Interreg
North-West Europe
TRANSFORM-CE
European Regional Development Fund

Resource Efficiency Performance of Treament Options

Resource Efficiency Performance of Treatment Options

This report identifies the treatment options that waste plastic can go through at the end of its first cycle of use. It compares the impacts of resource usage between the options.

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Deliverable WPLT 1.3 Resource Efficiency Performance of Treatment Options

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Definitions and abbreviations

List of Abbreviations/Acronyms

AI	Artificial Intelligence
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
eq.	equivalent
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-Government 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

Executive Summary

This report is the third in a series that looked at the processes in the lifecycle of thin film waste packaging plastic. It identifies three common treatment options for plastic waste, the plastic can be landfilled, or burned to produce energy, in both cases it is considered as end of life, or it can be recycled. Recycling has further secondary treatment option to prepare the plastic for use in additive manufacturing (AM) or in extrusion intrusion moulding manufacturing (IEM).

Environmental and economic data were drawn from the life cycle analysis carried out within this project. It was shown through the LCA that the best option for the plastic is to recycle it rather than landfilling or generating energy from it.

The plastic can be reused up to 10 times with intrusion extrusion moulding manufacturing and 3 times with additive manufacturing. A plastic fence has a single use lifespan of 40 to 50 years, and if reused 10 time a full lifecycle of 400 to 500 years. If it replaces and therefore substitutes for a wooden fence with a lifespan of 15 years, then on a conservative estimate one volume of plastic would replace 26.6 wooden fences over a 400-year period, excluding conversion losses each cycle.

As AM products are plastic, the use of recycled plastic is only substituting for virgin plastic. Over the lifecycle if the plastic there will be at least 4 substitutions of virgin plastic and if additives are used to elongate the polymer chains and an additional 30% of virgin plastic is added to the recyclant, at least 70% or the original plastic can displace virgin plastic an additional 4-time.

Licensees of the waste management system are prone to change at the end of their licence period. This introduces uncertainty in the long-term relationships between licensees of the waste management system and those that use their feedstock in a manufacturing process. A change in the managements of a municipal waste recovery system introduces a large uncertainty in the supply chain for the use of waste plastics as a feedstock. Therefore, it was found that there is a need for high level government policy to guarantee the recycling option for low grade thin film plastic. This could be implemented as part of the recycling regulations or laws to guarantee its widespread take up of low-grade plastic by the waste management companies and a recyclant that must not end up in landfill or be burnt to generate energy.

This report focuses on the different treatment options available for the collected waste. It looks at the level of sorting required, and what recourses are used in the processing of the plastic. A comparison will be made between the different treatment options and the recourses used for the different plastic waste streams destined for the AM and IEM industry respectively.

It is concluded that over the very long lifetime of the plastic used in AM and IEM compared to the other treatment options, i.e., landfilling or burning to generate energy, and including the multiple savings of materials being substituted, the TRANSFORM-CE AM and IEM processes give great economic and environmental gains as well as preserving resources for future generations to be able to use.

1. Introduction

1.1 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 2019 EU plastic production was 53.6 Mt with 29.5 Mt collected for recycling, of which only 10.1Mt actually recycled and only 4.6 Mt were used in new plastic products (Plastics Europe, 2020). The rest was exported. The EU is reliant on imports of virgin plastic and there is a huge opportunity to valorise, 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 NWE forces pre-segregated and mixed waste plastics into landfill and or energy-from-waste (EfW) plants. This approach is not resource efficient and will not enable EU recycling targets to be achieved and clearly does not promote a circular economy (CM) 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 in 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 plants and landfill. This is an economic loss to the EU and reinforces the wasteful linear economic model of ‘use once and discard’. The EU Packaging Waste Directive and Extended Producer Responsibility (EPR) scheme (EU Commision, 1994), 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, 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 SUPs 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 of SUPs for manufacturing new products from. The TRANSFORM-CE project uses all types of SUPs 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 and containers, are processed into filaments to be used to make additively 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 processes 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.

The unique novelty of the IEM processes developed within the TRANSFORM-CE project is that Save Plastics have developed a recipe that can use, 100% low grade mixed plastic thin film waste, to make products. Other companies may include a small percentage of thin films in their formular, or only use single polymer thin films to produce pellets, but most of the feedstocks are higher grade HDPE or LDPE which are rigid plastics.

1.2 Focus of this report

This report is the third in a series of three reports. It looks at the long-term prospects of providing a steady stream of recycled plastic in viable volumes for the AM and IEM markets.

In the previous report in this series, Long-Term 1.1, it was shown that for the foreseeable future, there will be adequate feedstock to grow the IEM and AM industries for the next 5 and 10 year periods. One of the factors that affects the quantity of SUP available for AM and IEM is the quality of plastic in the recycling system. In the second report Long-Term 1.2, 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

This report focuses on the different treatment options available for the collected waste. It looks at the level of sorting required, and what recourses are used in the processing of the plastic. A comparison will be made between the different treatment options and the recourses used for the different plastic waste streams destined for the AM and IEM industry respectively.

1.3 Origins of plastic used in products

New plastic products can be made from virgin plastic, with recycled plastic or with a combination of both. Each year the global production of new plastics that are manufactured from fossil fuels is more than 330 Mt, while less than 33 Mt are recycled see Figure 1 volumes of virgin plastic produced each year (Plastic Europe, 2022). Some countries have a rule that at least 30% recycled plastic should be used, e.g., the UK plastic packaging tax (GOV.UK, 2022) is on products with less than 30% recyclant in them. A goal of this project is to decrease the number of products made exclusively from virgin plastic and substitute recycled plastic from the waste management system. A second goal is to use plastic that is currently not recycled to make products, that can be substituted for wood and concreate, which will last for up to 50 years per product cycle.

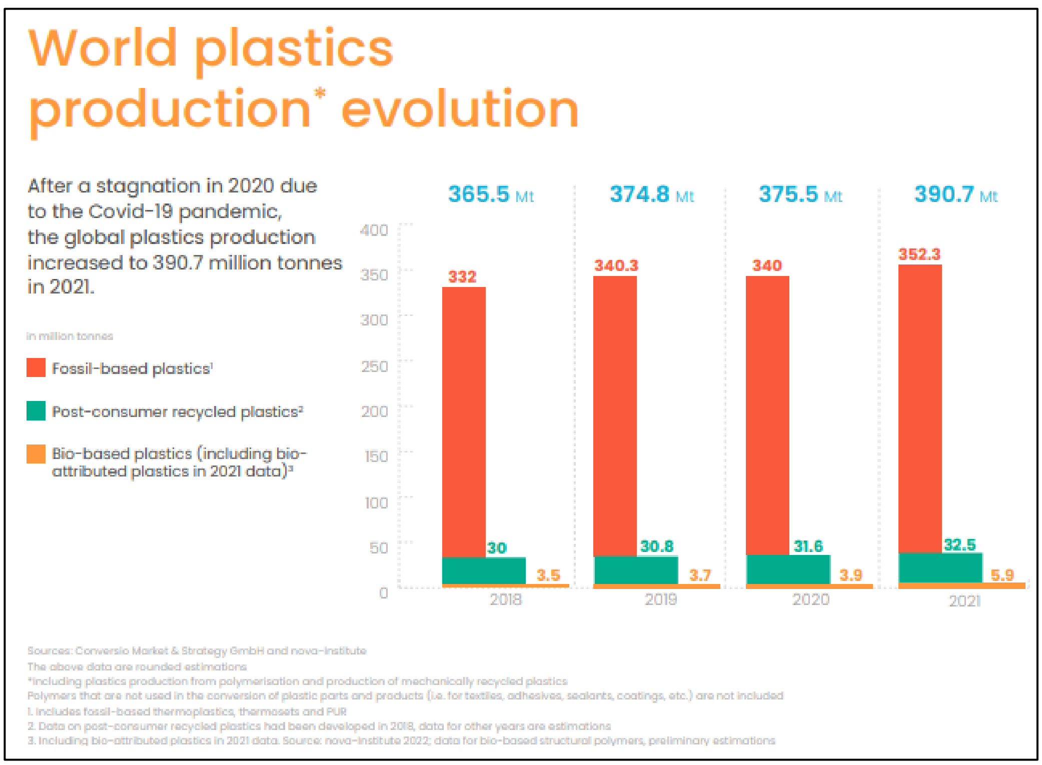

Figure 1 volumes of virgin plastic produced each year (Plastic Europe, 2022)

Within the recycling system there are two grades of plastic that end up as feedstock for plastic products, food grade and non-food grade. Much of the food grade plastic comes into the recycling system through deposit return schemes, as in Germany and the Netherlands, and through special plastic collection routes. The non-food grade plastic comes from the residual of the food grade plastic that has been contaminated and can't be used again for food, or from other consumer products. However, there is a huge amount of plastic that is rejected from or never makes it into, the recycling system. This plastic enters the waste system, via residual waste collections or as plastic rejected by the recycling system and end up in either landfill or waste for energy generation, (or as what is sometimes termed 'refuse derived fuel').

The aim of this projects is to show the feasibility of increasing the number of different plastics that can be recycled. This is both low and high grade plastics, that at this time have very limited reuse and therefore are not recycled in adequate enough volumes. From previous research, (the LT 1.2 report) it was found that waste management companies are unwilling to put recourses into sorting and processing plastics if the offtake market is either very small or non-existent in their area. This project seeks to divert previously unrecycled plastics and show the feasibility of using them in IEM manufacturing, and to increase the offtake market for high grade non-food grade plastic for use in the AM industry. The 'as is' situation and the projected changes are depicted in Figure 2 schematic of the proposed proportion of plastics used for future products below.

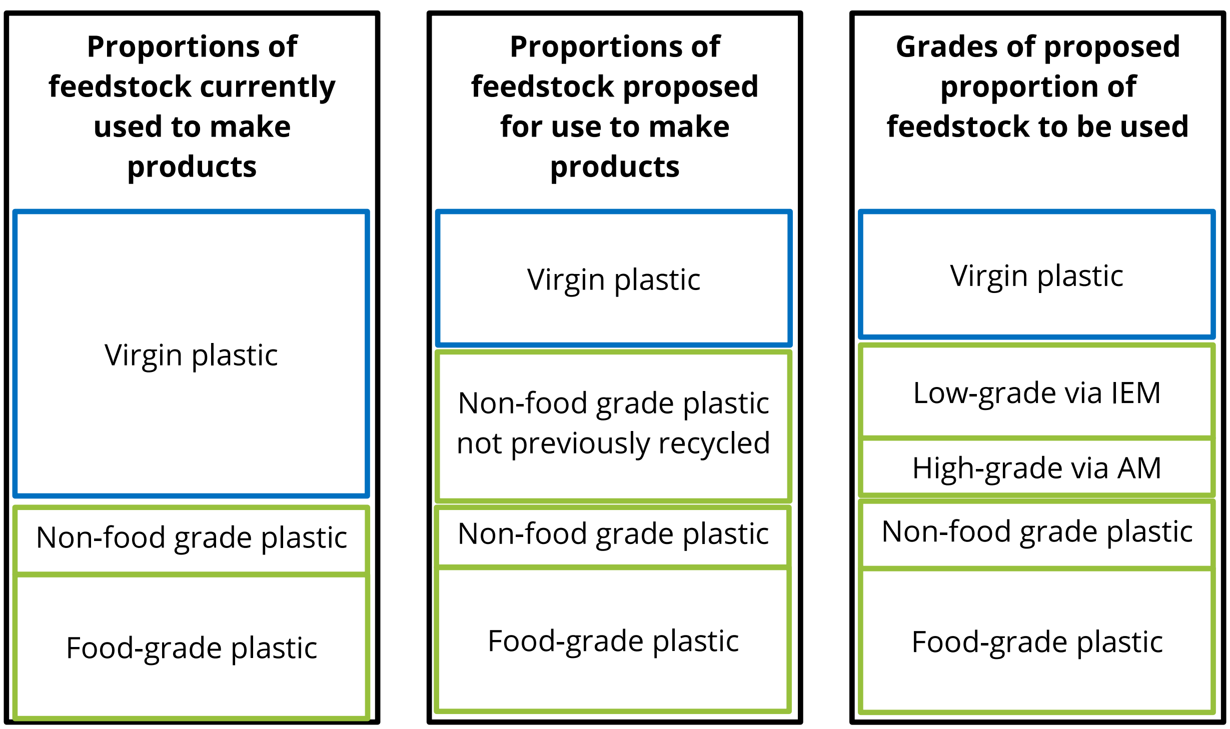

Figure 2 schematic of the proposed proportion of plastics used for future products

IEM opens new markets for the use of recycled plastics that are not yet fully developed. IEM makes products by melting plastic and squeezing it into a mould to make small or large items. At the Save

Plastic factory (Saveplastics, 2022) low grade plastic waste is made into large panels and beams. For example, the panels are used to substitute for concreate garden and wall panels or to substitute for the wood that would do be used in street and recreational furniture. AM is not just a manufacturing method; it is also very much used as a prototyping tool. Using a 3D printer, prototypes, that might have conventionally used metal and a huge milling machine to produce, can now be easily made quicker and cheaper. With an extruder the prototype can be melted down and used again. However, with a metal prototype, once produces it cannot be reused in a new iteration, and each iteration needs new raw materials to produce it.

The predominant method of recycling plastics is mechanical, while an emerging technology called chemical recycling is gaining traction(Zhang et al., 2021). **Mechanical recycling** refers to the processing of plastic waste into secondary raw material or products without significantly changing the chemical or molecular structure of the materials. **Chemical recycling** refers to several different technologies that convert sorted plastic waste into their original or similar molecular building blocks using thermal or chemical processes (SUEZ, 2021, p. 21). The treatment options covered by this report only look at mechanical recycling systems, as chemical cycling is mostly carried out in pilot projects or at small scale.

1.4 Defining what the common treatment options for the plastics used in IEM and AM

Waste management policy must look at all the options available to deal with the growing problem of plastics. Different options exist, some of them are bad options, like dumping plastics into the environment e.g. the sea, while others are good like a circular economy for the plastics. The options available to deal with waste plastics are labelled "***treatment options***", and are defined by this report as being the decision taken as how to process or deal with waste. This report focuses on the treatment options for post-consumer single use plastics from packaging that is found within the municipal waste management system.

Figure 3 bellow, shows the three primary treatment options used to decide how to process waste plastics. These are (1) landfill, (2) waste for energy (WfE) plants and (3) sending the waste to a materials recovery facility (MRF) for recycling. The WfE is the linear model of 'once use and then destroy'. The landfill option is also 'use once and then bury', however there is always a future possibility of recovering the plastics during enhanced landfill mining in conjunction with chemical recycling, (Canopoli et al., 2018; Cappucci et al., 2020). However, chemical reprocessing is an emerging technology and as an industry, is in its initial stages. The third option is the recycling rout via a MRF. Recycling has two options, the first is to sends the waste to be sorted, cleaned, and repurposed into new products, the second option is to bale up the plastic and export it for further processing overseas. While there may be other treatment options these three listed by this project and labelled "***common treatment options***".

There are two inputs to the waste system. On the left of Figure 3 is the residual waste that is collected in black bins or bags, most of which is destined to go to either landfill or a WfE facility, and minority of which gets recycled. On the right of Figure 3 is the pre-sorted recyclant that is processed in a MRF and only a minority of which should be going into landfill or WfE facility. However, as there isn't an offtake market for many of the recyclable types of plastics, only a small percentage ends up being recycled and ends up being the feedstock for new products.

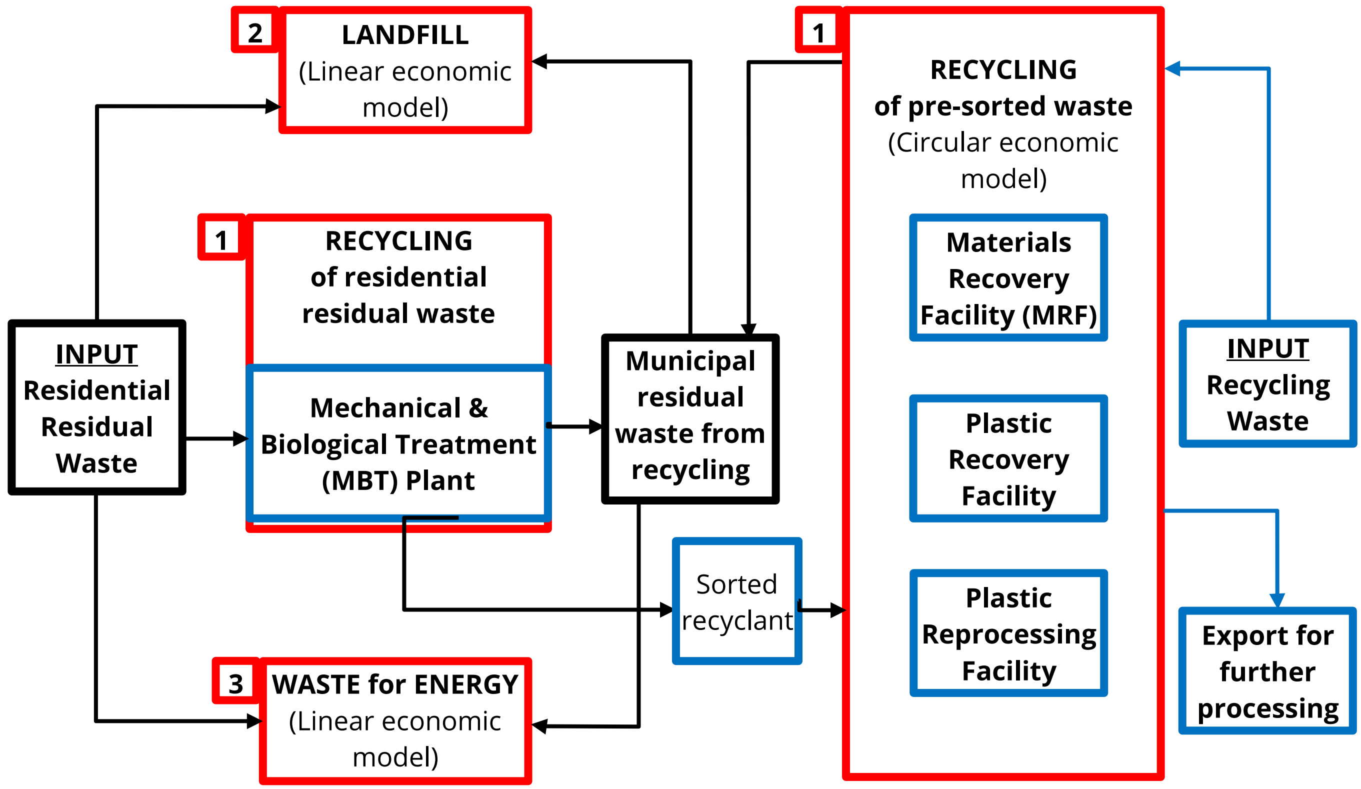

Figure 3 Waste flows into the primary treatment options for plastic waste

Historically the recycled materials were deposited by the consumer in a public place away from their residence. For example, in the UK only glass, paper and cardboard were recycled, and the consumer had to save it up at home and take it, usually to a supermarket, and deposit the recycling materials in huge containers. Then recycling collections moved to the residence and became part of the kerbside collection system along with the residual waste. Many EU countries used to send the residential residual waste directly to landfill, this changed with the opening of waste for energy plants. There was lots of resistance and nimbyism, which led to much of the residual waste still going directly to landfill.

Throughout Europe, the level of pre-sorting of the waste by the consumer has gradually changed to a more detailed sorting, see the Long Term 1.2 report of sorting mechanises for more details. The pre-sorted plastic waste is collected at the kerbside and is taken to a materials recovery facility, and the kerbside residual waste is sent to a mechanical & biological treatment (MBT) Plant. Recently, European countries, for example Germany since 2015, have banned the practice of sending residual waste directly to landfill, and all residual waste is sent for sorting usually in an MBT.

These primary treatment options are part of the first stage in the waste management system. The waste management company together with policy makers set out the rules for what types of plastic can be put into the pre-sorted recycle bin and what must be put into the residual bin. Previous work, as set out in the 1.1 and 1.2 Long Term reports, highlighted the inconsistences within the recycling rules across the four countries represented in this project. Therefore, the consumer, to some extent, has to make their own decision (based on what they understand to be the local recycling rules) as what to recycle and what to put into the residual bin. This means the consumer is part of the primary treatment options decision making process.

Once the waste enters a MRF or MBT, the same decisions will be made; what will go to residual waste and be landfilled, what has a high calorific value and will be sent to WfE plants and what will go on to be recycled. These decisions are bult into the mechanical sorting system and can be classified as the ***secondary treatment options***. The same decision tree is carried out as part of the continued processing of the plastic; will it carry on being recycled or will it be rejected and end up in landfill or for WfE? German statistics for these three treatment options for 2020 and 2040 can be seen in Figure 4 below.

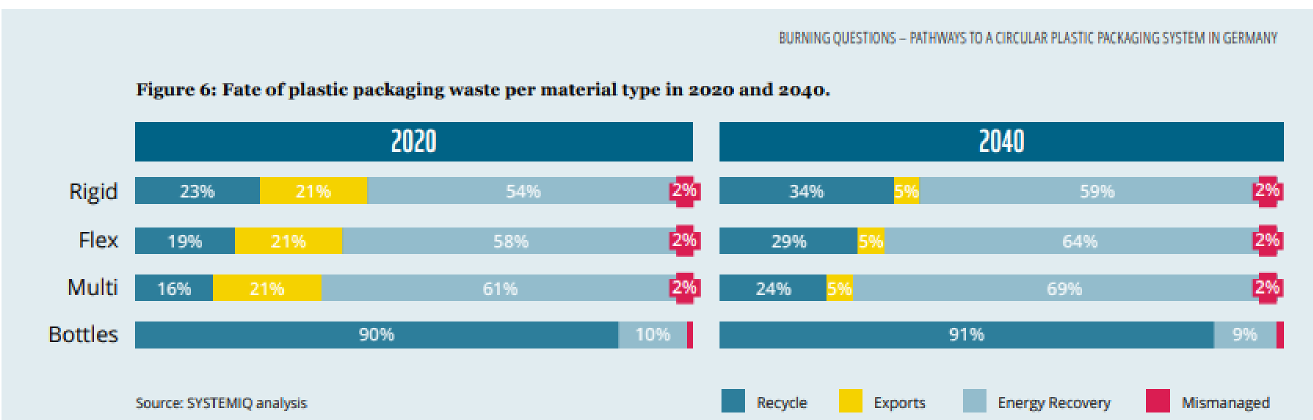

Figure 4 German statistics for plastic waste treatment options for 2020 and 2040 (WWF Deutschland, 2021)a

1.5 The aims of the TRANSFORM-CE project in context of the common treatment options

The main aim of this project is to divert plastics that would normally be sent to landfill to be used in the AM and IEM industries. However, currently, these industries are still growing and do not have the capacity to absorb the available quantities. The TRANSFORM-CE project is only diverting around 300 tonnes, which compared with the amount of plastic in the waste system, measured in millions of tonnes, is a very small amount. However, this project is a proof-of-concept activity and only employs pilot plants for both IEM and AM. When upscaled to commercial size production plants, and when the number of new facilities that could be opened are taken into consideration, the IEM and AM industry will be able to make a significant impact on the amount of waste plastics that stay in the circular economy.

The ultimate goal is that a circular economy for plastics will become ubiquitous, where negligible to zero amounts of plastic will be sent to landfill and incineration, and all other plastics will be recycled. The TRANSFORM-CE project is a step in the direction of reducing the amount of plastic that is sent to landfill and incineration and increasing the amount that is recycled into products that will be part of the circular economy for plastics, see Figure 5 below. Note: in a truly circular economy for plastics, no plastic should end up in landfill or incineration, hence the arrows are grey and not black.

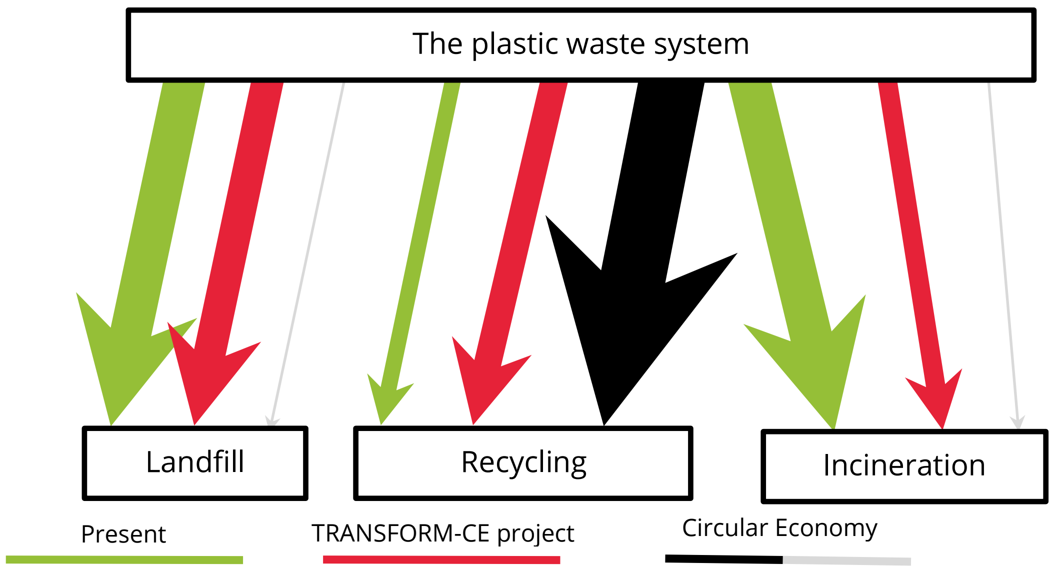

Figure 5 schematic of the changes in flows of plastic waste

1.6 The secondary treatment options within the recycling treatment option

Once the plastic enters the materials recovery part of the recycling system, the secondary treatment options start. Materials recovery takes place within BMTs, MRFs, PRFs, and reprocessing facilities. The options for treating the plastic as it flows through the recycling system will depend on the design, and output feedstock of the facility. Figure 6 below shows the common treatment options within the recycling system. For each of these options decisions will have to be made about how each option will be implemented. Those decisions will impact on the resources need to carry them out and therefore the carbon footprint of the activity. The goal here is to explain in general terms the treatment options across the recycling system as one unit, and to identify the differences in the processing of the plastic between that used for AM and IEM manufacturing. There are two different facilities, the plastic processing plant and the plastic reprocessing plant. In the plastic processing plant, the plastic waste comes from a MRF as semi-sorted washes and chipped plastic. It may or may not be multi-polymer (mixed plastic). The processes in the plastic processing facility take the wet mixed plastic and tun in into dry single polymer plastic pellets for later use by a reprocessor. In the reprocessing facility, the high quality plastic pellets can be extruded into filaments for 3D printers, or for low quality plastic for IEM products, they are extruded and moulded into products.

A simplified overview of the different **secondary treatment options** that consume resources during the plastic waste sorting and processing for AM and IEM

Type of plant	**Materials Recycling Facility**	**Mechanical & Biological Treatment (MBT)**	**Plastic Processing Plant**	**Plastic Reprocessing Plant**	
Options				**AM**	**IEM**
Handling the waste	✓	✓	✓	✓	✓
Sorting	✓	✓	✓	✓	✓
Cleaning			✓	✓	
Transportation	✓	✓	✓	✓	✓
Processing into pellets			✓	✓	
Reprocessing				✓	✓
Manufacturing				✓	✓

Figure 6 secondary common treatment options within the primary treatment option of recycling

<u>Waste handling</u>

When the waste enters the facility a design decision has to be made whether a diesel loader will be required or an electric grabber. These are used to load the waste into the feeder hopper to start the waste processing journey. The design of the facility should be optimised to reduce the lengths of the conveyor belts to save on the rescores used. To increase the purity of the output waste, the waste can be passed through the sorting machine multiple times. In a very large MRF, there may be two sorting machines to increase the purity of the recyclant. After the waste has traverser the facility it needs to be packaged up and transported to a storage area. All these handling process will use up resources that will add up to an economic and CO2 cost. Human picker/sorters are used for quality control purposes.

<u>Sorting</u>

There are different mechanical and optical devices that act as sieves or air blowers to direct the plastic to a different conveyor belt during the sorting process. In modern facilities there may be artificial intelligence robots sorting the waste.

Cleaning

The cleaning process is there to remove contaminants like food, and non-plastic attachments to the plastic, for example paper, glue, or other types of plastic label. The basic liquid used is water but, in some instances, de-gluing and de-greasing agents like caustic soda or detergents are used.

Transportation

Within the recycling system plastics are processed and then transported to either a PRF or a PPF. Often the plastic gets transported across the world for processing or as feedstocks for manufacturing new products. The TRANSFORM-CE project focuses on AM and IEM manufacturing as these are envisioned to be local businesses that are set up close to a recycling facility. The goal, for the TRANSFORM-CE project is that the waste plastic should be locally sourced from homes and offices or special street bin collections and can go straight a local AM filament production plant, or an IEM plant for sorting and then processing into new products. The traveling distance the plastic goes through is minimised within a circular economic business model.

Processing the plastic into pellets

The plastic comes into the plastic processing plant either as single polymer, or mixed polymer bails or as washed and granulated small pieces. At the plant the plastic will be processed to the specification of a particular customer or as a standard feedstock. To supply the IEM industry the output will be a bail of shredded mixed thin films. As not all plastics or contaminants can be included into the feedstock for IEM, the sorting mechanisms will remove PVC, any rigid plastic, and as much non plastic items as possible. The requirements for AM using ordinary 3D printers requires a very clean single polymer granual. This means that a very good sorting mechanism, such as magnetic density separation, and perhaps followed by a near infrared sorter will provide a washed very pure 100% single polymer granules that can be made into filaments for 3D printing. If the plastic is for use in a robotic arm with a large print nozzle of up to 30 mm, it is usually formulated into a compound that is tailored to the specific application of the product being manufactured. For example a Dutch company called 10-xl (2022), used a robotic arm to print large items up to 12m long, uses different compound formulars one of which is PP and PE. These compounds are formulated at the plastic processing plant.

Manufacturing new products

Before the plastic is used in IEM manufacturing, a manual inspection is carried out that removes about 10% by weight of contaminants. No further sorting is carried out for AM as the plastic pellets are provided with the correct purity for the filament extrusion process. However, in the large robotic 3D printing that uses compounds, laser filter technology is used to provide the required purity.

1.7 A more detailed treatment process for PET bottle recycling

The plastic in bottle-to-bottle recycling has to go through many processes in order to be made into a new bottle. The process and the amount of resources used, will depend on the design of the plant and the product that will be made from the plastic. In the example shown below in Figure 7, the whole process of bottle-to-bottle and making other products from the PET bottles is described. These processes will take place at different facilities, each of which may or may not carry out the processes described. It should be noted that the amounts of washing, grinding, and heating as describer in Figure 7 is relevant to the plant as describe by Kasetsart University and Indorama Venture PCL and will be different at other facilities.

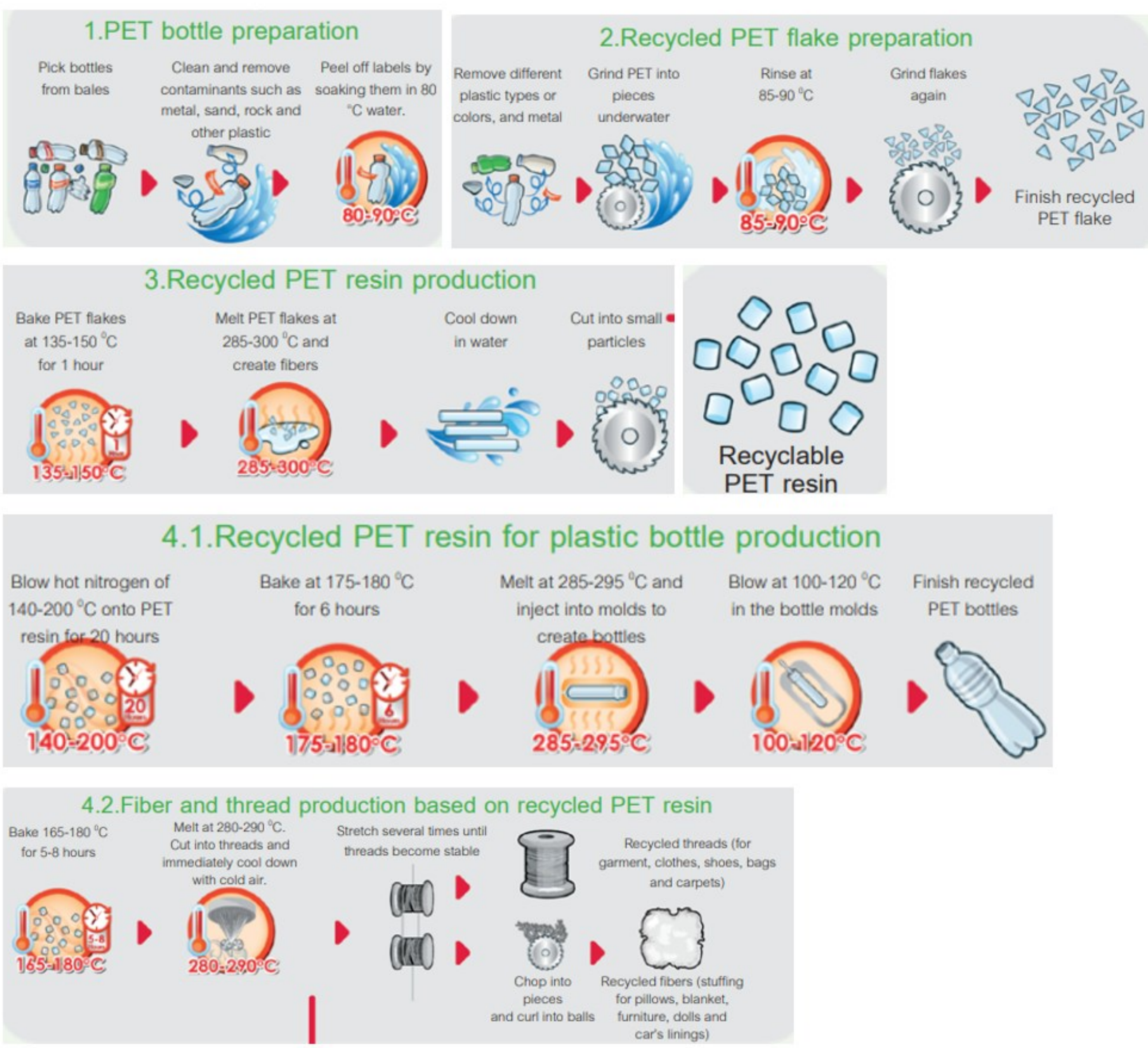

Figure 7 the secondary treatment options for PET bottles (Kasetsart University & Indorama Venture PCL, 2022)

In Figure 7 above, the output from stages one and two is a clean PET flake. As describes hot water in industrial washing machine is used to remove labels and dirt from the plastic. The plastic is then reduced to small flakes by grinding or shredding. In process three, the clean flakes are heated, melted together, extruded into a rod that is cooled and then cut up into tiny pellets which they call PET resin. This resin is then used to make a new bottle, it can be processed to make plastic fibbers, or it can be extruded (Figure 8) again to make filaments for AM.

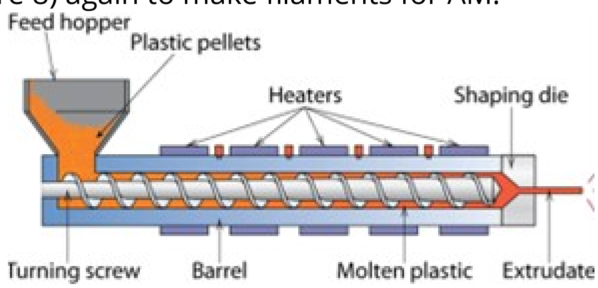

Figure 8 a typical extruder

For IEM most of these processed are not needed as the plastic can be melted and extruded as is without washing and removing many of the contaminants. For AM it is crucial that the plastic has a low moisture content before extruding the filament, therefore the pellets are heated at sixty degrees in an oven for a few hours to reduce the moisture content to the desired level.

1.8 A typical Materials Recovery Facility showing the sorting of the waste

Set out above are the three common treatment options for the waste plastic; burn for energy, place in a landfill, or recycle using circular economy principles. For the recycling option, the individual processes that the plastic waste goes through, uses different resources at each stage of the process. Bellow, in Figure 9, is a typical MRF that shows where manual handling of the waste occurs and shows the typical sorting machinery used to produce the bales of mixed plastic that are sent to the plastic processing plant Figure 10.

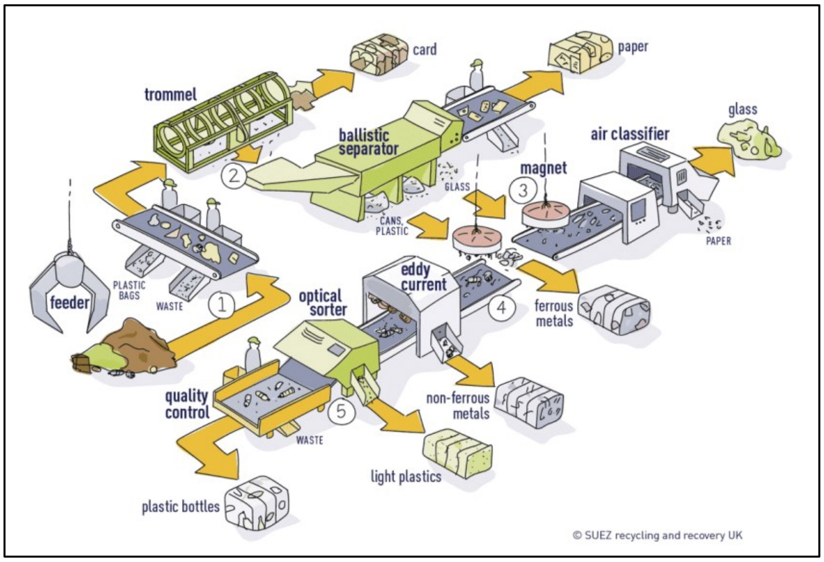

Figure 9 typical MRF (SUEZ)

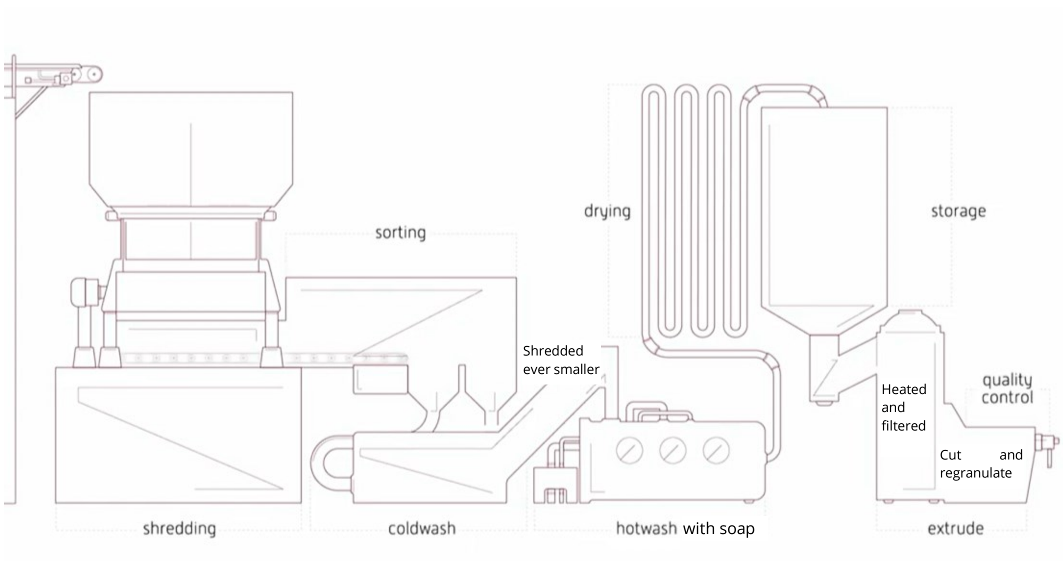

Figure 10 Attero's thin film polymer recycling plant in Wijster the Netherlands (from company video) 24 kt per year

Figure 10 above shows the type of machinery in a typical plastic processing plant. The uniqueness of this Attero plant is that it uses thin films, whereas most other plants that produce pellets only use ridged plastic. Its input are the bales of plastic from a MRF, and the output is plastic pellets or granules. These pellets become the feedstock for AM facilities to produce filaments for 3D printers or can be used for all other manufacturing for example injection moulding or IEM.

1.9 Resources used to sort and process the waste plastic

Figure 11 below, sets out the resources used during the whole recycling process, from input to a MRF to the production of AM filaments or moulded products.

A simplified overview of the **resource options** used during the plastic waste sorting and processing for AM and IEM				
Type of plant	**Materials Recycling Facility**	**Mechanical & Biological Treatment (MBT)**	**Plastic Processing Plant**	**Plastic Reprocessing Plant**
Resource				
Human labour	✓	✓	✓	✓
Fossil fuels	✓	✓	✓	✓
Electricity			✓	✓
water	✓	✓	✓	
solvents			✓	
Additives			✓	✓

Figure 11 Resources used to implement the secondary treatment options

Human labour

In conventional MRF/MBT and PPT facilities many people are used for quality control and to hand pick contaminants out of each waste stream. More modern and perhaps sophisticated machinery require less people for quality control. Where AI is used, even less people are used. As the manual processes to sort and treat plastics for IEM manufacturing, are much less than AM and conventional plastics recycling, the use of the plastics for IEM has a lower economic and CO2 cost.

Fossil fuels

Fossil fuels such as diesel are used to run mechanical loaders and bale handling equipment. As these are at the beginning and at the end of the possesses, it is presumed that the apportioning amount for each type of plastic on the loader end and bale handling should be the same for both AM and IEM. Furthermore, if the overall costs are apportioned per tonne, then the cost per tonne is the same for each tonne outputted regardless of the waste stream.

Electricity

Electricity is used to operate all manner of equipment throughout the recycling facilities. Since more processes are used to sort and treat the plastic for AM, plastics for AM have a higher energy and CO2 cost. This would be approximately the same for high quality plastic, that may be used for food-to-food or single polymer recyclant. However, as IEM does not need to go through almost all the sorting and treatment processes associated with high quality plastic recycling, the cost and carbon footprint to sort and treat the plastic for IEM is lower.

Water

Water is used for both separating and cleaning of the plastic chips. Different plastics have different densities. In a water bath the low-density plastics either float or sink much slower than the high-density plastics. Different screw mechanisms placed at different depts in the water are used to draw out the different types of plastics based of their density. Water is further used to wash off any contaminants. As will be explained chemicals, e.g., caustic soda, may be put in the water to help in the cleaning process. Water and other special fluids are used in a magnetic density separator to sort the different plastics into single polymer outputs. The use of water and other liquids is only to produce high quality plastic pellets that can be used for AM. The production of pellets from plastic flacks, is the same process if the pellets are used as AM or non-AM feedstock, they must be of the same high-quality grade. Therefore, the water used to produce the pellets foe standard plastics industry and that for AM manufacturing should be the same.

In the IEM agglomeration process, the plastic heats up and the thin films melt together at the same time they are being chopped up with the blades, a bit like a slow blender. To cool the plastic before it forms one huge chunk, 1 litre of water is added to each 100 kg to stop the process. This water evaporates off the hot plastic leaving no residue. Water is used to cooldown the plastic while it is in the mould. The water is usually in a closed loop system, that may need topping up but overall, the volume water usage is stable to that which can fill the cooling system.

<u>Solvents</u>
Plastic bottles have either a plastic label or a paper label, that is fixed to the bottle using adhesive. The bottle is shredded and on many of the pieces is either glue or paper that is glued on. Also, there may be printing on the bottle itself, for example a batch number and a use/sell by date. Cold water by itself will not be able to remove all the glue or residue of the label. Furthermore, food residual that contains oils could also be present on the plastic. Hot water with chemical solvers like caustic soda is used to clean the plastic chips from all these contaminates. This cleaning proses is only required for AM and not for IEM manufacturing.

<u>Additives</u>
Single pure plastic polymers are not very versatile. Therefore, in the production of filaments for AM manufacturing, chemicals are added to provide the required specification for printing products using 3D printing technology. The additives include, stabilizers, colorants, plasticizers, fillers and reinforcing fibres, ultraviolet absorbers, antioxidants as well as processing aids including lubricants and flow promoters, (Shamsuyeva & Endres, 2021). Many of these additives are also put into the plastic used for IEM. However, it will depend on the end user market as to which chemicals are added.

2. Comparisons between plastic handling within and without the TRANSFORM-CE project

2.1 Introduction

IEM production **1st time** recycled	IEM production up to **9 times** recycled	AM production **1st time** recycled	AM production Up to **2 times** recycled
Not burnt for generating energy	Not burnt for generating energy	Not burnt for generating energy	Not burnt for generating energy
Avoided the use of virgin plastic	Avoided 9 more times use of virgin plastic	Avoided the use of virgin plastic	Avoided 2 more times use of virgin plastic
Substitution of wood or concrete	9 more Substitutions of wood or concrete	No Substitution of other materials	No Substitution of other materials 3 times

Figure 12 schematic of advantages to using recycled plastic instead of virgin plastic

When a manufacture makes the decision to use plastic as a substitute for wood or concrete it has two options, to use recycled plastic or virgin plastic. From the point of view of the TRANSFORM-CE project, the substitution of virgin plastic is not a one-off occurrence but happens each time the plastic is ground up and reprocessed. For the IEM products the reuse of the plastic is up to 10-times, this implies a savings of 10 times the virgin plastic that has not needed to be used, and for AM it will be 3 time that virgin plastic is not needed. This implies savings in resources, and in the environmental and economic impacts that will happen multiple times during the reuse lifetime of the plastic. Furthermore, when assessing the first use of the plastic in the IEM process an LCA is usually carried out on a one-to-one basis. This means calculating the savings in a direct comparison to a wooden or concrete product that the plastic one is replacing. However, for example, a wooden fence panel, its lifetime is anywhere between 10 and 15 years, whereas the IEM plastic fence panel has a 40 to 50 years usable lifespan. This means if the wooden fence panel is substituted for a plastic one, then there is a need to compare between three and five wooden fence panels for one plastic panel. By taking into consideration the longevity of the plastic outdoor products, compared to wood and concrete equivalents there is a need to take into consideration the multiple savings over the lifespan of the plastic product compared to which other material is being replaced. Furthermore, for a wooden fence panel to last longer, it will need to be painted with a wood preserver several times during its lifetime, this is something that is usually not taken into consideration as part of a LCA, as this is an ongoing input rather than being there at the beginning of the installation. Similarly, during the lifetime of a concreate walkway there may be the need for repairs as the earth moves and cracks or chipping develops. This maintenance is something that is minimal by a plastic decked pathway and used less resources.

For a large fencepost that weighs 20 kgs, the initial processing included all the collection, sorting, cleaning, bailing, and the agglomeration stages, before the IEM manufacturing process could begin. However, the first time it is reprocessed it will need much less resources, this is because, the resources used to process 20 kgs of light weight thin films will be very much larger than a reprocessing a single solid 20 kg post. It will still need to be delivered to an IEM plant but will not require all the resources before entering the IEM plant. It will just need to be ground up and put into the extruder and will not need agglomeration. Therefore, the LCA caried out for the initial substitution of wood or concrete with plastic will always show conservative values for most indicators, compared to successive rescue cycles of the plastic over its full usable lifetime. It is important to note that if the 20 kgs of plastic were to have been landfilled then the surface area of the plastic that could leach into the environment is enormous. Compare that surface area to the same 20 kgs that is 10 cm square and 2 meters long, it will be many times smaller.

In many European countries waste must be send to an energy from waste facility before it can be landfilled. The UK is the only a country within the four regions of this project that still landfills plastic. An LCA was carried out within work package T2 and is deliverable 2.2. to determine the advantages of the project. A comparison was made between all three treatment options: generating energy, reusing it within the IEM industry and landfill. It uses a displacement factor of one, which means it uses a like for like comparison, i.e., one panel or slab of concrete or wood, compared to one of plastic. However, it does not take into consideration multiple substitution cycles or any lifetime repairs needed for any of the different materials used in the scenarios.

2.2 Comparing the environmental impact of IEM manufacture using plastic substitution

Below are the quantified effects of the recycling system relative to the baseline waste end-of-life treatment by being burnt to generate fuel, and the production of products from primary materials, e.g. wood or cement/concreate. For each impact category, a positive value means a net negative impact of the recycling system, relative to the alternative treatment and the production of similar products with primary materials, while a negative value indicates a net positive benefit. Net benefits of the system are highlighted in green, net impacts in red. To get a clearer view, the results are expressed per unit of product (i.e., one cladding panel, one street pavement or one spool of recycled filaments). As an example, the recycling of post-consumer polyolefin films to produce one cladding panel through IEM recycling has a net benefit on climate change of 6.5 kg CO_2 eq., in the case of fibre cement substitution, and a net benefit of 4.4 kg CO_2 eq., in the case of softwood substitution.

The net environmental results for each system are displayed Table 1 and Table 2 below.

Table 1Net environmental effects of IEM recycling to produce one product (cladding panel or street pavement) relative to baseline end-of-life treatment and production from primary materials (work package T2 deliverable 2.2)

		Net environmental effects of Transform-CE recycling technologies relative to baseline end-of-life scenario		
Impact category	**Unit**	IEM recycling Fibre cement panels substituted	IEM recycling Softwood panels substituted	IEM recycling Concrete pavements substituted
Climate Change	kg CO_2 eq.	- 6.5	- 4.4	-5.3
Ozone Depletion	kg CFC^{-11} eq.	- 5.78 E-8	2.15 E-9	3.42 E-8
Particulate Matter/Respiratory Inorganics	Disease incident	- 1.61 E-8	- 9.55E-8	5.47 E-8
Ionizing Radiation – human health effects	kBq U_{235} eq. (to air)	- 0.024	0.163	0.301
Photochemical Ozone Formation	kg NMVOC eq.	- 0.0020	-0.0021	0.0054
Acidification	mol H^+ eq.	- 0.0021	0.0028	0.0074
Eutrophication –	kg P eq.	- 7.48 E-5	0.00016	0.00069

freshwater				
Eutrophication – marine	kg N eq.	0.00024	0.00107	0.00202
Eutrophication – terrestrial	mol N eq.	- 0.0021	0.0081	0.0160
Water scarcity	m^3 water eq.	- 1.06	- 0.459	- 0.410
Land Use	Pt	- 49.7	- 411.3	- 13.9
Resource use, fossil	MJ	59.1	71.6	100.2
Resource use, minerals and metals	kg Sb eq.	- 4.02 E-5	- 5.94 E-7	7.19 E-7
Human Toxicity – non-cancer effects	CTUh	- 3.15 E-8	- 1.73 E-9	5.80 E-9
Human Toxicity - cancer effects	CTUh	- 7.57 E-10	9.20 E-11	7.10 E-10
Ecotoxicity for aquatic freshwater	CTUe	- 22.5	- 0.89	5.05

2.3 Outcomes from the LCA for recycling via IEM treatment option

The LCA study brought out the following observations.

- Potential impacts linked to collection, sorting and transport steps appear to be very low in comparison with the impacts/benefits linked with the recycling process, avoided incineration and substituted primary products. The latter thus appear to be much more relevant to the study.
- Regarding climate change impacts, avoiding incineration of waste is shown to be the most relevant step to the net benefits of the three systems, linked with the high GHG emissions of incineration, considered to be avoided. All systems show excellent performances on climate change potential benefits.
- For the majority of the other impact categories, it can be seen that avoiding incineration of the waste implies a net impact. This is due to the consideration of waste-to-energy incineration avoidance. In that respect, this energy production avoided has to be produced from classical sources (country-specific electricity mixes used as baseline), implying an increase in environmental impacts.
- Following previous point, it can be seen that for the system to be net beneficial (at the exception of climate change), the benefits from avoided primary production have to be higher that the impacts from recycling and avoided waste-to-energy incineration. This highlights the primary importance of the choice of the products manufactured from IEM; the applications targeted should have environmental added value. As a matter of fact, targeting the production of cladding panels appears more relevant than the production of concrete pavements. The results also show the environmental relevance of targeting

specific market-segments for each product, the substitution of fibre cement panels being more beneficial than the substitution of softwood panels.

It is worthy to note that these observations are relevant to a one-to-one comparison over a single recycling iteration. However, the products produce using IEM methods have an additional recyclability potential of up to 9 more times before they are depolymerised to be used again. The displacement potential of IEM products can be up to a few hundred years. This implies the savings of other materials (wood, concrete, and cement) multiple times.

2.4 Comparing the environmental impact of AM manufacture with recycled plastic

Below are the quantified effects of the recycling system relative to the baseline waste end-of-life treatment by being burnt to generate fuel, and the production of products from virgin plastic. For each impact category, a positive value means a net negative impact of the recycling system, relative to the alternative treatment and the production of similar products from virgin plastic, while a negative value indicates a net positive benefit. Net benefits of the system are highlighted in green, net impacts in red. To get a clearer view, the results are expressed for 1 kg spools of fibre. As an example, the recycling of post-consumer waste plastics to produce 1 kg spools of PET fibre id 3.1 kg CO_2 eq., and for 1 kg of PP it is 3.5 kg CO_2 eq.

Table 2 Net environmental effects of extrusion-spooling recycling to produce one spool (1 kg) relative to baseline end-of-life treatment and production from primary polymers (work package T2 deliverable 2.2)

		Net environmental effects of Transform-CE recycling technologies relative to baseline end-of-life scenario			
Impact category	**Unit**	Extrusion-spooling PET	Extrusion-spooling PP	Extrusion-spooling PMMA	Extrusion-spooling PLA
Climate Change	kg CO_2 eq.	- 3.1	- 3.5	- 7.7	- 2.0
Ozone Depletion	kg CFC^{-11} eq.	- 1.35 E-5	4.26 E-9	2.68 E-8	- 1.58 E-7
Particulate Matter/Respiratory Inorganics	Disease incident	- 5.53E-8	- 4.97E-8	- 3.57E-7	- 1.24 E-7
Ionizing Radiation – human health effects	kBq U_{235} eq. (to air)	0.414	0.800	0.530	0.241
Photochemical Ozone Formation	kg NMVOC eq.	- 0.0047	- 0.0042	- 0.0253	- 0.0083
Acidification	mol H^+ eq.	- 0.0069	- 0.0045	- 0.0405	- 0.0160
Eutrophication – freshwater	kg P eq.	- 0.00022	- 0.00016	- 0.00037	- 0.00088
Eutrophication – marine	kg N eq.	- 0.00077	- 0.00061	- 0.00476	- 0.00697 *(- 0.00771)**
Eutrophication – terrestrial	mol N eq.	- 0.011	- 0.0076	- 0.044	- 0.052
Water scarcity	m^3 water eq.	- 1.19	- 0.89	- 1.04	- 3.91
Land Use	Pt	2.34	3.50	3.14	- 25.3
Resource use, fossil	MJ	- 29.6	- 21.2	- 78.5	- 19.5

Resource use, minerals and metals	kg Sb eq.	- 2.62 E-5	- 1.02E-5	- 4.59 E-6	- 2.14 E-5
Human Toxicity – non-cancer effects	CTUh	- 1.77 E-8	- 3.71E-9	- 8.14 E-9	- 3.92 E-8 *(- 4.23 E-8)**
Human Toxicity - cancer effects	CTUh	- 7.61E-10	- 2.91E-10	- 3.98 E-10	- 1.72 E-9 *(- 1.76 E-9)**
Ecotoxicity for aquatic freshwater	CTUe	1.57	12.9	0.628	- 95.6 *(- 128.5)**

*Values including long-term emissions from landfilling

2.5 Outcomes from the LCA for using recycled plastic for AM

The LCA study brought out the following observations.

- Potential impacts linked to collection, sorting and transport steps appear to be very low in comparison with the impacts/benefits linked with the recycling process, avoided incineration, and substituted primary products. The latter thus appear to be much more relevant to the study.
- For all types of polymers, the system is net beneficial for almost all impact categories, mainly due to the avoided virgin production of primary products.
- Regarding PLA, it can be noted that avoided incineration (both with and without energy recovery) doesn't lead to environmental benefits, notably for climate change category for which benefits could have been expected. Because PLA is a biobased material, most of its carbon content is biogenic, thus, carbon emissions related to its incineration are considered to be neutral, leading this step to be much less impactful on climate change than for the other petroleum-based polymers. In that respect, avoiding incineration of biobased materials does not lead to substantial environmental benefits.

Regarding PET, the production of flakes from bales appears to be far from negligible. This step is not highlighted for the other polymers but is directly accounted in the extrusion-spooling stage. See the work package T2 2.1 report for more details.

It is worthy to note that these observations are relevant to a one-to-one comparison over a single recycling iteration. However, products made from recycled filaments can be additional recycled 2 more times before chemical additive and or a percentage of virgin plastic is mixed with the recyclant to start the process off again where another 4 additional cycles can take place. This implies a savings of virgin polymer each time it is recycled.

3. Economic analysis of the treatment options

3.1 Landfilling

The UK, among the partner countries within the TRANSFORM-CE project, is the only country that allows direct landfilling of waste materials. The other countries have a legal obligation to send the waste to an energy from waste (EfW) facility to produce electricity and heat energy. Only the residual from the EfW plant can be landfilled.

The transportation cost to take the plastic waste to the landfill is not known and will depend on distance travelled from the owner to the landfill site. The mean cost to put the plastic in a non-hazardous landfill was £116.70 per tonne for 2022 (WRAP, 2022). Once in the landfill it gets completely contaminated and can begin the breakdown/degradation of its structure. Therefore, for every tonne saved from land fill there will be a savings of £116.70. this means value of a tonne of plastic that would have gone to a landfill but is now used for IEM or AM starts of at a -£116.70. It is not known whether this value offsets the transportation cots to an EM of AM reprocessing plant or if there is a savings on each truckload a waste management company sends to a IEM or AM plant. However, if the plant operates using circular economic principles, like the Save Plastics plant, the MRF (Cirwinn) is very close by, therefore there will be negligible transportation costs, and a CO_2 savings in transportation fuel.

3.2 Burning to make fuel at an energy from waste (EfW) plant

The transportation cost to take the plastic waste to the EfW plant is not known and will depend on distance travelled from the waste owner to the EfW plant. However, if the IEM or AM processing and production facility in on or next to the MRF there will be no traveling of the plastic. When the waste gets the EfW the gate fee will be £90.00 per tonne for 2022 (WRAP, 2022). In the Netherlands it is between €100 and €150. Once in the EfW plant it gets completely destroyed by burning. It is presumed that there is no residue plastic left to send to landfill. The £90 should be taken as a full saving, as it excludes transportation cost. If the IEM or AM filaments plant procures the waste plastic according to circular economy rules, then the distance the waste travels is minimised. This means a further saving in the costs of the feedstock. Therefore, in accounting terms, the feedstock comes with a savings that represents a negative value that will offset the equivalent value in the processing costs of the plastic.

3.3 Producer Responsibility Scheme (PRS)

Under the PRS, the MRF receives between 150-250 euros per tonne of packaging plastic it processes. If it must then pay to send it to the EfW plant, this is a cost. Therefore, giving it away for free to an IEM plant has an economic advantage to the MRF over sending it to an EfW plant, especially if the MRF does not pay for the delivery to the IEM plant.

3.4 Using plastic for AM and IEM

It is understood that when comparing the three common treatment options the calorific content of the plastic waste will be the same and therefore there is no need to know its actual value. What is know is that when the plastic is burnt the calorific content is destroyed after one use. When put in landfill while it is not destroyed it will degrade over time but not get completely destroyed for hundreds of years. However, when single use plastic is used in IEM the calorific value of the plastic is not only preserved but it is used multiple times thus displacing multiple calorific contents of virgin plastic. It must be understood that the use of single use foils that are at this time not being recycled implies that the first time it is used for IEM is a savings of co_2. This means that by reusing the plastic multiple times, there will be multiple savings of virgin plastic, plus the preservation of the original plastic.

If it is used as part of a circular economy, then after use there is the possibility of using chemical recycling to bring it back into 'virgin' plastic. Any loss of plastic that happens each time the plastic is reused is not taken into consideration as it is not known.

4. Recommendations

"It was reported that MRF residues (10-12% of total input material) have been sent from waste management providers to Energy Recovery treatment, which included plastic pots, tubs and trays and 'low-grade plastics. Contractors have said this 'non-target' plastic ends up in Energy Recovery, Refuse Derived Fuel (RDF) and Solid Recovered Fuel (SRF). Plastic film was generally reported to be going to Energy Recovery, and there is strong feeling that film collection and recycling isn't being addressed in a logical way. It was reported there needs to be an incentive to collect, sort and recycle film, but only as long as there are practical collection and sorting solutions and commercially viable end markets." (RECOUP, 2019). Similarly, a Local Authority reported at a TRANSFORM-CE workshop that "*they are struggling to find markets for the 'mixed plastics'*". Therefore, if the AM market, that uses non-food grade plastic, and the IEM industry that uses low grade plastics, are to successfully grow, there is a need to secure a long-term reliable supply of feedstock.

To secure a long-term reliable supply of feedstock there must be the political will. The municipalities are ultimately the ones who give the waste management licenses to the MRFs. This means that if, for example, the Greater Manchester Waste Management Authority change the company from Viola to Viridor to Suez every few years, the operators of the IEM plants lose their local supplier of feedstock and must not only negotiate with the new MRF licensee but have to convince them about the socioeconomic value and the environmental sustainability of sorting or providing the correct feedstock for the IEM plant. At the beginning of a new contract the waste management company concentrate on providing the ordinary MRF outputs streams without warrying about the secondary supply of low value thin films to a local IEM company. Therefore, the collecting, sorting and provision of feedstocks for any new AM or IEM plants must be embedded into the political landscape and become policy.

The problem with local politics it that power can change hands to different political persuasions more often than the contract period that the waste management companies receive. This means that unless there is local will or the IEM company gets its' feedstock from far away, something that is not within the remit of a circular economic model, the company will be forced out of business. Therefore, one way of securing long term success is if collecting and sorting low value thin film plastics will be a central government decision backed up by legislation. This is similar to the banning of direct landfilling of plastics, which now have to be burnt for energy generation, a policy which was only taken up by everyone once it became law.

4.1 Future research recommendations

So far, as part of the LCA for this project, analysis on the advantages of AM and IEM have been carried out on a one-to-one basis. Future work should look at how the multiple reuses of IEM embedded plastics up to 9 more times and AM up to two more time, will affect the environmental and economic LCA over all these iterations. This should be carried out with a comparison of the amount of wood or concrete substituted over the full 10 times of IEM and 3 times for AM.

For example, if a wooden fence, without being painted multiple time with wood preserve, lasts 15 years, then given the conservative estimate of 400 years of 10 plastic fences the comparison will have to be, 10 plastic fences must be compared to 26.6 wooden fences. Future work can look at different scenarios and different materials that are being substituted.

For the negative impacts on any of the criteria within the LCA, further work will have to be carried out to identify how many iterations of the use of the plastics will have to occur before the impact becomes positive.

5. Conclusions

This report identifies three common treatment options for plastic waste, landfill, burn it to generate energy or recycle into new products using AM and IEM technology. The first two are end-of-life treatments while the Transform-CE recycling technologies are upcycling and recycling plastics for up to 10 iterations each time substituting for a comparable material.

The following conclusions were identified through the LCA.

- Regarding climate change impacts, avoiding incineration of waste is shown to be the most relevant step to the net benefits, as incineration is linked with the high GHG emissions.

- The multiple use of waste plastics in AM and IEM manufacturing leads to excellent climate change potential benefits.
- For success of the waste plastic flows collecting and sorting will only be successful if embedded into central government policy.
- Potential impacts linked to collection, sorting and transport steps appear to be very low in comparison with the impacts/benefits linked with the recycling process, avoided incineration and substituted primary products.
- For the majority of the other impact categories, avoiding incineration of the waste implies a net impact. This is due to the consideration of waste-to-energy incineration avoidance. In that respect, this energy production avoided has to be produced from classical sources (country-specific electricity mixes used as baseline), implying an increase in environmental impacts.
- For all types of polymers, the system is net beneficial for almost all impact categories, mainly due to the avoided production using virgin plastics.

It is worthy to note that the observations carried out by the LCA were relevant to a one-to-one comparison over a single recycling iteration. However, products made from recycled filaments can be additional recycled 2 more times before chemical additive and or a percentage of virgin plastic is mixed with the recyclant to start the process off again where another 3 additional cycles can take place. This implies a savings of virgin polymer each time it is recycled. Therefore, the whole time period (for IEM 400 years) must be considered.

This should be carried out with a comparison of the amount of wood or concrete substituted over the full 10 times of IEM and 3 times for AM. For example, if a wooden fence, without being painted multiple time with wood preserve, lasts 15 years, then given the conservative estimate of 400 years for 10 plastic fences, the comparison will have to be, 10 plastic fences must be compared to 26.6 wooden fences and just 10.

As a very high degree of purity of a single polymer is required for AM feedstock, the processes the plastic has to go through is equivalent to that of commercially available plastic pellets. Therefore, there is also no extra impacts, besides extra drying, if the plastic is used for AM. However, IEM manufacturing can use low quality plastics, therefore IEM needs far less stages of handling. Therefore, for the handling aspect of the treatment IEM offers savings of both economic and environmental impacts.

Plastic for IEM manufacturing does not need any cleaning. Therefore, IEM consumes less water, chemicals, and energy to run the cleaning process than that for AM. However, as high-quality plastics are used for other manufacturing processes besides AM, AM offers no advantage or disadvantages in resources used during the cleaning prosses over the use of the same plastic in other commercial manufacturing processes.

The use of low-grade mixed polymer thin film plastic is a unique novelty of the IEM processes developed within the TRANSFORM-CE project. Save Plastics have developed a recipe that can use, 100% low grade mixed plastic thin film waste, to make products. Other companies may include a small percentage of thin films in their formular, or only use single polymer thin films to produce pellets, but most of the feedstocks are higher grade HDPE or LDPE which are hard plastics.

It can be concluded that there is a smaller economic and CO2 emissions cost for IEM than for AM manufacturing. This is due to the purity of the recyclant. For AM that requires very dry single polymer plastic more stages of treatment are needed and therefore more recourses are expanded. However, for IEM much less processing and therefore resources are required.

It is concluded that over the very long lifetime of the plastic used in AM and IEM compared to the other treatment options, i.e., landfilling or burning to generate energy, and including the multiple savings of materials being substituted, the TRANSFORM-CE AM and IEM processes give great economic and environmental and use of resources gains

6. References

10-xl. (2022). https://10-xl.nl/

Canopoli, L., Fidalgo, B., Coulon, F., & Wagland, S. T. (2018). Physico-chemical properties of excavated plastic from landfill mining and current recycling routes. *Waste Manag*, *76*, 55-67. https://doi.org/10.1016/j.wasman.2018.03.043

Cappucci, G. M., Avolio, R., Carfagna, C., Cocca, M., Gentile, G., Scarpellini, S., Spina, F., Tealdo, G., Errico, M. E., & Ferrari, A. M. (2020). Environmental life cycle assessment of the recycling processes of waste plastics recovered by landfill mining. *Waste Manag*, *118*, 68-78. https://doi.org/10.1016/j.wasman.2020.07.048

EU Commision. (1994). *Packaging and packaging waste EUROPEAN PARLIAMENT AND COUNCIL DIRECTIVE 94/62/EC*. https://bit.ly/3XmNvz7

GOV.UK. (2022). *Plastic Packaging Tax: steps to take*. https://www.gov.uk/guidance/check-if-you-need-to-register-for-plastic-packaging-tax

Kasetsart University & Indorama Venture PCL. (2022). Municipal Solid Waste Sorting and Plastic Waste Management. https://bit.ly/3TgZLiR

Plastic Europe. (2022). *Plastics – the Facts 2022*. https://bit.ly/3EGk0Rz

Plastics Europe. (2020). *The Circular Economy for PLastics, A European Ovewrview*

RECOUP. (2019). *Local Authority Plastics End Market Analysis, May 2019*.

Saveplastics. (2022). *#we_save*. Retrieved 2023 from https://saveplastics.nl/

Shamsuyeva, M., & Endres, H.-J. (2021). Plastics in the context of the circular economy and sustainable plastics recycling: Comprehensive review on research development, standardization and market. *Composites Part C: Open Access*, *6*, 100168.

SUEZ. (2021). *Mapping the value chain for flexible plastic packaging in the UK*. https://www.suez.co.uk/en-gb/news/list-of-publications

WRAP. (2022). *Comparing the costs of alternative waste treatment options*. https://bit.ly/3znL9qx

WWF Deutschland. (2021). *Burning Questions – Pathways to a circular plastic packaging system in Germany*. https://bit.ly/3gJDA7F

Zhang, F., Zhao, Y., Wang, D., Yan, M., Zhang, J., Zhang, P., Ding, T., Chen, L., & Chen, C. (2021). Current technologies for plastic waste treatment: A review. *Journal of Cleaner Production*, *282*, 124523.

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