it is possible to trace the volume and contents of household bins to issue penalties, but it comes under privacy implications.

Additionally, putting a high price on incineration can promote plastic recovery, increasing plastic capture. Yet, the repercussions of this have not been discussed. The UK group discussed the possibility and viability of implementing deposit return systems, particularly for low-grade plastics as local authorities often are not able to successfully manage them. Yet, again, this is something that needs to be further explored.

3.6.1 Incentives/Rewards

In general, incentives may refer to any kind of benefit received by consumers because of their participation in a recycling process or program (Varotto & Spagnolli, 2017). For instance, gifts, monetary prizes, refund programs, lottery tickets, and discount coupons are incentives towards recycling behaviour. It was found that interventions providing incentives on an individual level seem to be more efficient than those providing awards based on the performance of an entire group (Diamond & Loewy, 1991; Harder & Woodard, 2007; Varotto & Spagnolli, 2017).

Recommendation 7: Householders' recycling behaviour can be improved by financial rewards

Everyone is familiar with a smart meter that gives real-time data on energy usage. The data given by the smart meter incentivises people to change behaviours and provides a visual output against which to measure success. This gives the user feedback and provides a feel-good factor that something good is happening. This is an example of a non-financial incentive to change people's environmental behaver, (Liebe et al., 2018). This type of non-financial incentive has yet to be researched in the recycling context and is therefore recommended for further work.

3.6.2 Penalties

From the discussions at the workshop carried out as part of work package T1, the feedback received was that policy makers are reluctant to introduce penalties as a means to reduce the contamination in the recyclant and reduce the overall amount of residual waste. There are only a handful of studies that provided evidence that an increase in financial penalties increases the probability that householders will participate in the recycling process/program (e.g. (Wang et al., 2020)), while others (e.g. (Shaw & Maynard, 2008)) identified mixed views on penalties for refusing to recycle and mixed effects of penalties on recycling behaviour. In circumstances where the revenue of such penalties would be invested in environmental benefits, householders had a positive view on the implementation of penalties, (Keramitsoglou & Tsagarakis, 2013; Seacat & Boileau, 2018).

Previous research (Price, 2001; Shaw & Maynard, 2008) has highlighted the effectiveness of variable and direct charging through pay-as-you-throw (PAYT) schemes. PAYT is based on the quantity of residual waste collected from each household and delivers financial penalties and rewards through a single mechanism. Householders who reduce residual waste are rewarded by lower charges, whilst those who fail to reduce residual waste face penalties in the form of higher disposal costs. This type of scheme could be classified as a regressive tax, as it can disproportionally affect low-income people more than the affluent. In principle with a PAYT scheme consumers will be less likely to put plastic in the general waste system. However, if the UK is a past example, this scheme could lead to more widespread dumping of waste on private and public land, and more contaminants being hidden in the recycling bins, including a neighbours' bin, to reduce the weight of the general waste they must pay for.

3.6.3 How effective are incentive interventions?

A drawback of some of these incentive intervention strategies is that it requires constant observation of household recycling behaviour (Varotto & Spagnolli, 2017). Furthermore, the cost of such interventions often is greater than the economic benefits of recycling, most importantly, after the termination of a reward/incentive program, recycling often tends to return to baseline levels (Li et al., 2021; Schultz et al., 1995), unless it has been established as a habit. Hence, the termination of the extrinsic reward can sometimes lead to the drop-off of recycling rates to levels similar with those prior to the intervention. It is therefore concluded that these intervention types have been found successful in increasing recycling behaviour for the duration of the intervention itself (Varotto & Spagnolli, 2017). However, the long-lasting effects of these treatments remained largely untested, with obvious adverse implications for authorities and policymakers.

4. Municipal collection mechanisms

The waste management system must be profitable to operate, and even if it is publicly owned and has its goal to stop an ecological disaster, the architectures of the MRFs will still depend on the market to which they are processing materials for. To be profitable it must be able to collect the right types of waste that can be sorted, processed, and sold for remanufacturing into products that consumers want. Therefore, before considering recycling more plastics that are currently not recycled, it is imperative to understand if consumers will be willing to buy products made from recycled plastics.

4.1 The willingness of consumers to buy products or become prosumers

Consumers create push and pull pressures on the recycling system. There is a push pressure on the system for the uptake of increasing volumes of consumer generated SUP waste, and there is a pull mechanism on the plastic recycling system from consumers who want products made from recycled plastic. Both this push and the pull are input pressures that affect policy and investment in the municipal waste system. At this time there is a huge imbalance between the push pressure of increasing volumes of waste generated, and the willingness of consumers to demand or buy products made from recycled plastics.

Table 2below is a list of barriers to the uptake of recycled plastic in new products that was derived from workshops carried out across all four TRANSFORM-CE partner countries. This list was labelled *Cultural Factors*.

Table 2 A list of cultural factors that affect the willingness of consumers to take products that are made from recycled plastic (Table 1 From 'Inventory of barriers and enablers for the uptake of recycled plastic' Work Package T3 deliverable 2.2)

Consumer demand and acceptance
Unwillingness to pay
Difficulty in gaining market share
Lack of customer requests
Limited visual appearance of recycled products
Lack of experience from product designers
Setting unnecessary high standards for products of recycled materials
Resistance to change
Perception of (recycled) plastic
Lack of knowledge, information, and education

While these barriers exist, three enablers were identified through the workshops that will increase consumer demand and acceptance of products made from recycled plastic. The first is a regulatory change that demands the inclusion of recycled materials in new products. For example, in the UK the government target is at least 30% of recycled plastic in net plastic drinks bottles. Followed from this, is an education or marketing campaign to increase awareness about the sustainability of recycled plastics and to show the possibilities of using these plastics in new ways.

The AM market is growing rapidly with small scale producers of products for sale. However, there is a very large potential market where consumers make product for themselves printed at home on their 3D printers. Such consumers are called prosumers. But, the question still remains unclear as to the willingness of users to use recycled 3D objects and eventually to become 'prosumers' in the recycling process (Kreiger et al., 2014; Sanchez et al., 2020, p. 13). Educational courses on distributed recycling are perceived as a means to encourage students to think about the access to the digital manufacturing capabilities and their sustainability-related issues (Jaksic, 2016; Schelly & Pearce, 2019).

There are economic advantages to using recycled printed products, (Sanchez et al., 2020, p. 13). For example, Petersen et al. (2017) proved that the cost to fabricate a Lego block could be reduced from 6 cents per block to about 0.5 of a cent per block. In the toy market, the reduction for final users can range between 75% and 90% under the condition that open-source software design files remain available. For larger products, the use of fused granular fabrication, only proved that large high-value sporting products (e.g., snowshoes), and only in the extreme case of producing only 1 per week, was not economic. The return of investment for all other capacity factors ranged from 10 to 240% without including labour (Byard et al., 2019). This means that making replacement parts using AM manufacturing can be economical.

"Global sustainability trends and increasing consumer awareness on plastic waste is a cultural driver. The main rationale for vehicle manufacturers sustainability strategy, including using recycled plastic, is consumer awareness". (Baldassarre et al., 2022, p. 40)

Therefore to even out the balance between consumer push and pull it is necessary to investigate the willingness of consumers to 1) accept AM printed plastic goods, 2) take up the use of recycled filament, and 3) the potential of the majority of consumers to become producers, (Kreiger et al., 2014). The same should be true for the willingness of consumers to want to buy IEM products made from recycled plastic.

4.2 Public authorities' attitudes to plastics collection and sorting mechanisms

In May 2022, Work Package T1 organised an international online workshop, at which feedback was received from decision makers from local waste management authorities in all four project regions.

In general, the importance of creating a stable offtake market for recycled materials, was highlighted. The German breakout group stressed that capturing large volumes of plastics in recycling centres is highly dependent on the economic marketability of recyclates. Importantly, by creating a demand for plastics in the market, particularly low grades, it can incentivise better collection and separation, providing a better service without raising municipality and citizen costs. Furthermore, three out of four breakout rooms spoke on transitioning away from incineration towards practices higher up in the value chain. For instance, the Belgium breakout room cited “pricing incineration at a disadvantage to promote recovery”, whilst the UK group declared that the cost of incineration can be used as “an incentive for finding other options”. Moreover, the Dutch group revealed that facilities in The Netherlands are beginning to ban the incineration of recyclable waste to give rise to more circular ways of disposal.

Crucially, citizens must improve their awareness of material separation as contamination is a big problem. Improving the quality of plastic waste from residential waste will lead to a reduction in rejected plastic which ends up in residual waste after sorting. The Dutch breakout group highlighted that to improve the quality of plastic waste, “better social control at individual level” is critical. Authorities have been tackling this problem by offering direct feedback to local households on what should and should not be put in plastic waste containers. Likewise, authorities in Germany believe awareness education is crucial to improve plastic waste capture. Campaigns and educational training have been provided to residents to demonstrate “what belongs in the yellow bag”. However, in contrast, the UK group voiced that “local authorities are limited in terms of their agency to make change happen”.

Furthermore, the UK breakout group spoke about some of the current limitations that have impeded plastic waste capture. Firstly, better data is required to provide a clearer picture of commercial waste as this waste stream is easier to collect and sort than household waste, indicating it has a larger capture potential. The government have tried to fund commercial waste processing, but it is currently shelved. However, zoning systems are currently of interest in parts of the UK to overcome this challenge. Zoning systems have proven to double diversion rates of recyclables, thus, helping to improve the efficiency of recycling services. This method of waste collection should be progressed in all European regions, yet more discussions are needed.

4.3 Existing collection mechanisms in each region

Across the four countries within this project there are many variations in the collection systems for household waste. For example, there are over 30 materially different variations of collection systems currently practised in the UK, (SUEZ, 2021, p. 16). However, only the three general waste collection systems, which are, (1) source separated, (2) multi-mingled stream, and (3) fully mingled, are discussed here. Where is the waste collected from? How is it presented for collection? And pre-collection sorting, will be discussed.

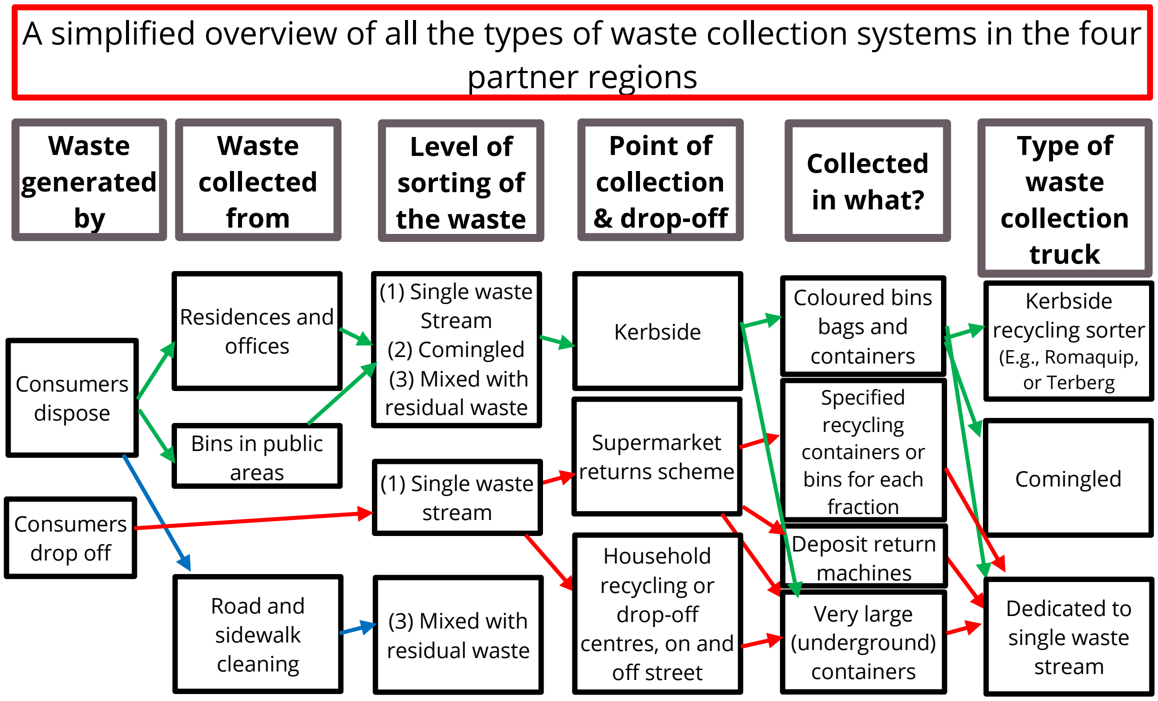

Figure 4 collection mechanisms

4.3.1 Collection points

The TRANSFORM-CE project is looking at single use plastics that can be upcycled from municipal plastic waste. In general, there are three collection points for municipal waste, (1) at the kerbside, (2) at retail outlets and (3) household waste recycling sites or what is known as drop off centres. However, there are non-municipal waste collection routes, they include company takebacks, and private waste management companies. The non-municipal waste collection routes are out of the scope of this report. Across the four regions of this report, different collection mechanisms are used to collect the different plastic waste fractions at each collection point.

4.3.2 Kerbside collections

Kerbside collection can be either doorstep collections at private residents, large multiple occupancy buildings, public buildings or from public waste bins found on street corners or in parks etc. Depending on the number of bins and bags that make up the waste collection system, and depending on the recycling capabilities of the municipality, there will be different levels of separation of the waste. While there may be many different collection mechanisms (SUEZ, 2021), only the three most prevalent are discussed here. In most places within the four regions of this project the waste is separated into the different bins and bags by the consumer, this is known as 'source separated collections'. The first type is when the waste is sorted into single streams for example, there may be separate bins or bags for paper and plastics, but occasionally they are sorted into simple combined streams like metals and glass together. The second is designated multi-mingled or co-mingled stream collections (SUEZ, 2021). In this collection method the consumer separates the recycling streams into a number of combined streams. For example, in

Manchester UK, there will be one bin for paper and one for all the other recyclables that are mixed together, this includes glass, plastic and metals. Or as in Wallonia in Belgium where they mix 10 types of plastic together with metal and drinks cartons in a P+MC collection.

The third type of collection of recycling waste, is when everything is mixed together with general waste and is all sorted at the MBT or a MRF. This third type of collection system is becoming more obsolete as municipal waste management companies and policy makers have realised that this system produces the most contaminated waste streams, where very little can be salvaged for conventional type recycling. It should be noted that in Germany, where landfill has been banned since 2015, all residual waste is sent for sorting at a MBT where the plastic fraction is sorted out and sent to EfW facilities.

An example of such a system was shown as part of the data gathering carried out by work package T1 from data about the Almere Municipality in the Netherlands. It was noted that while Municipality 3 collected almost five times the waste per annum than Municipality 2, it had a 90% contamination rate and was only able to send 6% of plastics to high quality recycling. The reason for this was the two municipalities used different collection methods. Municipality 3 used a collection system that did not separate the plastics from the general waste (the third option above) and Municipality 2 collected the plastics separately from the general waste (second option above). This data shows that by having pre-sorted plastic waste presented for collection at the kerbside, contamination can be reduced to a minimum.

4.3.3 Collections at retail shops

In the UK, many of the large supermarket chains offer a plastic bag return scheme. For example in the UK, under the 4Rs strategy, Tesco are able to recover over 80% of the soft plastic returned to it by its customers with the remaining 20%, sent for energy recovery, (Tesco, 2022). What needs to be researched is, what is the capture rate across the UK for plastic bags and thin flexible films? The counter argument to only using supermarket return schemes for collecting flexible plastics is found in the RECOUP (2022) survey, which identified that these schemes are not readily used by consumers in the UK.

In two of the partner countries, Germany and the Netherlands, a deposit returns scheme for PET drinking bottles is in operation. These schemes have proved to be very successful in collecting high grade plastic for bottle-to-bottle manufacturing. In the Netherlands, since the nineteen eighties a deposit return system has been in place for plastic bottles of 1 litre or more (about 700 million bottles per year). There is also a deposit system on beer crates and beer bottles (about 3 billion bottles per year). These products can be handed in at most supermarkets. More than 95% of products with a deposit system are returned in the Netherlands. The plastic bottles are recycled, and the beer crates and beer bottles are reused. In July 2021, a deposit return system was introduced for small plastic bottles (smaller than 1 litre). In addition, there will also be a deposit on cans in 2022 if industry fails to reduce the number of cans in litter by 70 percent

Figure 5 Return Station at supermarket Jumbo in the Netherlands

For Germany, where a deposit returns scheme is in operation, about 94 % of the plastic is recycled. 34 % of the recycled PET is used for producing new PET bottles, although more than 90 % of all recycled bottles are suitable for bottle-to-bottle recycling (Gesellschaft für Verpackungsmarktforschung mbH, 2008). The British government have finally, after many years, published their strategy for such a system for 2023 (Gov.UK, 2022). For the other countries in the UK a deposit return scheme is a devolved government issue, and each country is looking into future schemes. There is currently no deposit return system in place in Belgium.

4.3.4 Collection at municipal household waste recycling site

Currently, all the four partner countries operate some level of municipal waste drop-off sites. At these sites there is the ability to have many multiples of different containers compared to what is available at the kerbside. For example in the Netherlands national government and municipalities have Introduced recycling centres with minimal of 20 types of waste that can be separated, (Mul, 2020).

In Germany almost, each public waste management authority operates one or more waste recycling centres. But it is not common practice to collect plastic at these sites. Since it is apparently not economically viable, there are only individual cases where non-packaging plastics can be handed in. However, many recycling centres accept packaging waste on behalf of the system operators. This is then the same path as the kerbside collection of the yellow bag or yellow bin.

In the UK, household recycling centres are no different than the normal kerbside collections, and they do not accept soft plastics, which must be put into the residual waste bin. However, they do accept hard plastics, (R4GM, 2022).

4.3.5 Collection bins in partner countries where sorting takes place before collection

As has been explained in the first paper of this series LT1.1, there is a lack of harmonisation across the partner countries of the colours for the collection bins and bags, and what can and can't be recycled in any designated bin. However, this is also true within each country. For example, in Greater Manchester each local authority has a different colour scheme. Below is a sample of bins and bags used in the partner countries.

Germany

Figure 6 The recycle bins and bags used in Germany

The following fractions should be collected in these waste flows:

Residual waste: Supposed to be only waste fractions that are not collected separately in another waste flow, such as hygiene products, in reality also contains false throws of plastic, paper and organic waste

Organic waste: Supposed to be food and kitchen wastes, small quantities of greenery and animal wastes, non-contaminated wood, in reality also contains false throws of plastic and paper

Packaging waste: Packaging waste made of plastic, metals and composite materials (often collected by municipal waste management but not under their responsibility)

Deposit return: Glass and plastic bottles (mainly PET)

C&I waste: Depends on the specifications of the respective company

In addition, paper and cardboard are collected in a blue bin or via depot containers on the street. (Note: This was not analysed in WP T1 because it does not contain plastics.)

Brussels, Belgium

For the most recent classification in Wallonia Belgium for the sorting of the so-called P+MC collected waste (household recyclable packaging waste including extended range of plastics 'P+', metals 'M' and cartons for beverage 'C') includes 14 categories, 10 of which being for plastics. Those are listed as follows (source: calls for tenders for sorting facilities): 1. Aluminium – 2. Steel – 3. Cartons for beverage – 4. PET H: uncoloured bottles – 5. PET B: blue bottles – 6. PET C: coloured bottles – 7. PET T: formed PET packaging (trays) – 8. HDPE bottles and other packages – 9. PP bottles and other packages – 10. PS – 11. PE films (including P+MC collecting bags) – 12. Other plastic films – 13. MPO: mixed plastics with high rigid polyolefins content – 14. Residue, (Talon, 2020). In Brussels bags are used, however, in other parts of Belgium there is a mix of bins and bags.

General Waste (white)	Plastics, metals (blue)	Paper (yellow)	Organic matter (green)
			

Figure 7 The recycle bins and bags used in Brussels Belgium

Waste glass cannot be placed in either of these bags. Consumers have to put their empty bottles in the white and coloured glass containers.

<u>The Hague, the Netherlands</u>

General Waste (black lid)	Plastic packaging tin and drinks cartons (orange lid)	Paper (Blue lid)	Organic matter (Green lid)
			

Figure 8 The recycle bins and bags used in the Hague the Netherlands

The most commonly used combinations of collection bins in the Netherlands are:

- Four bins
- Three bins for organic, packaging and paper waste + underground container for residual waste
- Three bins for residual, organic and paper waste + bag for packaging waste

<u>Bury Council, Manchester, UK</u>

General Waste (black)	Plastic, glass, aluminium (blue)	Paper, carton, Tetra packs (green)	Organic matter (Brown)
			

Figure 9 The recycle bins used in Bury UK

While Bury Council use these colours, the City Councils of Salford and Manchester use different colours. This can be confusing for consumers who live in the Greater Manchester area and move to a different council in the same city where the colour and the list of recyclables will be different.

4.4 Collecting low value thin films for the IEM industry

One of the goals of the TRANSFORM-CE project is to demonstrate that thin films, that are currently not being recycled in any meaningful volumes, can be upcycled into long lasting products that are manufactured using IEM technology. The question is why are they not being collected now and what will have to be in place as a future collection mechanism? As stated above in Germany thin films are included in packaging waste and are normally sorted out for EfW at the MRF if they could not identify as a single Polymer. Similar in the Netherlands they are collected in the PMD+ bags and in Belgium in the PMC+ bags. However, the only detailed data found for thin film plastics was from the UK centric repots.

See Section 5.2 below where the sorting of plastic films out of residual waste is discussed, and Section 5.4.2 where a processing plant for plastic film is discussed.

As of April 2021, 100% of Local Authorities in the UK collect plastic bottles for recycling at kerbside, 87% collect Pots, Tubs and Trays, but only 13% collect Film, (RECOUP, 2022, p. 9). Similarly SUEZ (2021, p. 9) found that currently only 10-17% of UK local authorities collect some form of plastic film or flexible packaging. They also found that the vast majority of flexible plastic packaging from both households and businesses currently ends up in the residual waste stream that is sent for energy recovery or to landfill. SUEZ estimate that the average household's consumption per week of flexible plastic is 292 g, of which in the initial stages of a new waste flexible plastics collection scheme, only 56% will be collected. This equates to 164 g of flexible plastic packaging will be collected per household per week. There are approximately 27.8 million households in the UK (ONS, 2021), therefore the amount of flexible plastic that could be available in the UK at a capture rate of 54% will be approximately 4.5 Mt per year, with potential to go up to 8.1 Mt at 100% capture rate.

There are several practical barriers which prevent film being compatible with many existing UK collection and MRF systems. For example, plastic bags are in essence large sized plastic films and can clog up MRF equipment. This can cause a shutdown of the plant and pose a hazard to workers who must manually remove the plastic (Waste managment, 2022). See Figure 10 below

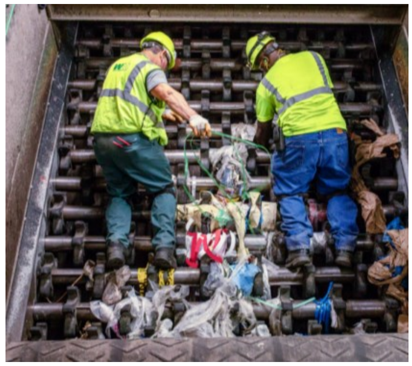

Figure 10 Workers removing thin plastics from a clogged disk sorting machine

Flexible plastics in the form of thin films can contaminate established plastic bottle bales and paper lines. Thin film plastic packaging waste presents itself to the optical sorting machines as either two-dimensional or three dimensional. Because of this, fibre-based products (e.g., paper card and cloth) will be sorted together with the plastic and end up contaminating the plastic. By its design, flexible packaging often presents as small in scale and light in weight, and as such some of the materials collected might be lost in sorting centres that sort by size or operate conveyor belts at speed. If the plastic is wet or has food on it, it will contaminate the fibre based products, e.g., paper and cardboard. Therefore, it is recommended that thin films and flexible plastics should be collected in a separate collection bin or bag (SUEZ, 2021, p. 15). As part of the kerbside collection system, SUEZ have experience in Europe handling thin films and flexible plastic, however the MRFs that can handle these are few. Therefore, there will be a need to reconfigure existing MRFs to handle this waste fraction.

With a complex decision-making process undertaken by consumers in deciding where to place the various types of plastic film for recycling, operational sorting issues in MRFs and lack of end market value, it is unlikely more collections of plastic films will be added without significant financial investment or incentivisation. The only bespoke UK facility to recycle post-consumer films and bags, PlasRecycle, went into administration in 2016. It was designed to accepted 20,000 tonnes per annum with a plastic granulate output that can be used to manufacture items like new bags and damp-proof membranes. RECOUP (2020, p. 24) are aware about small quantities of plastic film that are being reprocessed with commercial material, but there is not a consistent outlet for this plastic format even in nominal quantities.

This is where this project finds its niche. Plastic films of all kinds are the perfect feedstock for use in IEM manufacturing. TRANSFORM-CE is about closing the circle in the circular economic model. IEM manufacture stops plastic films from taking the linear path to being burnt or into landfill and upcycles them. This technology can be the catalyst to show that there is a market for the thin films, therefore there is a reason to put resources into changing the collection, sorting and treatment of these type of plastics throughout the waste management system.

5. Sorting mechanisms for plastic waste

5.1 Pre-sorting at kerbside

As explained in Section 3 above, consumers start the sorting process in the home or office and pre-sort the waste into designated bins and/or bags. In some municipalities a second stage pre-sort takes place at the kerbside which is carried out by the waste truck operators for example the Romaquip or Terberg trucks. These are special trucks with many more compartments than are available to the consumer. See Figure 11 below which is a Romaquip truck that has seven different waste bins for nine different waste fractions.

Figure 11 A specialist Romaquip kerb-sort waste truck for second stage kerbside pre-sorting (https://www.romaquip.com/kerb-sort)

This report would recognise that the more pre-sorting that is carried out, the less contaminants enter the recycling system and recommends that as much as possible pre-sorting should take place. Therefore, it recommends a widespread rollout of kerbside pre-sort trucks. The standard Romaquip 5m truck has collection volume of 37.2 m^3 (Romaquip, 2022), whereas the standard 26T RCV is one third smaller at 21 m^3 (email from truck rental company). Given the smaller weight (12 tonnes) of the 5 meter Romaquip compared to the 26 tonne split back RCV (SUEZ, 2021, p. 17), it is presumed that the Romaquip uses less fuel than the conventional split back RCV, and therefore adds a reduction of carbon footprint of waste collection if smaller kerbside pre-sort trucks are used.

5.2 Municipal sorting mechanisms

Sorting is the process of taking the delivered, collected materials and separating them into waste fraction. The sorting process will depend on the collection process and the type and size of the facility. Following the collection process waste will traverse several waste management facilities before it is turned into the final raw material suitable for making a new product. Across the four partner regions within this project there are four basic types of facilities that plastic could go through. The first stage is a materials recovery facility (MRF) if the waste is source-separated material. This means that the waste comes from one type of collection bin, for example the PMD+ in the Netherlands, or PMC+ in Belgium. However, if the waste is not source-separated but comes from the residual waste, which is all mixed together, it may end up in a mechanical and biological treatment (MBT) plant. In response to the amended European Union landfill directive (Commision, 2015), new MBT plants have been installed all over Europe. These plants take in mixed municipal solid residual waste, (in the UK from the black bin plus organic waste) and are able to produce a feedstock for a reprocessing plant equal to that which comes out of a MRF whose input is pre-sorted plastics, (Feil et al., 2017). In conventional MBTs the plastics would be burnt to produce energy from which electricity is generated, (as is usual in Germany). However, now MBTs have been upgraded to recycle plastics. An example sorting process given by Jansen et al., (2013) in Figure 8, is for the Attero MBT plant in Wijster in the Netherlands. See Section 5.4.2 for a description of the Attero MBT.

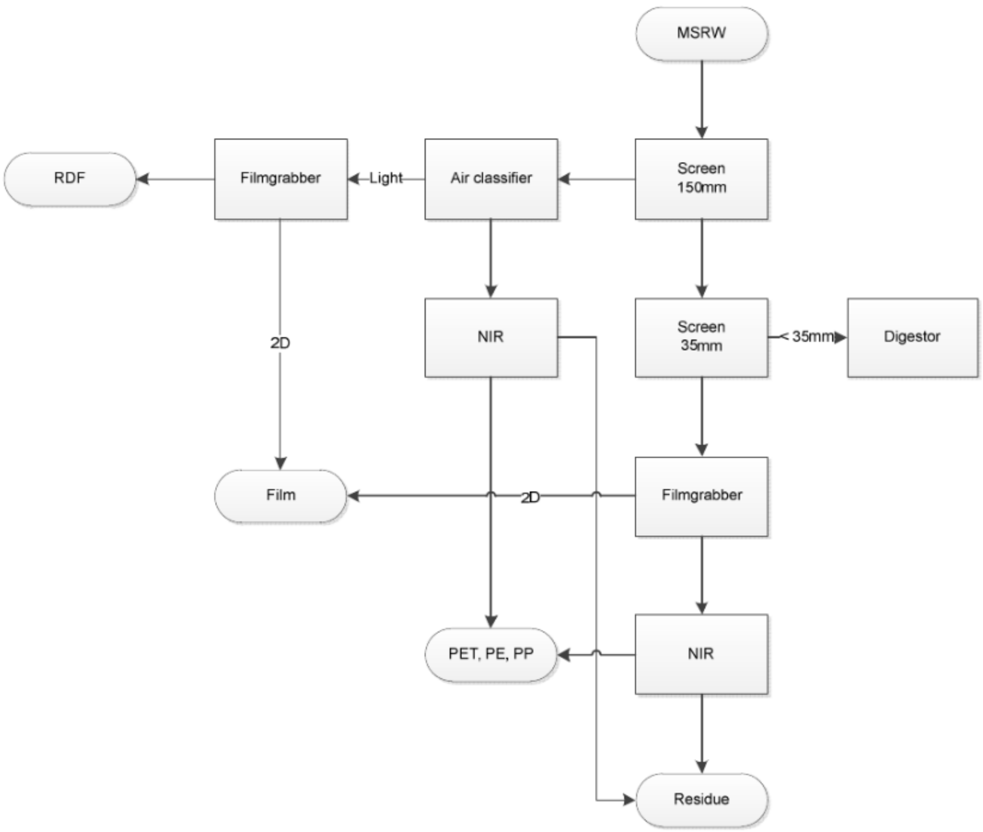

Figure 6 Flowchart of the plant in Wijster

Figure 12 Flowchart of the Attero MBT plant in Wijster in the Netherlands (Jansen et al., 2013)

The output from both the MBTs and MRFs is the first stage, and usually provided segregated bales of mixed or 80% to 90% single type plastic. The bales of plastic then go to a plastic recovery facility (PRF) where they are turned into single polymer outputs ready for reprocessing. The fourth stage is the reprocessing, which could take place at a plastics reprocessing plant (PRP) that may or may not be part of a PRF. At the reprocessing plant, the single polymer recyclant is processed into small plastic pellets that are used my manufacturers to make new plastic products. For AM, the plastic needs to go through this whole process as the outputted pellets must be of very high quality to be used in making durable products using AM methods. However, the advantage of IEM production is that it can use contaminated low-grade plastics, which do not need to go through many of the sorting and processing stages.

These four facilities can be four separate plants at different sites or even different countries, or depending on the size of the plants, a facility may contain two or three of the plants combined on one site. It is therefore difficult to give a details picture of a 'typical' facility in the four countries within this project. Therefore, this report will just breakdown the processes that plastic goes through from when it enters each facility until it leaves. It is presumed that the process has the three stages MRF or MBT, then PRF, and then reprocessing. 21 individual possible processes have been identified and are shown in Figure 12 above. It should be noted that some will be found in older facilities while others are now coming into more widespread usage. For example, only some facilities will employ artificial intelligence robots, use mid-range infra-red (MIR) for black plastic sorting, or use magnetic density separation technology.

In a conventional MRF thin film plastics like shopping or dustbin bags clog up the rotating disks of the sorting screens, see Figure 10 above, and are therefore manually removed as one of the first processes. However, in a MRF that first uses a trommel to sieve out the small fractions waste, a secondary air classifier may be used to sort and divert this type of thin film plastic.

Type of plant	Materials Recovery Facility (MRF)	Mechanical & Biological Treatment (MBT)	Plastic Recovery Facility (PRF)	Plastic Reprocessing Plant (PRP)
Processes				
Front loader/feeder	✓	✓	✓	✓
Bag opener	?	✓		
Manual sorting	✓	✓	✓	✓
Trommel screen	✓	✓	?	
Rotating shaft and disc screening	✓	✓		
Ballistic sorter	✓	✓	?	
Rotating crusher	✓	✓		
shredder	✓	✓	✓	
Magnetic separator	✓	✓	✓	
Eddy current separator	✓	✓	✓	
Near infrared sorter	✓	✓	?	
MIR or Deep LAiser sorter for Black plastic	?	?	✓	
Artificial Intelligent (AI) robots	?	?	?	
Baler	✓	✓		
In Tote bag			✓	
Colour sorting			✓	?
Water Separator			✓	?
Cold washing and hot with chemicals			✓	?
Magnetic Density separation			?	
Melting extrusion				✓
Pelletisation				✓

KEY
✓ **Usually found at plant**
? **Possibly found at plant**

Figure 13 A simplified overview of the different sorting mechanisms plastic waste could go through to become raw materials for AM and IEM

5.3 Sorting mechanisms in typical MRF

The design of a MRF will depend on the intended type of outputs. For example, a MRF that is attached to a paper recycling plant will typically receive either pre-sorted paper bales or the kerbside collection of the paper and cardboard bin. Unfortunately, consumers deposit many other types of materials in the wrong bin as misthrow. The paper sorting machines will typically remove the large carton first and then the paper. The plastics in the waste should not be there and therefore are sorted out in a later process.

Mechanical recycling is the primary process used in MRFs. Below in Figure 14, is a typical MRF that SUEZ use to sort the mixed recyclant into their constituent waste fractions.

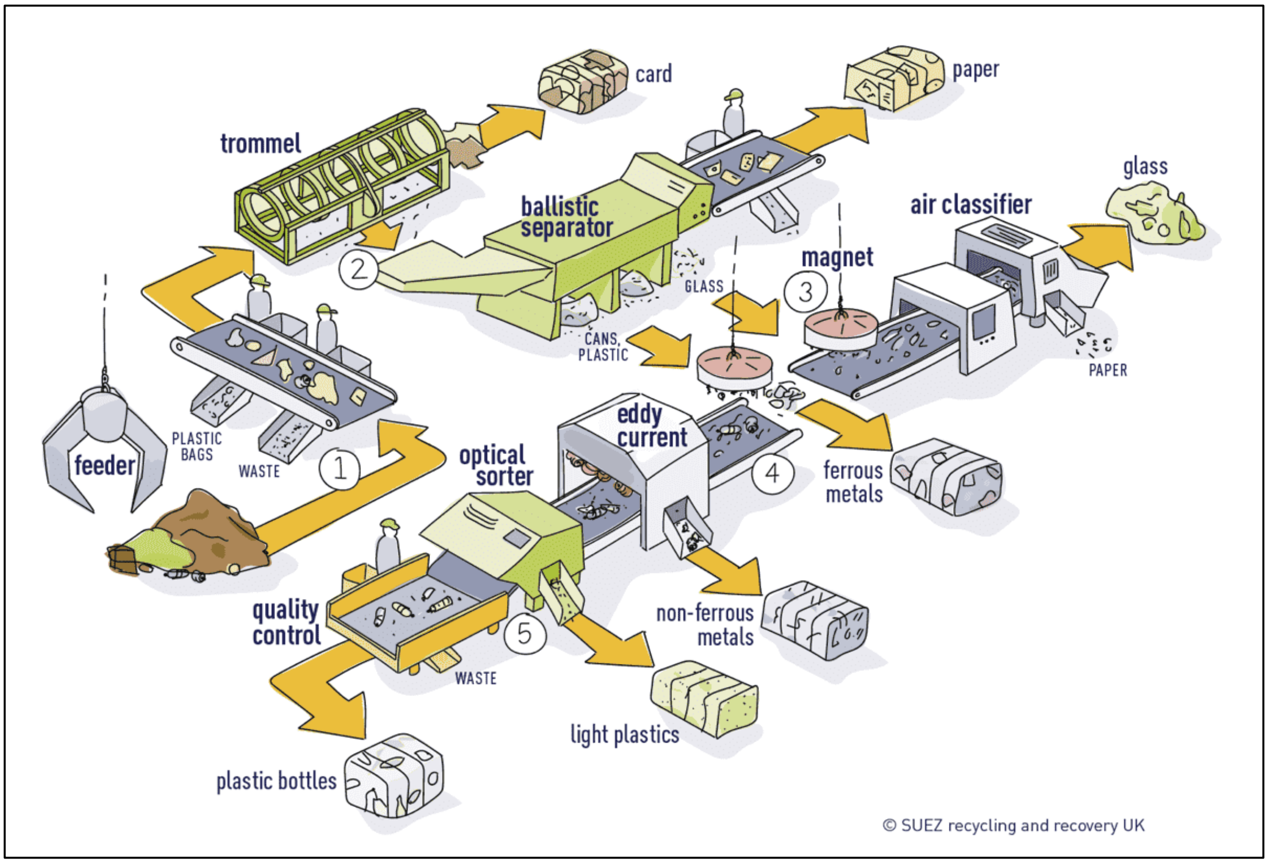

Figure 14 A typical municipal metatrails recycling facility used for pre-sorted mixed recyclant

Figure 14 shows the different sorting stages that the waste goes through at the MRF. It is noted that this plant is of the older design and does not incorporate artificial intelligence systems, or magnetic density separation. There are three plastic fractions outputted from this MRF. The first is the hand-picked plastic bags that are sorted out in stage 1 of the process. The other two are light plastics and plastic bottles at stage 5. As at this time many municipalities do not accept thin film plastic for recycling, the volume of plastic sorted out in stage 1 will be much small that that in stage

5. This fraction should be available to IEM manufacturing. However, as the volume is not known, the feasibility of relying on this handpicked stage 1 plastic fraction as a constant supply for IEM, needs more research. These bales of plastic are ready to be shipped to a plastics processing facility for further sorting into more plastic fractions.

5.4 Sorting mechanisms in typical PRF

The plastic recovery facility (PRF) is the next stage of sorting the plastic. Depending on the size and scale of the MRF, part or full plastic processing may take place on-site. Otherwise, it will be shipped to a dedicated PPF. At the PPF the plastic is sorted by plastics format and colour, which are typically:

- Clear and light blue PET bottles.
- Natural HDPE (High-Density Polyethylene) (milk) bottles.
- Grade A Mixed Plastic Bottles (includes more clear PET and natural HDPE).
- Grade B Mixed Plastic Bottles (includes more coloured PET and HDPE).
- Coloured HDPE and PET.
- Mixed non-bottle plastic packaging – typically targeting PP and HDPE content.

(RECOUP, 2020, p. 18)

5.4.1 Making clean plastic pellets from flakes for AM

The first stage in the plastic processing, is to make clean single polymer plastic flakes. These may have already gone through an optical colour sorter or will go through the optical colour sorter after they have been cleaned. Figure 15 below shows the typical processes the baled PET will go through in a PPF, (this example is from Indonesia). It is worthy to note that there is a need in stage 2 to remove unwanted non-PET plastics and metal from the recyclant that have made it through the sorting stages at the MRF. From the flakes, the recycled PET is further processed into pellets. The details for this process are discussed in the next report in this series.

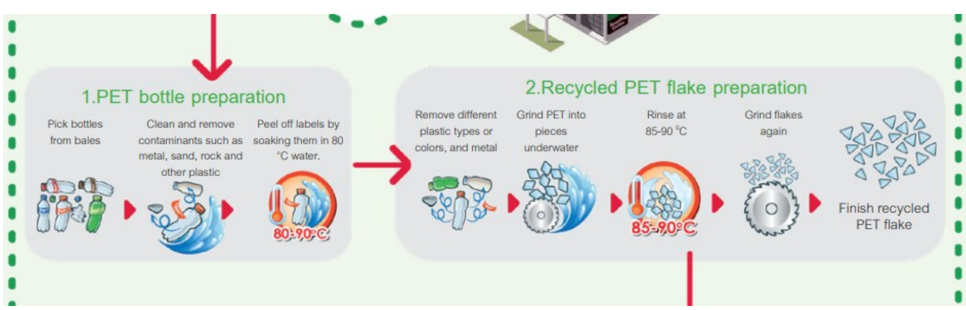

Figure 15 (Kasetsart University & Indorama Venture PCL, 2022)

5.4.2 Modern thin film processing plant

It should be noted that the RECOUP (2020, p. 18) report does not mention plastic films, as the UK currently does not collect and sort thin flexible plastics. However, in Europe they do collect and can sort flexible plastic packaging waste (SUEZ, 2021) in some MBTs and MRFs. Following on from sorting the plastic is shredded washed, heated up and pelletised. The process at Attero's thin film polymer recycling plant in Wijster the Netherlands (Attero, 2022) is shown in Figure 16 below. It should be noted that the Attero process for plastic films is almost the same as the PET process carried out in Indonesia. Further discussion about the treatment and resources used in the processes described, will be presented in the third report of this series. A sorting stage is always needed to maintain a very high purity to the outputted plastic pellets/granules.

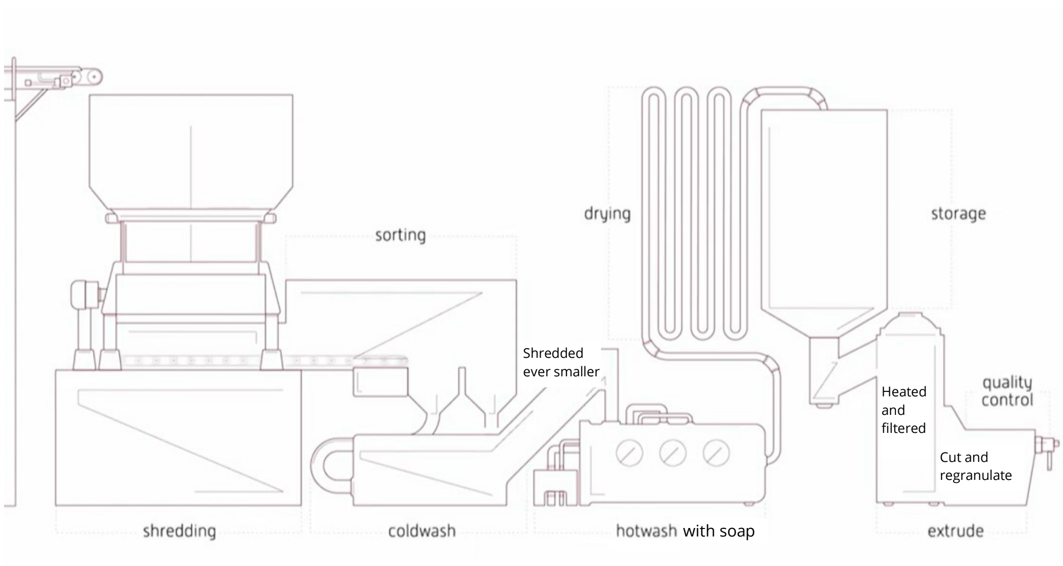

Figure 16 Attero's thin film polymer recycling plant in Wijster the Netherlands (from company video https://bit.ly/3UrGLjl)

5.4.3 UK cost of sorted plastic

The costs incurred for sorted plastic will vary depending on how the materials are collected, whether the materials are mingled during collection and, if they are a co-mingled collection, or on the combination of materials that are collected together. Costs of sorting also vary by the volume of collected materials that can be processed per hour. For materials collected in a source-separated manner, the costs of sorting are relatively low, but the costs of collection are higher. With co-mingled collection systems, the costs of collection are relatively low, but the cost of sorting is higher. In Europe SUEZ has the capabilities to sort flexible packaging and plastic films into plastic streams suitable for further reprocessing. It was difficult to find data for other European countries therefore only the data for the UK is presented here. Cost estimates for sorting vary between 14 pence and 45 pence per kg depending on the conditions stated above and applies for waste collected from both households and businesses. (SUEZ, 2021, p. 20).

5.4.4 Source separation and rejection rate at MRFs

Figure 17 below shows the rate of inputs and outputs at several MRFs, that researchers working on the T1 work package within the TRANCEFORM-CE project were able to gather.

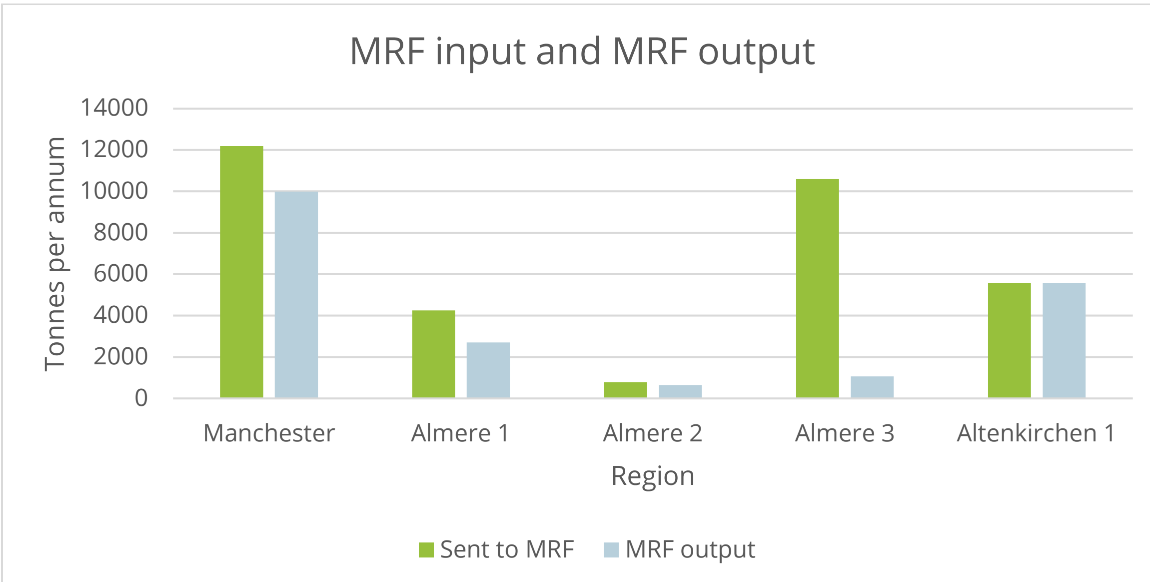

Figure 17. A graph showcasing the total tonnage of waste sent to the MRF and the subsequent output. (WP T1 D2.1)

It can be concluded from this data, that the waste from Almere 3, that was not sorted by consumers before depositing it in the waste bin, had the highest rejection rate. Furthermore, the data suggests that the better sorted and less contaminated the plastic waste was when entering the MRF, the higher the recycling rate and therefore less waste was rejected. While this data leads to the recommendation for source sorting for plastic waste, however, some European municipalities are moving to the co-mingled collection option. Their rational is that they have modern sophisticated equipment that has the ability to sort the co-mingles waste. More work needs to be carried out to ascertain what the rejection rate is for their new co-mingled collection system.

6. Recommendations and future work

6.1.1 More pre-sorting at source

This report would recognise that the more pre-sorting that is carried out, the less contaminants enter the recycling system and recommends that as much as possible pre-sorting should take place.

However, some European municipalities are moving to the co-mingled collection option. Their rational is that they have modern sophisticated equipment that has the ability to sort the co-mingles waste. More work needs to be carried out to ascertain what the rejection rate is for their new co-mingled collection system, compared to source sorted waste.

6.1.2 Collecting flexible plastic films

The techniques and costs developed, show that there is no reason why the UK should not be able to follow practice in some EU countries and collect flexible plastic packaging for recycling. (SUEZ p 23). RECOUP (2022) found that if an item, like plastic carrier bags, was not recyclable at the kerbside consumers of all ages were less likely to recycle in a local store collection scheme. Therefore, it is recommended that, for flexible plastic and films to become an item of waste collected for recycling, it has to be part of the kerbside collection system.

It is also recommended that flexible packaging waste should be collected in a separate waste container or bag

6.1.3 Recommendations to increase consumer capture rate of recycling plastic

1: Policy makers and community leaders should invest in prompts and informational campaigns to disseminate information that can augment householder's recycling behaviour and improve the quality of the materials recycled.

2: Feedback about publicly available recycling information may help to increase the capture rate and the quality of the waste.

3: Householders' recycling behaviour can be improved by the implementation of commitment interventions and campaigns that are coordinated by public bodies.

4: Householders' recycling behaviour can be improved by the use of social modelling interventions, potentially implemented through recruiting distinguished community members.

5: Householders' recycling behaviour can be improved by an optimized network of adequately designed recycling facilities (e.g., a special recycling bin for plastic films or soft plastics that are not now recycled by many municipalities).

6: Policymakers and local authorities should invest in providing feedback to households, either through traditional or new channels, to foster their recycling behaviour.

7: Householders' recycling behaviour can be improved by financial rewards.

6.1.4 Possible improvements to the existing sorting system

Quality issues, due to multi-polymers plastics and the difficulty separating post-consumer plastic waste into defined polymers or groups of polymers, is a technical barrier to the reuse of waste plastics in new products. Certain types of post-consumer plastic waste are largely available, but are often contaminated (i.e., contains impurities, hazardous substances, volatile organic compounds), overly aged, and are made up of uncertain composition. This makes it difficult to mechanically separate the different polymers and recycle them into high quality pellets and polymer grades for automotive applications (Plastic Recyclers Europe) (Baldassarre et al., 2022, p. 41), Therefore, better sorting equipment using the latest technology, e.g., artificial intelligence and robotic, may help to increase the quality of the recyclant.

6.1.5 Offtake market for flexible packaging

From the SUEZ report (page 22) it indicates that there is no offtake market for the flexible packaging in the UK. Therefore, there is a need to create a market demand for recycled plastic. The government is trying to do this by using fiscal levers, however the jury is still out as to whether it is actually working, (van der Werf et al., 2020).

6.1.6 Capital investment

Due to the recent import ban of plastic waste to China, there is currently more waste material than before stockpiled across EU states. To process all these materials, the recycling capacity within the EU, and consequently within individual countries needs to be increased. This will ensure more plastic waste material is available for the production of new products. (TRANSFORM -CE T3.2.2 report p16). Therefore, it is recommended that across Europe more investment is put into either upgrading the existing waste management infrastructure or new plastic processing and reprocessing plants are built.

6.1.7 The AM and IEM industries

It is recommended that policy makers put resources into the AM and IEM industries and promote the recognition that these industries close the circle in the circular economy for plastic waste. The AM and IEM industries should be developed to create the offtake market for all types of plastics currently sent to landfill or waste for energy plants.

Future consumer trends may impact future material compositions of plastics. For example, the move away from using HDPE for the lids on PET bottles to lids made from PET, or the transition away from single-use plastics and hard to recycle multi-polymer plastics, towards alternatives such as biodegradable packaging. It is recommended that AM and IEM facility managers should be monitoring, (1) consumption habits over the next decade, and (2) trends in the polymer makeup of plastic products, to see how these trends will affect the availability of feedstock, which may affect the ability to operate at full capacity.

7. Conclusions

Municipalities that require residents to sort their waste at kerbside experience less rejection and contamination, hence, more material can be sent to high quality recycling, increasing its circularity. Therefore, it is concluded that the sorting of plastic waste must be carried out firstly by the consumer at home and then at the kerbside by the operators of the collection trucks. Doing this should provide adequate high grade feedstock for AM.

The capture rate across all regions shows that there are still huge amounts of plastic to be captured for recycling that can be used as feedstock for the IEM and AM industries.

It is been concluded, that many interventions have been found to be successful in increasing consumers recycling behaviours during the intervention itself (Varotto & Spagnolli, 2017). However, the long-lasting effects of these treatments remained largely untested, with obvious adverse implications for authorities and policymakers.

The feedstock for an IEM plant will normally need less processing to enable it to be used as an input material, whereas the input specification for an AM plant will mean that significantly more sorting and processing will be required. Therefore, plastic films of all kinds are the perfect feedstock for use in IEM manufacturing. TRANSFORM-CE is about closing the circle in the circular economic model. IEM manufacture stops plastic films from taking the linear path, to being burnt for energy generation or being put into landfill, and upcycles them into durable products. The IEM industry will use the plastic foils as is, and is seen as a good alternative recycling pathway right now. This technology can be the catalyst to show that there is a uptake market for the thin films. Therefore, there is a reason to put resources into changing the collection, sorting and treatment of the plastics throughout the waste management system. How IEM will compete with chemical recycling, as and when it scales up to large commercial facilities, is left for further work.

Deposit Return Schemes and Extended Producer Responsibility are effective mechanisms to increase the volume of both high and low grade plastic materials collected.

The availability and accessibility of sufficient waste collection and sorting data has been a slight limitation for this report. There is therefore a requirement to harmonise the data collection mechanisms within the waste management industry of each country and across NWE

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Appendix 1: The Plastic Industry Association seven plastic categories

These are the seven types of plastic that are identified by the Plastic Industry Association that make up all the categories for plastic recycling.

1 PETE	Polyethylene Terephthalate (PETE or PET)
2 HDPE	High-Density Polyethylene (HDPE)
3 PVC	Polyvinyl Chloride (PVC)
4 LDPE	Low-Density Polyethylene (LDPE)
5 PP	Polypropylene (PP)
6 PS	Polystyrene or Styrofoam (PS)
7 OTHER	Miscellaneous plastics (includes: polycarbonate, polylactide, acrylic, acrylonitrile butadiene, styrene, fiberglass, and nylon)

Appendix 2: Glossary of Terms

Additive Manufacturing:
This is the process of turning a digitised three-dimensional model into a physical object ay adding layer upon layer of material to form the object.

Commercial waste:
Consists of waste from premises used mainly for the purposes of a trade or business or for the purpose of sport, recreation, education, or entertainment, this excludes household and industrial waste

Misthrow:
Waste that should not be in this waste stream, i.e., plastic put into general waste or contamination like organic matter placed in the plastic waste

Post-Consumer waste:
Post-consumer waste is the waste produced at the end of a consumer-product lifecycle, e.g., food and thin film packaging that tends to be dirty, within mixed wase and is difficult to recycle

Primary packaging:
This is the first layer of packaging, that has direct contact with the product. It is the one that the final customers interact with, like a cereal box or a wine bottle. Its purpose is to protect the actual product, but it is also an important marketing tool

Residual waste:
Non-hazardous waste material that cannot be re-used or recycled and needs to be sent to energy recovery or disposal in landfill.

Secondary packaging:

This is the middle layer of packaging, that protects the **primary packaging.** Used to pack together more individual products in an organized manner. Some examples could be the printed shrink film used for containing 12 cans of soda or the cardboard box that guards 12 jars with pickles

Transport /Transport packaging:

The outer layer of packaging placed for transportation, e.g., plastic film wrapped around a pallet

Valorisation:

This is a process of changing residues into energy or products with a much greater economic value, i.e. enhancing the value of the waste

Virgin plastic:

Plastic resin that has been newly created without any recycled materials. This type of plastic is produced (using natural gas or crude oil) in order to create brand new plastic products for the very first time

Waste fractions:

The grouping of waste according to its properties; plastic, wood, metal, biodegradable waste, earth, stones, etc

About the project

The problems associated with plastic waste and in particular its adverse impacts on the environment are gaining importance and attention in politics, economics, science and the media. Although plastic is widely used and millions of plastic products are manufactured each year, only 30% of total plastic waste is collected for recycling. Since demand for plastic is expected to increase in the coming years, whilst resources are further depleted, it is important to utilise plastic waste in a resourceful way.

TRANSFORM-CE aims to convert single-use plastic waste into valuable new products. The project intends to divert an estimated 308 tonnes of plastic between 2020 and 2023. Two innovative technologies – intrusion-extrusion moulding (IEM) and additive manufacturing (AM) – will be used to turn plastic waste into recycled feedstock and new products. To support this, an R&D Centre (UK) and Prototyping Unit (BE) have been set up to develop and scale the production of recycled filaments for AM, whilst an Intrusion-Extrusion Moulding Facility, the Green Plastic Factory, has been established in the NL to expand the range of products manufactured using IEM.

Moreover, the project will help to increase the adoption of technology and uptake of recycled feedstock by businesses. This will be promoted through research into the current and future supply of single-use plastic waste from municipal sources, technical information on the materials and recycling processes, and circular business models. In-depth support will also be provided to a range of businesses across North-West Europe, whilst the insights generated through TRANSFORM-CE will be consolidated into an EU Plastic Circular Economy Roadmap to provide wider businesses with the 'know-how' necessary to replicate and up-scale the developed solutions.

Lead partner organisation
Manchester Metropolitan University

Partner organisations
Materia Nova
Social Environmental and Economic Solutions (SOENECS) Ltd
Gemeente Almere
Save Plastics
Technische Universiteit Delft
Hogeschool Utrecht
Hochschule Trier Umwelt-Campus Birkenfeld Institut für angewandtes Stoffstrommanagement (IfaS)
bCircular GmbH

Countries
UK | BE | NL | DE

Timeline
2019-2023

www.nweurope.eu/transform-ce