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Recycling pathways of post-consumer plastic packaging waste in Europe

NTCP & HTP

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Executive summary

Project background

Invest-NL is looking for more insight and quantification on the technical and economical situation of recycling pathways for post-consumer plastic packaging waste within Europe related to the different European schemes.

Objectives

The objective is to provide Invest-NL with an overview and, where possible, a quantification of plastic recycling in Europe nowadays and developments towards the future to support their future investment decisions on plastic recycling technologies. This report focuses on the plastic packaging waste system on European level, country-specific level (for the Netherlands, Belgium, Germany, and France), and the Netherlands in-depth. Moreover, a technology scan discusses the current and upcoming technologies.

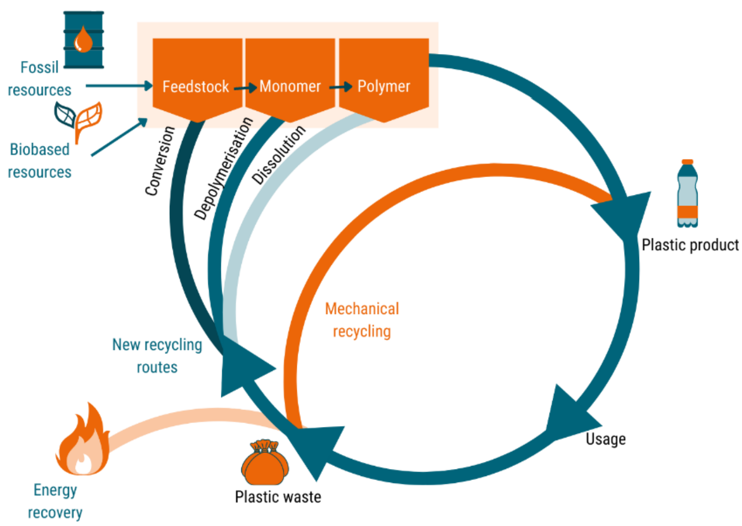
Current packaging waste system

On a market level, the co-mingled Municipal Solid Waste (MSW) is collected differently in different countries. This results in different requirements for sorting technologies. Additionally, the number of valuable sorting output streams varies from country to country. When it comes to plastic packaging, the sorting facilities in the Netherlands sort on PET bottle, PET tray, PE rigid, PP rigid, film, and mixed plastics (some exceptions exist). In comparison to other countries, this number of valuable sorting output streams is rather limited. Moreover, the amount of waste going to incineration and landfill varies as well.

In terms of legislation and guidelines, EPR schemes are implemented in all EU countries. The implementation per country differs. In addition, the recycling rates are often averaged over multiple systems per country, which could hide base performance in certain areas. Also, the current interface to calculate recycling rates is at the input of a reprocessing facility. The European directive has set targets for recycling rates. In 2025, 65 % of packaging needs to be recycled, and for plastic packaging, 50 % needs to be recycled. Currently, the rate for plastic packaging recycling is around 25 %.

There are different steps in the process of plastic packaging recycling. Plastic is first collected, then sorted, followed by reprocessing to a dry clean flake. This dry clean flake then enters either mechanical or chemical recycling. The figure below provides a (simple) overview of the system. Currently, the main recycling method is mechanical recycling. Facilities are designed and operated to be sufficient for the set targets by the Producer Responsibility Organisations (PROs). In the reprocessing step often yields are maximized, despite the amount of contamination. Overall, there are few incentives to increase the quality and yield at the same time.

One of the challenges in composing this report was the access to detailed data on the different plastic packaging waste streams. The market in this field is rather closed when it comes to sharing of waste stream and recycling data. Our advice to the players in the value chain is to develop an (anonymised) way of sharing this data.



Developments in the plastic packaging waste system

In the plastic packaging market we noticed various trends.

- A decrease in unit mass is observed linked to the focus on plastic reduction for packaging. As a consequence this leads to an increased use of flexible packaging, and subsequently, a higher demand for high barrier (multilayer) and composite materials. These multilayer and composite materials ensure that the packaging maintains the right properties. However, they also require different sorting, reprocessing, and recycling technologies.
- An overall increase in the use of packaging. An example of this is the increase in packaging used in e-commerce.
- An increase in the use of paper composites. While perceived as 'sustainable' by some, these composites are troublesome in sorting, reprocessing, and recycling.
- Bio-based and bio-degradable plastics volumes are increasing. Some bio-based polymers can be used as a drop-in replacement for virgin plastics. These polymers are not distinguishable from virgin, thus, good for maintaining a circular value chain. However, there are also bio-based polymers that are technically sortable, but still too low in volume and therefore not sorted (and recycled). Bio-degradable polymers are not circular since the idea is that they degrade.
- An increase in producer awareness of the usage of recycled plastics in their packaging. For example, producers choose polymers that are available as high-quality recyclates such as PET packaging in cleaning or dairy products. This could however have a negative effect on PET streams when no deposit refund scheme is in place.

Next to packaging developments, we also discussed developments on a market level.

- An increase in the use of reusable packaging. Examples of this are refill stations at supermarkets, to-go cups, and take-away food.
- Vertical integration in the market. Here companies such as packaging producers and retailers vertically integrate with companies on the 'other side' of the value chain such as recyclers (*e.g.* Schwarz Group).
- As a consequence of stricter export regulations, there has been a decrease in the transport of plastic packaging waste to countries outside of the EU. Next, in general, the capacity for reprocessing and recycling has been increasing, as well as the demand for more high-end recyclate. As mentioned above, there has been an increase in producer awareness. This relates to brand owners also taking more responsibility by for example joining pre-competitive consortia. In collaboration with other brand owners (and other stakeholders in the value chain) these consortia work on increasing the circularity and sustainability of the plastic packaging value chain.
- Newly built sorting facilities typically create more valuable output streams (especially PE flexibles).
- In order to meet the recycling targets, the collection schemes have been extended. For example in Belgium, they extended their packaging waste collection from certain plastic packaging to all plastic packaging. On a country level, in the Netherlands, there has been a decrease in litter due to the extension of the deposit refund scheme.

On legislation and guidelines, there have also been developments on both European and Dutch levels.

- On European level, there has been a change of measurement point with respect to what is called recycled material.
- The targets of the use of post-consumer recyclate in packaging products have been increased.
- Improvements in recycle checks are in place, which enable brand owners to check their packaging on recyclability. In the Netherlands, the deposit refund scheme extended to also include smaller PET bottles. In addition, there is also an extension of the EPR scheme to also include commercial household-like packaging waste.
- In the near future more extensive diversified PRO fees to increase the recyclability of packaging are expected.
- With respect to food safety EFSA is setting stricter requirements for the use of recycled plastics in food packaging materials. In this report we have not focused on this specific topic, but it will have an effect on the use of recycled plastics in food packaging.

The upcoming technologies we described are also an important part of the future outlook.

- Hot-wash development, designed to acquire high-quality recyclate, in the reprocessing step for polyolefins is gaining momentum.
- To improve the quality of recyclate there are also other developments such as extended deodorization, refreshing, and deinking.

- Artificial intelligence is getting attention in the industry. AI vision systems can be used to analyse waste streams or to assist in sorting.
- Other developments in sorting are the use of markers to sort packaging and the replacement of hand pickers in the quality line with robots. In general, there is an increase in automation in sorting and reprocessing steps.
- Different recycling technologies such as solvent-based mechanical recycling and depolymerization are being explored in addition to conventional mechanical recycling.
- Use of pyrolysis as a recycling technology for polyolefins has received more attention and is being scaled up. For this, there is a demand for polyolefins as feedstock, which could be in competition with mechanical recycling.

Conclusion

Our study indicates that the plastic recycling in Europe is complex: the market is not open but regulated by varying EPR schemes, no standard for input or output of treatment facilities and no clear preference yet for recycling routes. As such, it is very difficult to clearly identify the best technologies from a technological point of view. This is because the performance of these technologies

a) is depending on the system they will be deployed in, which are largely dominated by legislation that varies between countries, and
b) should be evaluated from its impact on the entire chain. For example, a very efficient technology may result in a very small high value-stream but may leave an exceptionally large low-value stream that ends up in the incinerator. Overall, application of this technology may therefore have a limited or even negative impact on sustainability criteria (use of fossil resources, CO_2 emission, *etc.*).

Both the system and the technologies that are operated in the system are currently in full and rapid development and are interdependent. We conclude that the system is still diverging with many innovative technologies being developed and it seems premature to clearly prioritize any at this point. On the short term, while the system is diverging, there is probably a benefit to support as much technology developments and as many initiatives as possible, but with the awareness that a selection of prospective technologies is expected once the system settles down and starts converging. For new technologies to be applicable in the (future) system, the following drivers are deducted from this study:

- demand for higher recycling rate to meet European recycling targets;
- application driven quality requirements to the recyclate;
- increased use of plastic packaging, in particular of flexible materials;
- stringent legislation regarding food-contact materials;
- increased use of bio-based (non-biodegradable) polymers.

This implies that not all technologies will prevail, which may be a consequence of legislative and other choices rather than technological performance. It is highly likely that successful technologies will be those that can combine high technological performance with a perfect fit to the system that it has to operate in, and maybe even those that are able to fit the system to their technology. In order to support and advise on the system choices that have to be made to get to a convergence of the system, it is recommended to set-up technology evaluation procedures that will not only consider technical and financial performance but also qualitatively and/or quantitively considers the impact of the technology on the entire chain. Thus, it is recommended to set-up performance indicators that consider the full chain, which will require a thorough understanding of the plastic recycling chain, and to challenge technology developers to quantify their impact on the entire chain rather than the technological performance alone.

Contents

1 Introduction

1.1 Invest-NL

Invest-NL is a Dutch investment organisation with the ambition to make the Netherlands more sustainable and more innovative towards the future. Their aim is to achieve this by financing projects and businesses, as well as by providing advice and/or carrying out research on how to enable financing for business cases. The increase of plastic recycling percentages is one of the focus areas of Invest-NL for which several potential projects are present in their portfolio.

1.2 NTCP

The National Test centre for Circular Plastics (NTCP) in Heerenveen (The Netherlands) was established in 2018 to facilitate the development of sorting and washing of the different plastic streams from municipal waste. A pilot scale sorting line, representative for European plastic sorting centres, fully customized for test- and research, is available to support the development of more efficient plastic recycling. This is done by facilitating the design process (support design for recyclability), facilitating technology development (real life testing of the process on pilot scale) and the development data-driven decision models for sorting. At this stage, a pilot scale washing line including industrial size equipment and customized for test- and research is being realized at the NTCP.

Figure 1. Sorting line (left) and schematic representation of recycling line (right) at NTCP.

1.3 HTP

Engineering company HTP GmbH & Co. KG is an independent, owner-managed planning and consulting company for the recycling and renewable energy sectors. Independence, flexibility, and dedication, combined with 25 years of experience and expertise gained at over 100 reference plants, have made HTP the leading engineering service provider in the field of process and plant design for waste management and recycling.

The core competencies of HTP cover the entire range of plant engineering for the treatment of waste, including residual waste and packaging as well as plastics, paper, C & I bulky waste.

HTP offers the right advice and support for processes and investments in the field of environmental technology: strategy development, technical consulting, engineering planning, project management, due diligence. HTP provides all of these services.

New construction or modernization of waste treatment and recycling facilities: with the support of experts from HTP, the implementation of investment projects is guaranteed to be innovative, safe, and professional.

The HTP experts provide advice, reviews, calculations, evaluations, assessments, and certifications based on the latest technology and many years of experience.

1.4 Project background

Invest-NL is looking for more insight and quantification on the technical and economical situation of recycling pathways for post consumer plastic packaging waste within Europe related to the different European schemes. A special focus on reprocessing pathways, including recovery rates, yields, purities, *etc.* for current recycling processes and future technologies in the market for PET, PP and PE. This information can be used for future investment decisions.

1.5 Project objectives

The objective is to provide Invest-NL with an overview and, where possible, a quantification of plastic recycling in Europe nowadays and developments towards the future to support their future investment decisions on plastic recycling technologies. Specifically, the following points are discussed in this report:

- General overview on definitions and terminology used within the plastic recycling market
- General setup of processes and current product range (input for subsequent reprocessing)
- General overall scheme of plastic packaging recycling in western Europe exemplary for the Netherlands, Belgium, Germany, and France including EPR instruments
- Detailed overview of plastic packaging sorting recycling processes in Netherlands (collection- sorting-reprocessing)
- Overview of existing technologies and upcoming technologies.

2 Glossary

This chapter provides an overview of the definitions of relevant terms used in this report. Moreover, it includes explanations of calculations. The following section also shows these calculations in a figure.

2.1 Sorting facility

Term	Definition
Sorting facility	Facility for the dry separation of waste on object level (e.g. bottle, tray, bag) by material type, colour, size etc. for further recycling
Object mass	Total mass of a waste object including cap, label, surface contamination, moisture, residual content, etc.
Mass Balance Yield	Mass-percentage of output material stream versus input stream
Process Yield/ Recovery	Mass-percentage of target objects in a specific output stream versus available target objects in the process input stream
Purity/ Quality Level	Mass-percentage of target objects versus other materials (object level) in a stream

2.2 Reprocessing facility

Term	Definition
Reprocessing facility	Facility for dry and wet cleaning of pre-sorted waste from sorting facilities on flake level; production of a flake product or regranulate
Dry mass	Total mass of dry objects/flakes/regranulate excluding non-target material (labels, caps, additives, etc.)
Wet mass	Total mass of wet objects/flakes/regranulate excluding non-target material (labels, caps, etc.)
Mass Balance Yield	Percentage of dry mass product stream versus dry mass input stream
Process Yield/ Recovery	Percentage of dry mass target material in a specific output stream versus available dry mass target material in the process input stream
Purity/ Quality Level	Mass-percentage of dry target material versus other dry material in a stream

2.3 Value chain

Term	Definition
EPR	Extended Producer Responsibility – Packaging producers (e.g. brand owners) are required to take financial and/or physical responsibility for the waste treatment of packaging they put on the market
PRO	Producer Responsibility Organisation – Organisations that assume the Extended Producer Responsibility of multiple producers for license fees and organize a joint waste collection and treatment system. Depending on the country only one or multiple PROs in place.
Source-separation	Separation of waste by material type at households (typically: Plastic packaging (+metal packaging & drinking cartons), paper + carton, Biowaste, residual waste)
Post-consumer separation	Partly or fully mixed collection of household waste to be separated at a sorting facility. (*e.g.* Dutch Nascheiding system: plastic packaging + residual waste)

3 Approach

During the kick-off meeting with participation of Invest-NL, NTCP and HTP, we discussed the approach and specific needs in relation to the objectives of this study. Based on that we came to the following approach.

3.1 System overview

To produce the plastic packaging system overview, we performed a literature review, consulted relevant industry experts, explored secondary data, and used our own knowledge built up in plastic value chain projects. During the process we gathered data from multiple sources and prioritised based on completeness of data sets.

The material flows in different European countries are based on different extended producer responsibility schemes in the different countries. This also gives an impression of the complexity of plastic packaging waste on a European level.

3.2 Technologies

For the overview of current technologies, we gather data from technology providers, sorters, recyclers, engineering companies, and public data. Despite the fact that the systems are not the same in different countries, the used technologies actually do not differ; it is only the order and how the technologies are used that differ (process design). With current technologies we mean those that are widely used in Europe.

For the assessment of any new technologies relevant for plastic recycling, we describe them based on the intended application with a listing of its strengths and weaknesses. Additionally, we list (existing) competitive technologies that could influence the choice for such a technology. Eventually, we score those technologies from "+ +" to "- -" on **maturity**, **costs**, **implementation effort**, **potential**, and **overall** and we present the rationale behind each of these ratings. We have chosen a qualitative rating as the choice of a technology is strongly dependent on the overall process flow.

4 Plastic packaging waste system – European Union

For most European countries, the impulses to build up and extend their waste management and recycling system, especially for post-consumer plastic packaging waste, have been given by the regulations and targets set by the European Union. Not only the current recycling targets but as well those already set for the future, do influence the packaging and recycling market in a way that innovation both in packaging design as in technology development is pushed. In the following chapter, the current and future requirements, and targets for plastic packaging waste on European level as well as the status of waste management and recycling regarding quotes and mass flows are discussed.

4.1 Legal framework

4.1.1 Waste framework directive 2008/98/EC

The waste framework directive, last amended in 2018, is setting the general framework for the handling and treatment of waste in the European Union. To have a collective understanding of the terminologies used, the directive set down the basic definitions on waste, recycling and the stakeholders involved.

Post-consumer plastic packaging waste is allocated under municipal waste in the waste framework directive.

Definition municipal waste: "mixed waste and separately collected waste from households, including paper and cardboard, glass, metals, plastics, biowaste, wood, textiles, packaging, waste electrical and electronic equipment, waste batteries and accumulators, and bulky waste, including mattresses and furniture [1].

4.1.1.1 Waste hierarchy

Key item of the waste framework directive is the waste hierarchy requiring the member states to encourage stakeholders reaching for the highest available level of waste prevention and/or treatment.

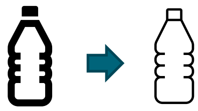
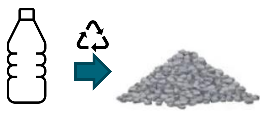
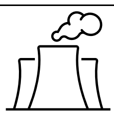
Prevention		Reduce the quantity e.g. by reducing weight of a plastic packaging; reduce adverse impact e.g. by designing a high-level recyclable packaging
Preparing for reuse		Use the item again after check + clean + repair *e.g.* reusable drink bottles via the deposit scheme
Recycling		Reprocessing (mechanical or chemical) of waste into a product/ material/ substance usable to replace virgin material *e.g.* regranulate from plastic recycling facilities replacing virgin plastic; usage as energy source (incineration) or for backfilling is specifically excluded here
Other recovery, e.g. energy recovery		Use of waste as an energy source, *e.g.* refuse-derived fuel (RDF) from municipal waste used in the cement kiln industry.
Disposal		Any operation which is not material recovery (recycling) or energy recovery, *e.g.* landfill

Figure 2. Waste hierarchy.

The effect of the implementation of the waste hierarchy is visible over the life cycle of plastic packaging.

Packaging producers acknowledged "prevention" in the past years by reducing the weight of packaging for instance by replacing rigid plastic packaging with film packaging or change from plastic to paper packaging with the expectation of providing a better recyclable good. Not all adaptions with the target of "prevention" can be rated solely positive. Even though a reduction of waste mass is positive, the shift from rigid monomaterial plastic packaging to film packaging caused in some cases a decrease of recyclability due to a recycling-critical multimaterial composition of the film which is necessary to provide comparable packaging functions. Also, the shift to paper packaging is to be seen critical when the recyclability is harmed by the multimaterial composition of e.g. paper and plastic to achieve the necessary wet strengths.

Systems for re-use are in place for several years now, the most popular is the deposit system for reusable glass and plastic bottles. In the past years, several food shops or event locations aimed to implement a re-use system as well for to-go cups or food trays.

Collected plastic packaging waste from households not adapted to a re-use system take their waste treatment pathway mostly either towards recycling or energy recovery. The decision of what pathway is chosen lies not only in the packaging design but as well in the technical feasibility and economic viability as pointed out in the waste framework directive (see Article 4, 2., section 3). Current reality shows that the implementation of a recycling pathway with collection-sorting-reprocessing-recycling for a certain plastic packaging type is not considered economically viable until a certain share (definitely more than 2 %) is available in the collected waste mix. Even though technically feasible this applies to e.g. PS in certain member states or types of Bioplastics.

4.1.1.2 End of waste

The concept of end-of-waste was established in the European Waste Framework Directive. Adoption in domestic law is achieved through Article 28 of the European Communities (Waste Directive) Regulations 2011. End-of-waste gives waste holders the opportunity to demonstrate, with an appropriate level of rigour, that:

- A waste material can be 'fully recovered' and no longer be defined as waste.
- The waste can be used as a 'secondary' resource in place of and fulfilling the same role as a non-waste derived or virgin 'primary' resource.
- New innovations can transform waste into a valuable resource.
- The fully recovered material can be used without causing overall adverse impacts to the environment or human health.

The end-of-waste test is made up of four pillars; all of the four pillars must be met.

- The substance or object is commonly used for specific purposes.
- A market or demand exists for such a substance or object.
- The substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products.
- Use of the substance or object will not lead to overall adverse environmental or human health impacts.

An overriding requirement is that the material must have undergone a recovery operation. In this context the extended producer responsibility scheme plays a significant role. The end-of-waste status is still open to interpretation and debate and no full description can be given and is eventually governed by domestic legislation. For innovative technologies, this debate may lead to difficulties in receiving an end-of-waste status for their output products.

4.1.1.3 Extended producer responsibility

The consideration of economic viability is significant for the operators of the waste treatment systems for plastic packaging waste from households. The waste framework directive specifies that the responsibility to install and operate the packaging waste collection and treatment lies with the packaging producers, so called "extended producer responsibility" (see article 8).

For post-consumer plastic packaging waste, common practice for the packaging producers is to license with a so-called producer responsibility organisation (PRO), which takes over the responsibility from the producers and takes license fees to fund the collection and treatment system. Umbrella organisation for PROs using the "Green Dot" trademark is PRO Europe with members like Afvalfonds Verpakkingen (NL), Fost Plus (BE), Der Grüne Punkt (DE), Citeo (FR) or ecoembes (ESP).

4.1.1.4 Waste management targets

Following the waste framework directive, member states are obliged to set target values (quantitative and qualitative) for the PROs to be achieved. As a minimum the following is required for municipal waste:

Table 1. Waste framework directive - waste management targets in mass fraction (Article 11, 2. (a)-(e)).

Waste hierarchy level	Target (in mass fraction)			
	2020	2025	2030	2035
Preparing for re-use + recycling	50 %	55 %	60 %	65 %

The recycling target values set by the European Union require a mixed calculation of the member states according to the various collection and recycling pathways in place for municipal waste like plastics, paper, metals, biowaste etc. which can lead to in imbalance of recycling rates in between the material types not visible in the quotes reported to the European Union. For example, high recycling rates for paper and cardboard might balance low recycling rates for plastics hiding the negative environmental impact of non-recycled plastics.

Putting packaging waste and especially plastic packaging waste more in focus of supervision, the European Union set an additional directive into force, the Packaging Directive.

4.1.1.5 Directive on packaging and packaging waste 94/62/EC

The packaging directive, last amended in 2018, harmonizes the understanding, handling and targets for packaging and packaging waste. Packaging is categorized following Article 3 of the directive in three types:

- Primary packaging / sales packaging - packaging containing the product to be sold; if private customers consume the product this packaging is most likely to end up in municipal waste
- Secondary packaging / grouped packaging – packaging containing a number of packed goods to be sold, for example a case for water bottles; depending on whether a good for private customers is sold with the secondary package or not, it either ends up in municipal waste or commercial waste
- Tertiary packaging / transport packaging – packaging used to secure the good during transport or enable handling of larger quantities for example a plastic bag; depending on whether the good is transported to a private household or an industrial customer it either ends up in municipal or commercial waste.

With the increase of e-commerce over the past years turning away from purchasing goods in shops, waste volumes of secondary and tertiary packaging increased in the collection scheme of household waste.

Picking up the Extended Producer responsibility introduced by the waste framework directive, the packaging directive obliges the member states to ensure the implementation of PROs or equal regimes for all packaging until end of 2024 (see article 7 (2)). The results are already visible with the extension of collection schemes all over Europe for example the extension of the separate collection for post-consumer packaging waste in Belgium by film packaging and rigid plastic packaging other than bottles (PMD+).

Following the waste hierarchy of the waste framework directive, the packaging directive is setting targets specified for packaging to be implemented by the EU member states.

<table>
<tr><td>Prevention</td><td colspan="2">Maximum consumption of lightweight carrier bags:
• by end of 2019 – 90 pieces / capita*a
• by end of 2025 – 40 pieces / capita*a
and/or
• by end of 2018 – pieces not provided free of charge (or measures equally effective)</td></tr>
<tr><td>Preparing for reuse</td><td colspan="2">A certain share of reusable sales packaging placed on the market for the first time can be considered within the recycling targets to be met.
Encouraging measures to increase share of reusable packaging, e.g.:
• use of deposit return schemes
• setting of qualitative or quantitative targets
• use economic incentives
• target value minimum percentage of reusable packaging placed on the market by packaging stream</td></tr>
<tr><td>Recycling</td><td>Recycling targets 2025 in mass fraction
– 65 % for all packaging
– 50 % for plastic packaging
– 70 % for ferrous metals packaging
– 50 % for aluminium packaging
– 75 % for paper + cardboard packaging
– 70 % for glass packaging
– 25 % for wood packaging</td><td>Recycling targets 2030 in mass fraction
– 70 % for all packaging
– 55 % for plastic packaging
– 80 % for ferrous metals packaging
– 60 % for aluminium packaging
– 80 % for paper + cardboard packaging
– 75 % for glass packaging
– 30 % for wood packaging</td></tr>
</table>

Following the packaging directive, the calculation of the recycling rates is based on the relation between generated and recycled packaging waste in a year.

If no collection figures or comparable are available, market figures are deemed to be equal for the amount of generated packaging. This equalization is to be seen critical regarding the evaluation and comparison of generated packaging waste in EU member states because the amount of collected packaging waste is in often lower than amount of packaging put on the market due to losses into other waste flows, littering or longer storage/use time (e.g. buckets and canisters).

The amount of recycled packaging waste is to be measured either at the infeed into the final recycling operation transforming waste into product/material/substance, or at the output of any sorting operation ensuring that the material is subsequently recycled and reduced by the non-recycled amount removed in the recycling process. This is different to the calculation method used until 2020, where no deductions from the sorted output had to be made.

With the Commission Implementing Decision (EU) 2019/665 the calculation point for the amount of recycled packaging is specified more in detail. For plastic packaging the amount of recycled material has to be measured right before entering a pelletisation, extrusion or moulding operation or at the status where they are provided as plastic flakes for direct use in a final product with no further processing. For composite and multi-material packaging only the material type entering recycling at the material-type specific calculation point is considered.

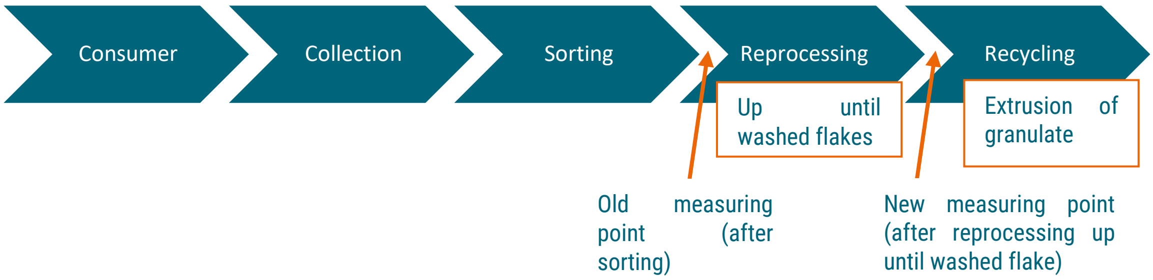


Figure 3. Change in measuring point.

Due to this interface change a drop in reported recycling rates takes place and during the implementation phase in every EU member state comparability is not given.

In a comparison of the old and new calculation method by the German Environment Agency of the recycling rates for plastic packaging reached in 2019 are 54.3 % to 43.3 %, respectively [2]. With the old calculation method, the recycling target for 2025 was already achieved and only a minor increase seemed necessary for the target set for 2030. With the new calculation method, the PROs are forced to take action to increase the efficiency of their waste treatment system significantly as well as include the packaging producers to bring packaging with a high recyclability on the market recoverable in the scheme.

With the instrument of Extended Producer Responsibility proven operable for the packaging waste recycling system, the European Union introduced this instrument as well in the sector of single-use plastics with the Single Use Plastics Directive EU 2019/904.

4.1.1.6 Single Use Plastics Directive EU 2019/904

The single-use plastics directive from 2019 defines further requirements regarding the handling of plastic waste including not only plastic packaging but plastic waste from single-use application in general.

Definition single-use plastic product: "'single use plastic product' means a product that is made wholly or partly from plastic and that is not conceived, designed or placed on the market to accomplish, within its life span, multiple trips or rotations by being returned to a producer for refill or re-used for the same purpose for which it was conceived;" (Article 3(2)). Examples are plastic cutlery, beverage bottles, lightweight plastic carrier bags or balloons.

With this directive, producers of products falling under the definition of single-use plastic products must take over extended producer responsibility as defined in the waste framework directive, contributing financially to the waste collection and treatment scheme (to be) established for single-use plastics.

Similar to the packaging directive, the waste hierarchy of the waste framework directive is the centre point. In the following table, an extract of key regulations influencing the existing waste treatment systems is shown.

Prevention	The following plastic items are prohibited from being placed on the market: • Cotton bud sticks • Cutlery and plates • Straws • Stirrers • Balloon sticks • To-go food and beverage containers + cups made of expanded polystyrene (EPS) Measurable quantitative market volume reduction of To-go food and beverage containers + cups by 2026 (reference 2022)
(Reuse)	Obligatory amount of recycled plastic in plastic beverage bottles ≤3l in mass fraction (overall average): • 2025: 25 % in PET bottles • 2030: 30 % in beverage bottles
Recycling	• Plastic caps and lids must remain attached to plastic beverage containers ≤3l and packaging during product use • Separate collection for recycling in mass fraction • 2025: 77 % of all plastic beverage bottles ≤3l placed on the market • 2029: 90 % of all plastic beverage bottles ≤3l placed on the market

The results of these regulations are already visible on the European market. To reach the collection targets for plastic beverage bottles e.g. the Netherlands already introduced a deposit system, Germany extended their long-time existing deposit scheme by juice bottles and Austria will implement a deposit scheme by 2025. With the extended collection of plastic beverage bottles recyclers are increasingly confronted with a material mix containing critical-to-recycle bottles, e.g. those with barrier layers and are therefore searching for technology improvement to secure the recyclate qualities and as well going into dialog with the producers.

With an obligatory amount of recycled plastic in plastic beverage bottles, the demand for high-quality recyclate has increased significantly and pushed the need for new recycling technologies able to provide such recyclate especially for non-PET bottles (e.g. chemical recycling technologies).

4.1.1.7 Private initiatives

Not only on government level but as well in the private sector, stakeholders like brand owners all over the world commit themselves for a circular economy. The Ellen MacArthur Foundation set up the “Global Commitment” program with over 1000 participants to commit to the following targets for plastic packaging to be reached in 2025 [3]:

- Reduction of packaging weight (so far commitment of big brands in between 5 % - 50 %)
- Use of post-consumer recycled content in plastic packaging (so far commitment of big brands in between 25 % -50 %)
- Percentage of packaging on the market that is reusable, recyclable, or compostable (so far commitment of big brands to 100 %)
- Percentage of packaging on the market that is reusable (so far commitment of big brands up to 1.7 %)

The plastic pact, a public-private coalition of European organisations has also created objectives for a circular plastics economy in Europe. The objectives are as follows for 2025:

- Design 100 % recyclable and reusable products where possible
- Use 20 % less virgin plastics with 10 % absolute reduction
- Increase recycling rate by 25 %
- Use at least 30 % of recycled plastics in new plastics [4]

4.1.1.8 European Food Safety Authority (EFSA)

With respect to food safety EFSA is setting stricter requirements for the use of recycled plastics in food packaging materials [5]. In this report we have not focused on this specific topic, but it will have an effect on the use of recycled plastics in food packaging.

4.2 Quotes and mass flows

In order to understand the impact of these set targets, it is necessary to have an overview of the current market figures as described in the following section., Furthermore, the specifics on the data in terms of discrepancies and fluctuations are discussed in the section 'Additional notes'.

4.2.1 Market Europe

Before going into detail on the different segments of the plastic value chain, it is first important to provide a complete overview of the plastic value chain. Plastics Europe has created such an overview on both European and country-level as shown in the following.

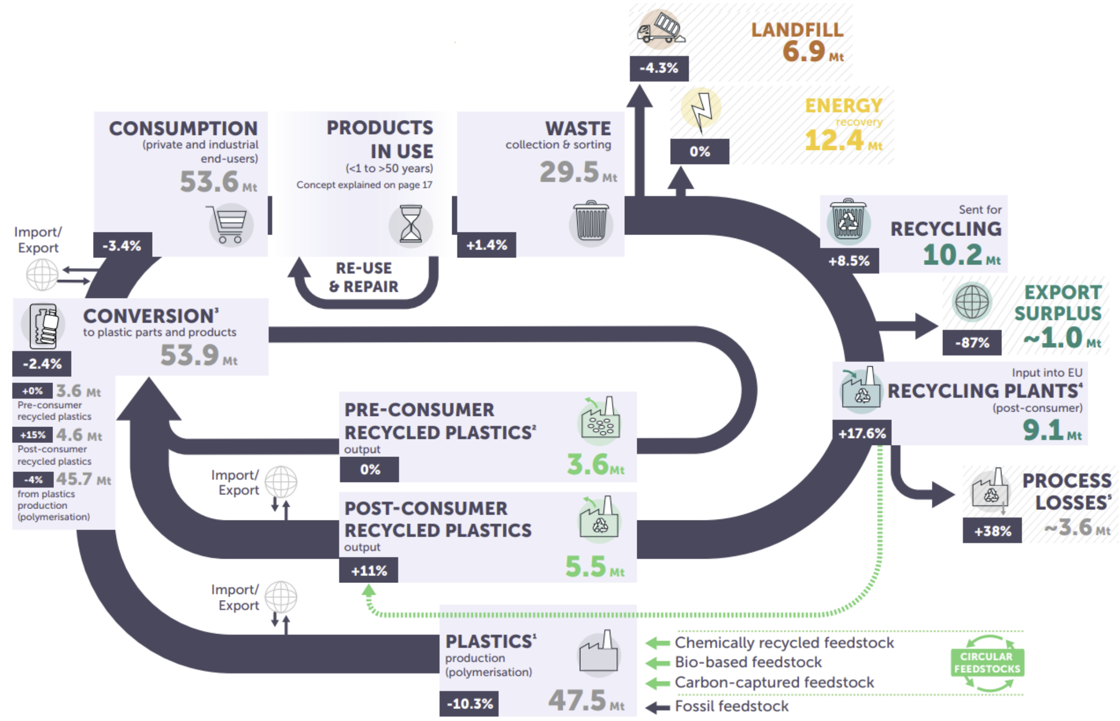


Figure 4. European plastic market [6]. Note, that thickness of the arrows does not represent the stream volumes.

Figure 4 presents their European overview of the plastic value chain for 2020. As the figure shows, in 2020 there was a production of 47.5 Mt of plastics. It is important to note here that this was the total production of plastics, and not the production of plastic packaging. The conversion rate is 53.9 Mt and hereby slightly higher than the production rate. This is cause by imports and exports, and inclusion of pre- and post-consumer recycled plastics. Then again, because of imports and exports as well as production waste, the consumption is slightly different from conversion rate with a consumption of 53.6 Mt. In terms of waste, 29.5 Mt of plastic waste has been collected and sorted in Europe in 2020. From this, 6.9 Mt ended up in landfill, 12.4 Mt was used for energy recovery and 10.2 Mt was sent for recycling. The input of recycling plants in Europe summed up to 9.1 Mt. Additionally, during the recycling process 3.6 Mt of losses occurred, which resulted in a final amount of 5.5 Mt of recycled plastics. Table 36 in Appendix B also provides an overview of the data. The losses in the recycling plant are mainly caused by removal of contaminants as part of the input material (labels, moisture, contaminants, residual content) during the recycling process. With the new calculation point for recycling of plastics following the packaging directive, this figure will be reduced in future.

Next to plastic, there are various different packaging materials that are used in Europe. Figure 5 provides an overview of the share division of these distinct types of packaging materials. In 2021, the total market volume of packaging was 114.1 million tonnes. As the figure shows, 22.5 % of the packaging on the market is made from plastic, which is 25.7 million tonnes. Table 37 in Appendix B also provides an overview of the data.

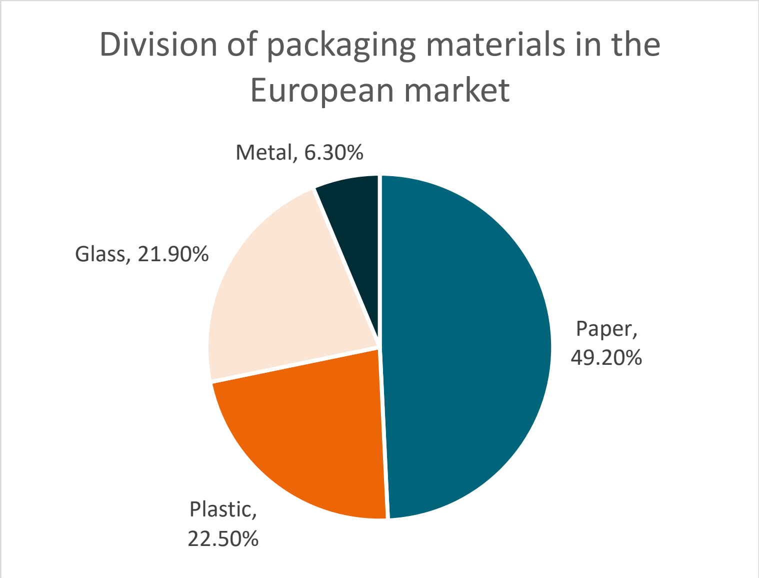


Figure 5. Division of packaging materials in the European market, shown in percentages for a total of 114.1 Mt, adopted from [7].

Figure 6 shows that in terms of market segmentation, Germany has the largest share of containers and packaging with 15.5 %. Moreover, France has a share of 10.8 %, the Netherlands 2.6 %, and Belgium 1.7 %. The share of market is based on the share in billions USD and the total amount on the market is $335.4. It is important to mention here that this source does not include all European countries in the "Rest of Europe," only 20 European countries are included in this calculation. Additionally, the defined containers and packaging consist of all packaging of various materials (glass, paper, metal, plastic), thus not only the household packaging sector. Table 38 in Appendix B also provides an overview of the data.

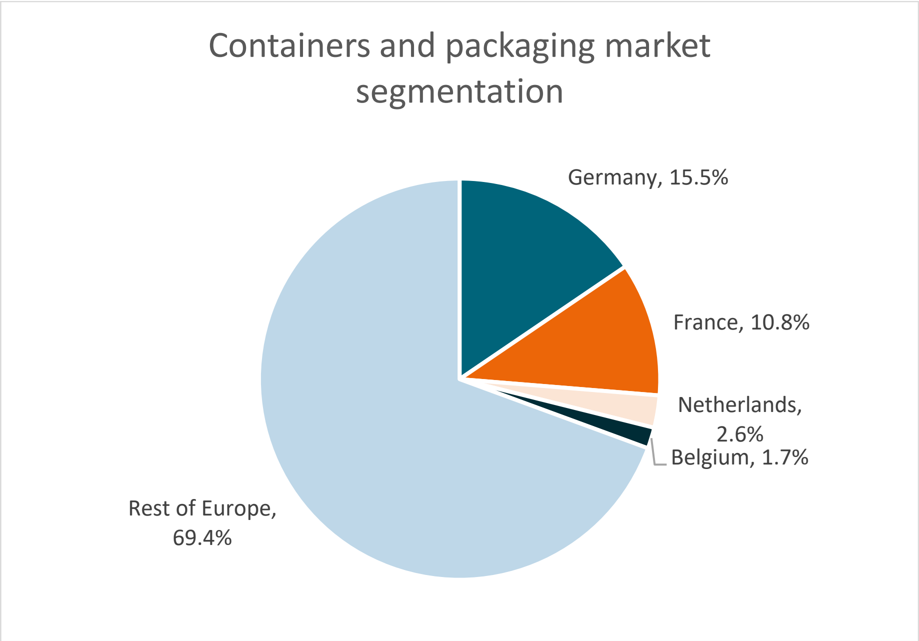


Figure 6. Containers and packaging market geography segmentation shown in percentages share for a total of $335.4 USD in 2021, adopted from [8].

4.2.1.1 Market demand

Plastic packaging has the largest demand for converters with 40.5 %. This means that from the 49.1 Mt (million tons) of total demand of plastic, 19.9 Mt is demand for packaging. It is important to note that this includes household, commercial and industrial packaging [9]. Moreover, the demand only refers to virgin plastics. Table 40 in Appendix

B also provides an overview of the data. In the following paragraphs, unless mentioned otherwise, the demand also refers to only virgin plastics.

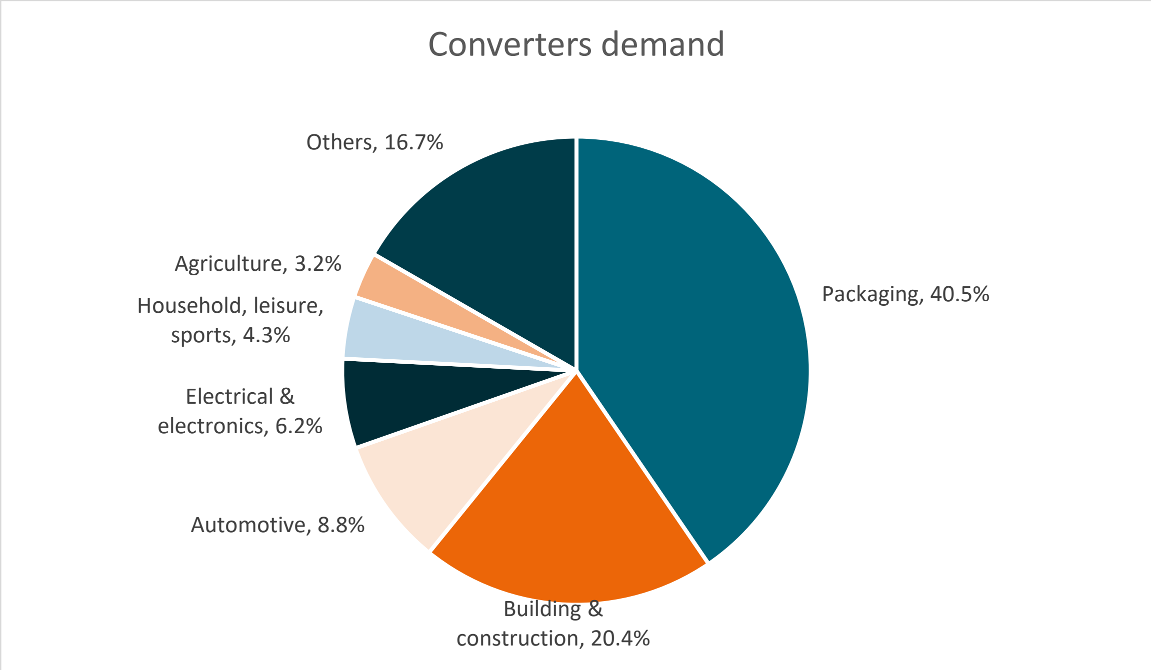


Figure 7. Converters demand per segment, shown in percentages for a total of 49.1 Mt, adopted from [9].

Figure 8 provides an overview of the converters demand by country for Germany, France, Belgium & Luxembourg, and the Netherlands. It is important to note that this is based on the total demand (49.1 Mt), so it includes all the different sectors above. Table 41 in Appendix B also provides an overview of the data. In terms of converters demand by country, Germany has the largest demand with 11.4 Mt, which is 23.3 % of the total demand of Europe. Additionally, Belgium and Luxembourg combined have a higher demand (4.7 %) than the Netherlands (4.3 %). However, it is unclear what the separate numbers are for Belgium & Luxembourg.

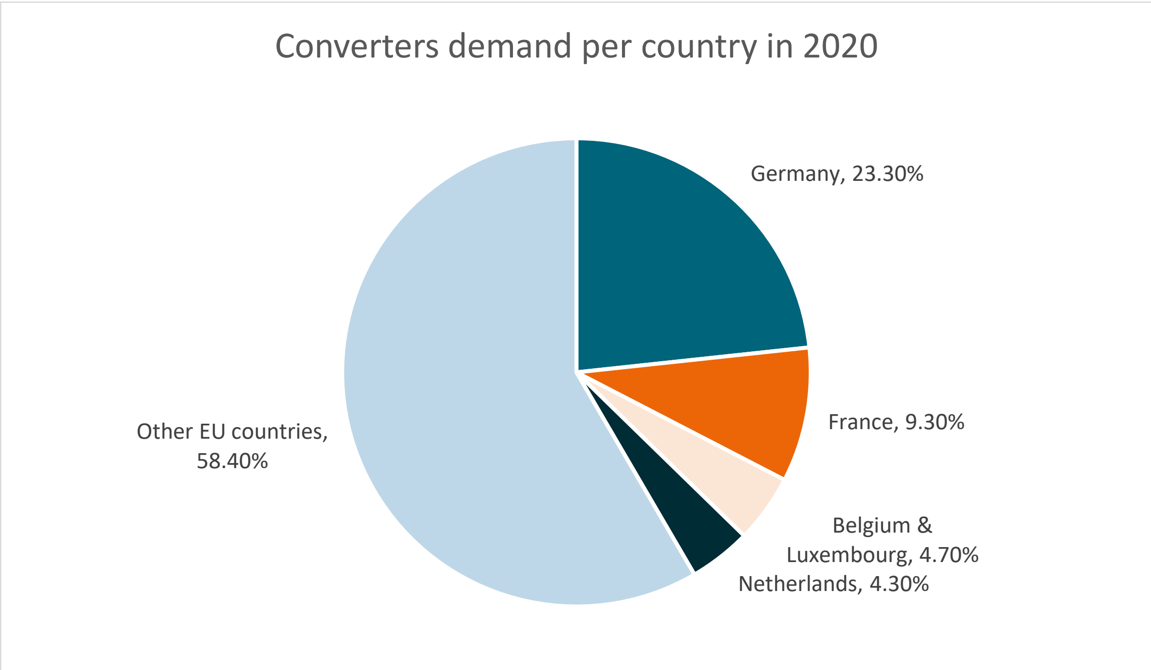


Figure 8 Converters demand by country, shown in percentages for a total of 49.1 Mt, adopted from [9]

Figure 9 shows the converters plastic demand per polymer type in Europe. This figure is based on the total demand of plastic (49.1 Mt) and therefore includes packaging, but also other sectors. Table 42 in Appendix B also provides an overview of the data. PP has the largest demand with 19.7 %. When combined as PE, LDPE and HDPE have the largest demand with 30.3 %. Additionally, PVC and PUR demand are higher than PET demand. It is important to mention here that these polymers are widely used in other sectors and not common for packaging.

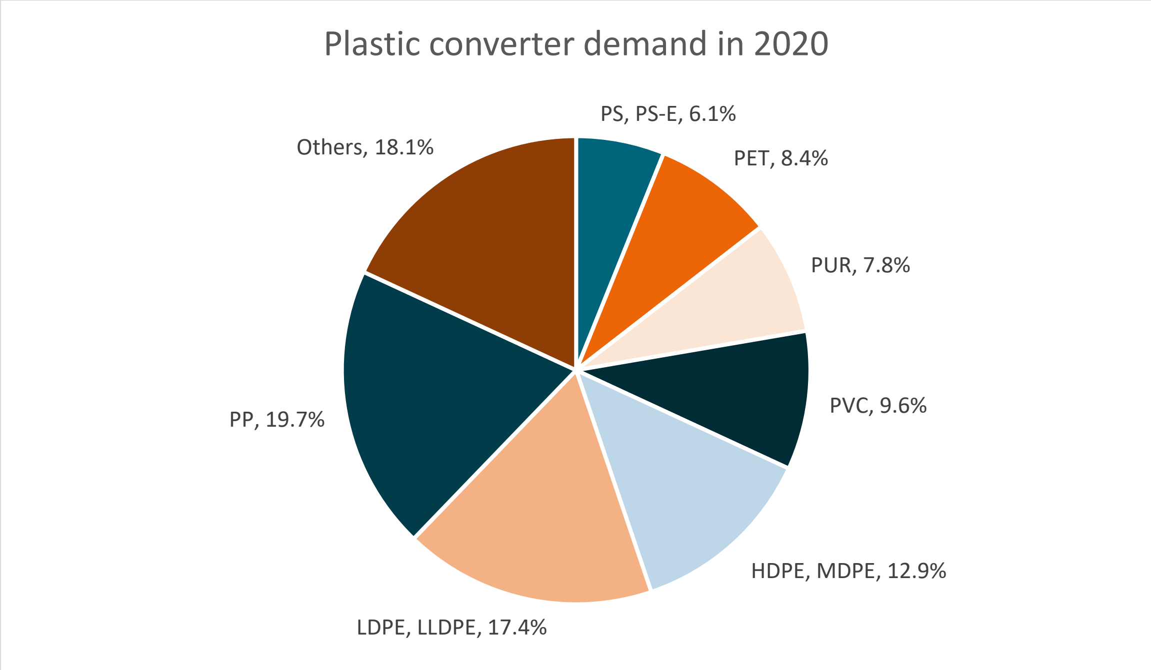


Figure 9. Plastic converter demand by polymer type in 2020, shown in percentages for a total of 49.1 Mt, adopted from [9].

4.2.1.2 Waste management Europe

Following Eurostat, the reported volumes of packaging waste generated in the European Union in relation to the volume put on the market increased largely in the last 10 years from round about 65 Mt in 2009 to about 80 Mt in 2019 [10]. In average this is a total collection of about 180 kg per capita in 2019. With a closer look it becomes clear that there is still a wide range in between the efficiency of the collection schemes set up in the EU member states as shown in Figure 10.

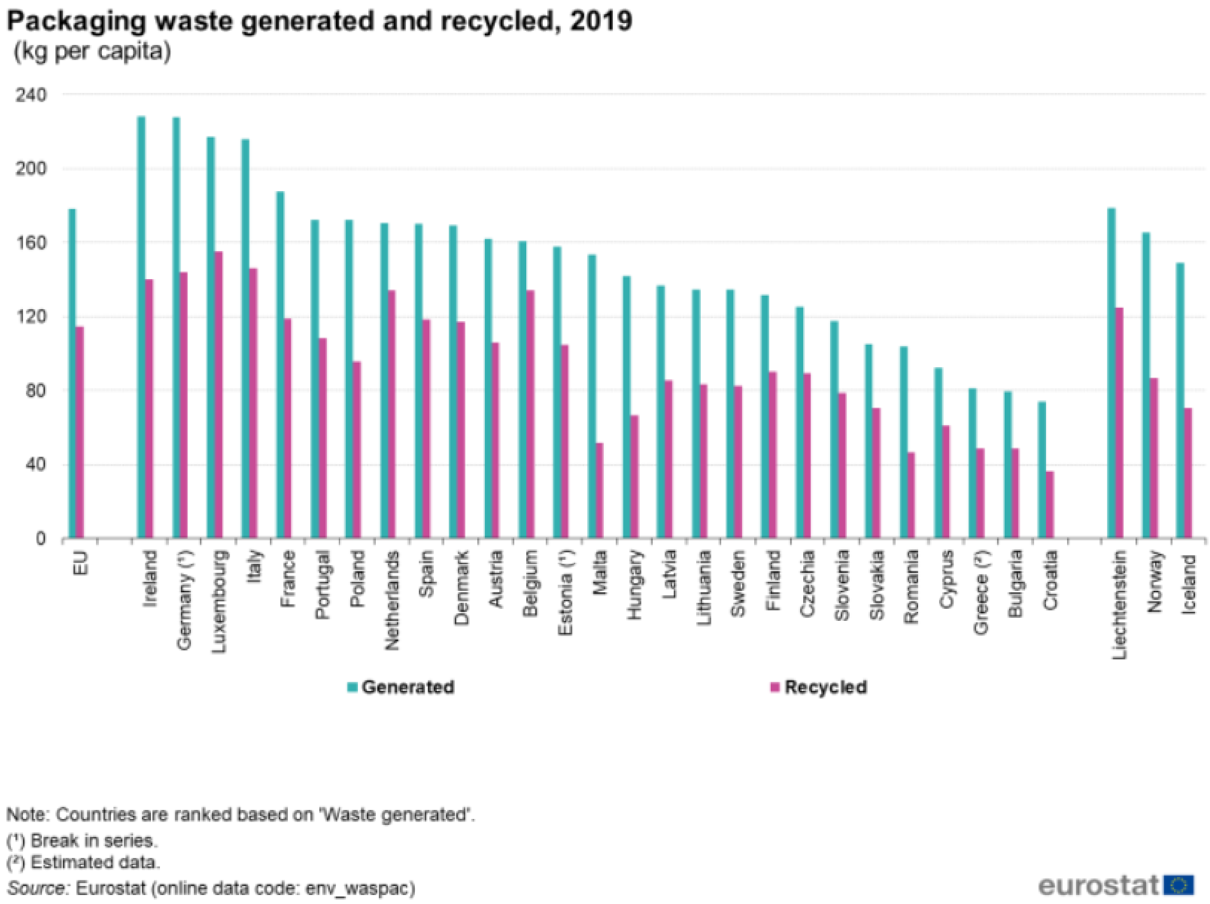


Figure 10. Packaging waste generated and recycled, 2019 [10].

Figure 11 shows that the majority of these amounts are on paper and cardboard packaging, whereas plastic packaging only sums up to an average collection in the EU of about 35 kg per capita in 2019.

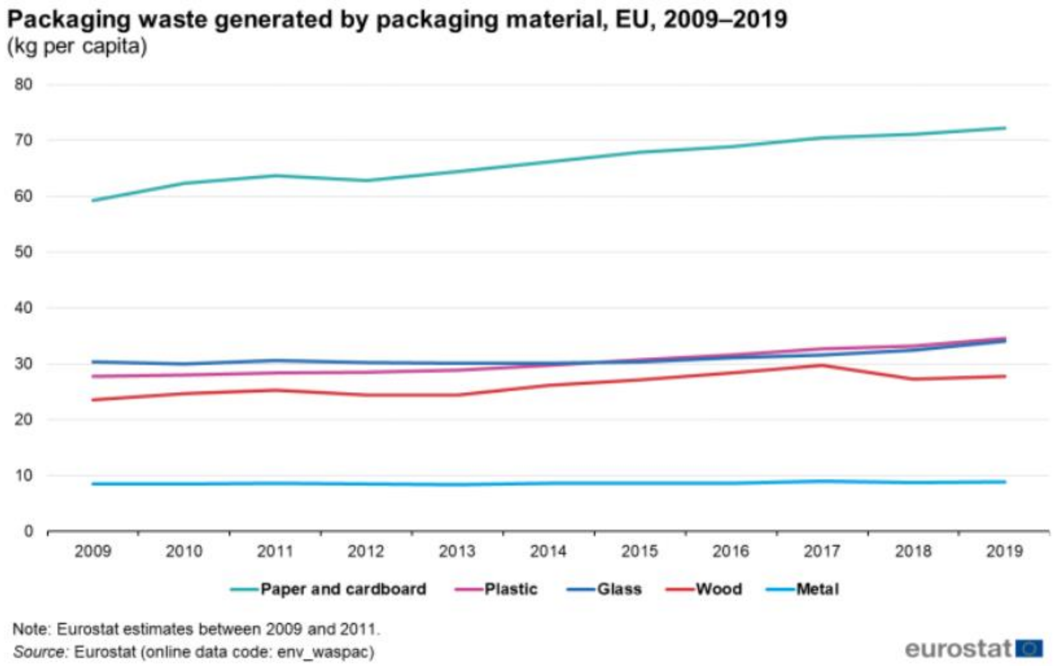


Figure 3: Packaging waste generated by packaging material, EU, 2009–2019

(kg per capita)

Source: Eurostat (env_waspac)

Figure 11. Packaging waste generated by packaging material, EU, 2009-2019 [10].

As elaborated with regard to the requirements of the packaging directive, the new recycling target on plastic packaging waste with 50 %, in relation with the new calculation point, requires a high improvement of the recycling schemes from all member states when looking at the reported status of 2019 with the existing target and old calculation point (see Figure 12).

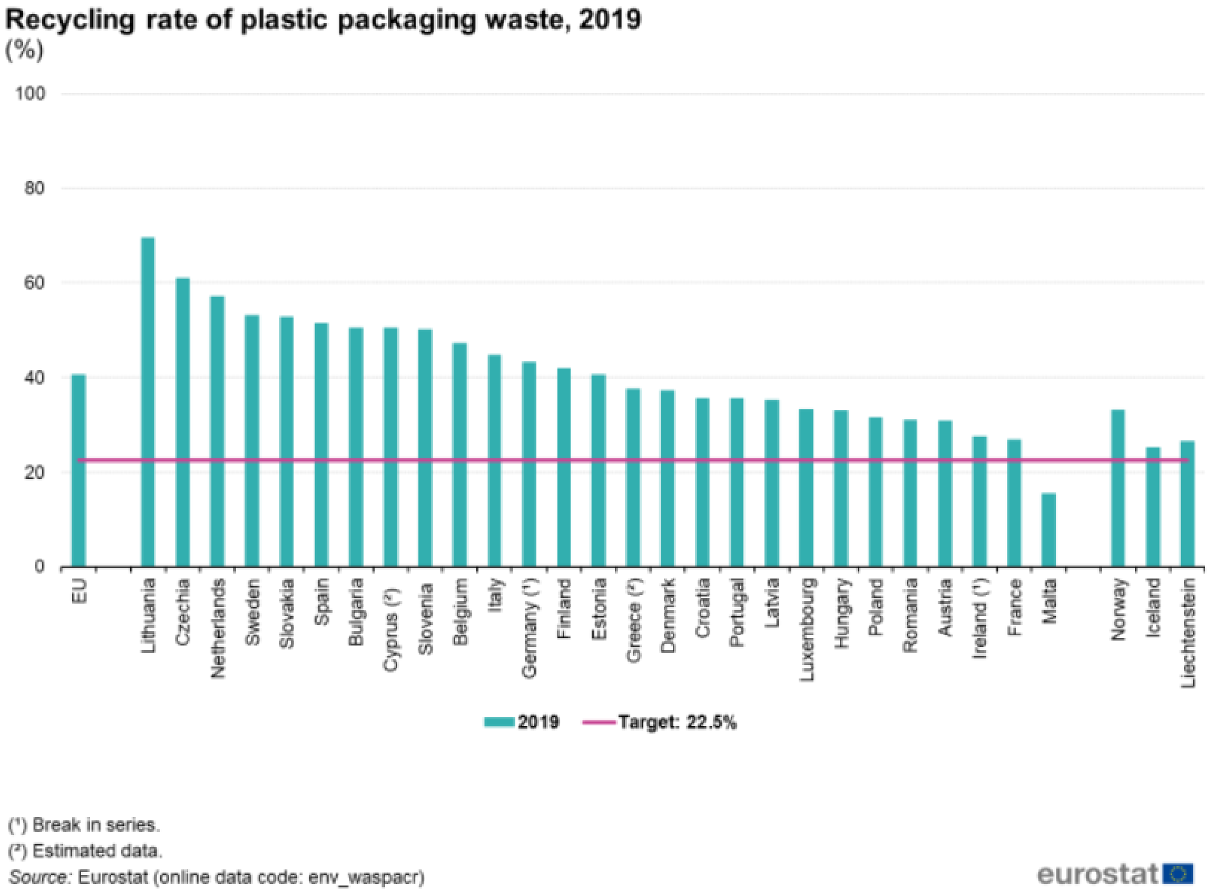


Figure 12. Recycling rate of plastic packaging waste, 2019 [10].

Nearly all reporting countries are not able to fulfil the new target at their status in 2019. In the past three years a huge shifting could be observed e.g. in Norway, France, or Belgium to extend their collections schemes for plastic packaging waste and create treatment possibilities with new sorting and recycling facilities (e.g. for Belgium new sorting plants of Indaver, PreZero, and Sitel).

There are various alternatives for waste management, such as, incineration, landfill, and recycling [11]. Figure 13 shows the destination of packaging waste per polymer type in Europe. It is important to note here that loss to the environment (e.g. litter) is not included in this figure. As the figure shows, for all types of polymers, waste-to-energy (incineration) is the most common destination. Moreover, little packaging is recycled back into packaging. If recycled, it mostly ends up in other sectors. The only exception to this is the polymer 'PET.' Table 39 in Appendix B also provides an overview of the data.

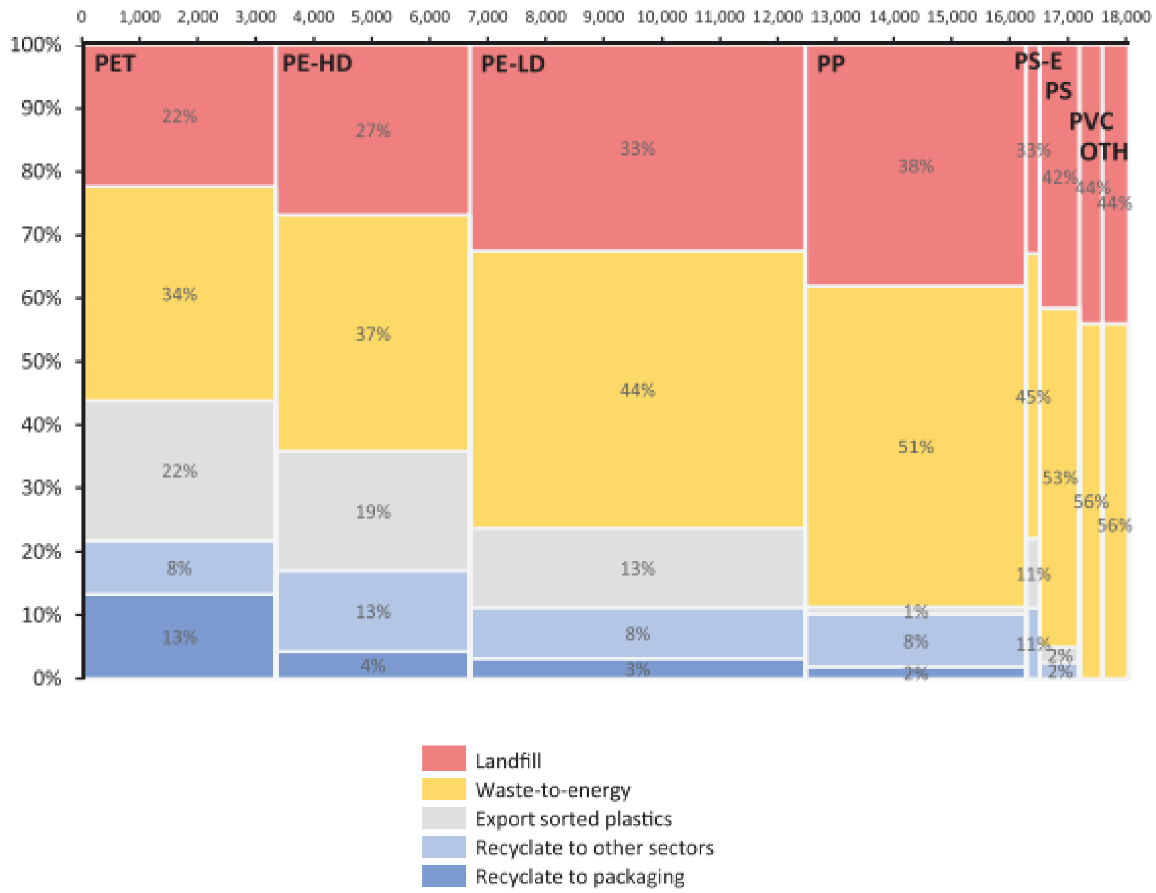


Figure 13. Destination per polymer type of generated pre-and postconsumer packaging waste (in kt & %) [11].

4.2.1.3 Recycling

In terms of capacity, Plastic Recyclers Europe defined the recycling capacity for various plastic streams (not specifically packaging). Table 2 provides a total overview of the recycling capacity for PET, HDPE/ PP, and PE film. For PET plastics, Plastic Recyclers Europe only describes the capacity for Germany, France, and the Benelux. This means that there are no separate numbers for the Netherlands and Belgium for PET. Moreover, in the other reports regarding HDPE/PP and PE film, Belgium is not even included.

Table 2. Recycling capacity Europe [12] [13] [14].

Plastic type	Capacity in the Netherlands	%	Capacity in Germany	%	Capacity in Belgium	%	Capacity in France	%	Total capacity in Europe	%
PET	144 kt	6 % Benelux	504 kt	21 %	144 kt	6 % Benelux	264 kt	11 %	2.4 Mt	100 %
HDPE/ PP	120 kt	8 %	372 kt	19 %	-	-	155 kt	9 %	1.7 Mt	100 %
PE film	192 kt	11 %	506 kt	30 %	-	-	163 kt	10 %	1.8 Mt	100 %

To acquire a better understanding of the relation between plastic demand and recycling, Figure 14 provides an overview of the demand for plastics, plastic waste collected, plastic waste going to recycling, and demand for recycled plastics (for 2016). As the figure shows, the demand for recycled plastics is significantly lower than the general demand for plastics. We do observe a trend for higher demand of (high-quality) recyclate related to sustainability targets to include more post consumer recycled plastics. Note, that despite the increased demand, the availability has increased but is still insufficient to cover the full demand of plastics.

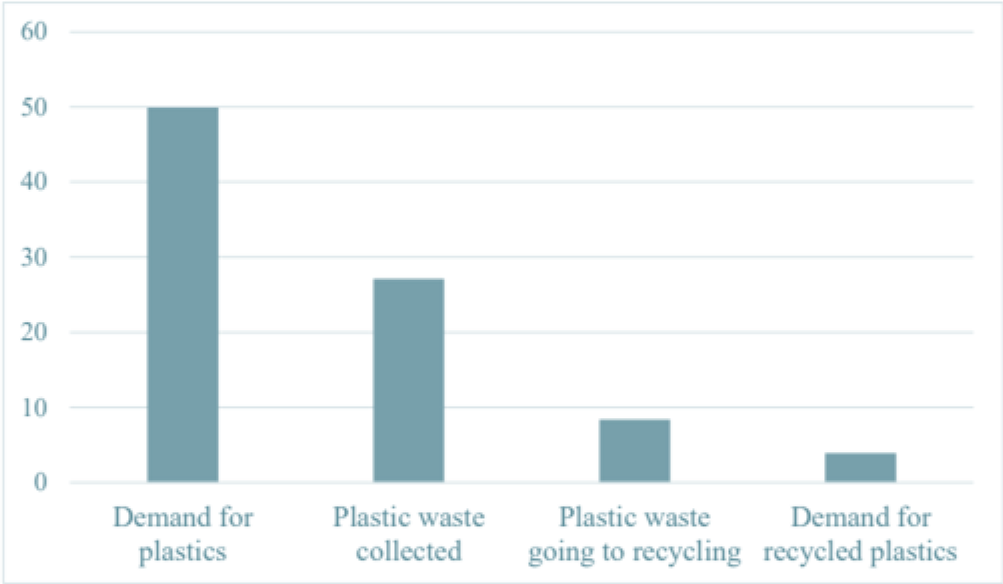


Figure 14. From plastics demand to recycled plastic demand, 2016, million tonnes [15].

4.2.1.4 Export

From the 187 countries that were part of the Basel convention, 180 countries made the decision to improve the regulations on the trade of mixed plastic waste in 2019. This decision resulted in a change in policy from the 1st of January 2021. From then on, only clean and sorted plastic waste that is suitable for direct recycling can be traded freely. Plastic waste that does not fall under this category cannot be traded freely [16].

Based on an average recovery efficiency scenario, Bishop et al. created an overview of the mass flows (in kg) of polyethylene (including all polyethylene, not only packaging) exported in 2017 from Europe [17]. Figure 67 in Appendix C shows this overview. As can be seen, Germany is the largest exporter of polyethylene. Moreover, China is the largest receiver of the exported material worldwide, while the Netherlands is the largest receiver in Europe.

4.2.1.5 Additional notes

Data gap

In the currently available waste statistics, there is a significant amount of plastic unaccounted for comparing market to production figures. There are different explanations for this data gap in the demand and waste data. Firstly, there could be an underestimation of plastic in mixed waste. Second, the plastics products lifetime could also be underestimated. Third, the levels of export could be higher than accounted for [18].

Differences in data

In this report you will notice that most presented data is coming from Plastics Europe. The reason for that is to have a consistent data set to make useful comparisons. Below, we describe the rationale in detail. This also emphasise the relevance and need for consistent and transparent data collection and presentation.

Next to the unaccounted plastics, there is also the problem that data for the plastic value chain differs per source. These differences in numbers arise from the scope and definitions used in data. Some studies use numbers from year 2020, while other numbers are only available from other years. On a European level, the waste management is described for EU27+1, but also EU27+3, or sometimes EU28+1. Additionally, some data is available for plastic packaging, while other data is only provided for all plastics (*e.g.* including other sectors such as automotive, or electronics). Also, there is a discrepancy in including only virgin plastics or all plastics. Moreover, if numbers are specified for packaging, some cases also distinguish household from commercial and industrial separation while others do not.

There is also variation in the definitions of terms between reports. Some studies distinguish between demand and production, while others perceive it as having a similar definition. Additionally, plastic waste generated is seen as either market share or collected plastic waste, but also sometimes as collected and sorted plastic waste. These discrepancies in definitions result in data that is difficult to use for comparison. Moreover, in most cases the definition and the scope are not clearly stated in the reports.

We reviewed various sources that have collected and / or discuss data on the plastic market, such as SYSTEMIQ, Plastics Recyclers Europe, Eurostat. For this report we have decided to use the data from Plastics Europe to provide an overview of the complete value chain. It is important to emphasize that the sources we did not use do still provide valid data. However, as described above, there are several ways in which this data differs in their definition. If we were to compare or use this data for calculations, it would lead to inaccurate assumptions. Thus, by showing data from one source (Plastics Europe in this case) we aim to provide a complete and accurate overview of the value chain on both European and national level. It should be noted however, that while we use Plastics Europe data to show the complete value chain, we do use other sources such as, Eurostat, and Plastic Recyclers Europe to provide data on specific components in the value chain.

4.3 Future Developments

While the previous sections described the current situation, it is also crucial to understand the future developments. The following section describes the ongoing changes and trends in the system. Subsequently, we provide a description of change in measurement point for recycling rates. It is important to address that the current trends and changes described are on a packaging and market level. The upcoming technologies will be discussed in Chapter 7.5 in the Plastic packaging waste treatment – technology scan.

4.3.1 Trends

4.3.1.1 Packaging trends

Over the past few years, various trends can be observed in the plastic market. Firstly, a decrease in unit weight has been observed. While the overall amount of packaging on the market has increased, all types of packaging have decreased in unit weight between 1990 and 2015. This reduction in weight could have several explanations, including financial motivations, and the Essential Requirements from the European Union.

A consequence of the ambition to use less plastic is the increase in usage of flexible packaging instead of rigid packaging. Compared to rigid plastic packaging, flexible plastics are much lighter. Flexible packaging does often require multiple layers and/ or materials to provide the same functionality as rigid packaging. Therefore, high barrier and composite material [19] are being used in flexible packaging. According to Thoden van Velzen et al., mono barrier film, which is seen as better recyclable, decreases the shelf life of products with a medium-long shelf life (such as cheese, smoked salmon, pre-baked bread) [20]. This shows that there is a clear trade-off in recyclability of packaging versus shelf life of product.

Next to weight reduction, there are also other developments in the market. There has been an increase in demand for bioplastics to meet sustainability targets. It is important to understand that bioplastics include bio-based plastics (plastics made from biomass) and bio degradable plastics (plastics that are able to degrade naturally). Up until 2018, bioplastics have increased close to five-fold within 15 years. However, the market share is still only around 1 % of the total plastic packaging market. Because of this small volume, bioplastics are not being sorted and hence not recycled but incinerated or sorted into a mixed plastics stream.

Another trend in the plastic packaging market is the increase in E-commerce packaging. Online shopping has increased over the years, resulting in an increased amount of packaging used for products bought online [19].

An effect from the implementation of the Single Use Plastic regulation is the increase in paper composites. These paper composites look as if it is made from 100 % paper, but it still contains plastic. They are extremely difficult to recycle since it is both not fully paper, but also not fully plastic. Current sorters do not sort out these paper composites, and paper waste processors have difficulties recycling these composites in the paper recycling process.

Additionally, we have noticed a slight shift from polyolefin to PET. This is most likely the result of the availability of high-quality food-contact approved recycled PET in comparison to the limited availability of post-consumer PO recyclate for food application so far. Deposit schemes for PET bottles implemented in different European countries contribute to availability of high-quality post consumer recycled PET. Furthermore, the requirements of the single-use plastics directive with the target to use 30 % recycled plastics in beverage bottles (not only PET but PO as well) by 2030 could have further pushed a preferred use of PET.

4.3.1.2 Market trends

While this report discusses recycling pathways for household plastic packaging, there is also an increase in use of reusable packaging. For small 'eco-friendly' supermarkets, reusing packaging is not a new concept (also not for people from older generations that were used to glass milk bottles in front of their house). However, large supermarket chains have also started to offer their customers products to put in reusable packaging. Figure 15 shows an example of the reusable packaging system in a supermarket.

Figure 15. Reusable packaging in the supermarket, (source: Albert Heijn).

Another trend we noticed is the vertical integration among the supply chain. The Schwarz Group for example, includes not only retailers such as Lidl, but now also recycler PreZero [21]. Another example is the Swedish furniture brand IKEA. They have invested in Morssinkhof Rymoplast Group, which is a recycler [22].

5 Plastic packaging waste system – National level

This chapter discusses the plastic packaging waste system on national level. In terms of structure, this chapter is similar to the chapter of plastic packaging waste system on European Level. First, we discuss the legal framework which, as mentioned before, is for a part legislation translated from EU level to country level. The next section discusses the waste management system, including rates. The countries described are the Netherlands, Belgium, Germany, and France. It is important to note that the current figures and data are not based on the new measuring point, unless mentioned otherwise.

5.1 Netherlands

5.1.1 Legal Framework

In the Netherlands plastic and packaging waste falls under the Environmental Management Act. Here there are several decrees relevant for plastic packaging [23]:

5.1.1.1 Decree single-use plastic products (implemented in 2021):

From 2021:

- Ban on certain single-use plastic products
- Deposit refund on bottles <1 litre
- Mandatory logo on certain products that describe that product contains plastics

From 2022 and later:

- Plastic from producers that contribute to litter a lot need to finance the costs for the cleaning of the litter
- Caps need to be stuck to the bottles and drinking packaging
- PET bottles need to be made out of 25 % recyclate from 2025
- The government will communicate to the consumer regarding reusable alternatives for single-use plastics [24]

5.1.1.2 Decree extended producer responsibility (implemented in 2020):

- Producer is responsible to fulfil the requirements regarding extended producer responsibility
- Producer ensures an adequate availability of a collection system
- Producer informs waste managers of the products they put on the market
- Producers can collaboratively decide practical implications (choose to use a Producer Responsibility Organisation) [25]

5.1.1.3 Decree packaging 2014 (implemented in 2014):

- Includes rules on composition of packaging, rules on amount of packaging waste, rules on collection and processing of packaging when turned into waste [26].
- Decree plastic drinking bottles (implemented in 2020):
- Change in the decree packaging 2014 by the inclusion of separated collection for plastic bottles
- Change in the decree packaging 2014 in regard to deposit refund for drinking packaging [27]

5.1.2 Waste Management System

The Dutch waste management system consists out of various steps.

Figure 16 provides an overview of the waste management. It can be seen that there are two different methods for collection waste (post consumer- and source-separation). A following section explains this in more detail.

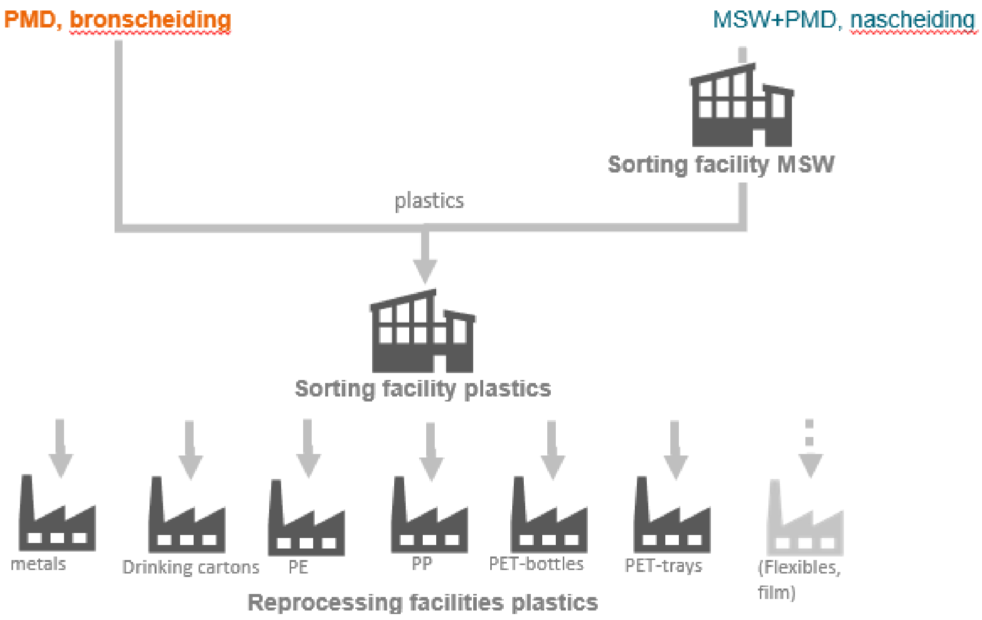


Figure 16. Dutch waste management system.

5.1.2.1 EPR scheme

In terms of Extended Producer Responsibility (EPR), there is a non-profit system with one Producer Responsibility Organisation in the Netherlands: Afvalfonds Verpakkingen [28]. This is the organisation that takes over the responsibility of the producers and importers (PI) to ensure recycling of their packaging. Thus, PI pay Afvalfonds Verpakkingen to take care of the waste management of their packaging.

The contributories that are included in the Dutch EPR system are businesses that are located in the Netherlands and put packaging on the market here, and organisations that are not located in the Netherlands, but directly import packaging to the Netherlands. Moreover, only organisations that put more than 50.000 kg of plastic packaging on the market are required to pay Afvalfonds for the waste management of their packaging. Organisations with less than 50.000 kg of plastic packaging on the market are excluded from the system and are required to be capable of proving this amount if requested. Within this EPR system, there is also an incentive for PI to put good recyclable packaging on the market. Afvalfonds Verpakkingen provides a differentiation fee for packaging that is defined as 'good recyclable' by the Recycle Checks developed by the Netherlands Institute for Sustainable Packaging (KIDV) [28]. These tariffs only differ on recyclability and not in terms of polymer type or packaging type.

The organisation Afvalfonds Verpakkingen also finances different organisations that are also involved in the plastic management system. These organisations are: NederlandSchoon, Nedvang b.v., Kennisinstituut Duurzaam Verpakken, and Statiegeld Nederland. Below these organisations and their purpose are briefly explained:

- **NederlandSchoon**: focuses on prevention and cleaning of litter.
- **Nedvang b.v.:** reports and organizes the collection, sorting, and recycling. They also do the communication with municipalities and waste management companies.
- **Kennisinstituut Duurzaam Verpakken (KIDV)**: helps companies improve the recyclability and sustainability of their packaging.
- **Statiegeld Nederland**: is responsible for the coordination and execution of the deposit refund requirement on plastic bottles. [28]

5.1.2.2 Collection of plastic packaging waste

In the Dutch waste management system, there are two main methods of collection for plastic packaging: source separation and post-consumer separation (see Figure 17. Collection systems in the Netherlands in 2017 .). In source-separation areas, PMD (plastic packaging, metal packaging, and beverage cartons) is disposed by the consumer in a separate bag or bin. For post-consumer separation, plastic packaging material is collected together with the residual waste. A waste sorter sorts this residual waste (nascheidingsinstallatie), and the plastic packaging fraction is transported to a plastic sorting facility (KSI). Next to source and post-consumer separation there is a deposit refund system (DRS) [29] for PET bottles.

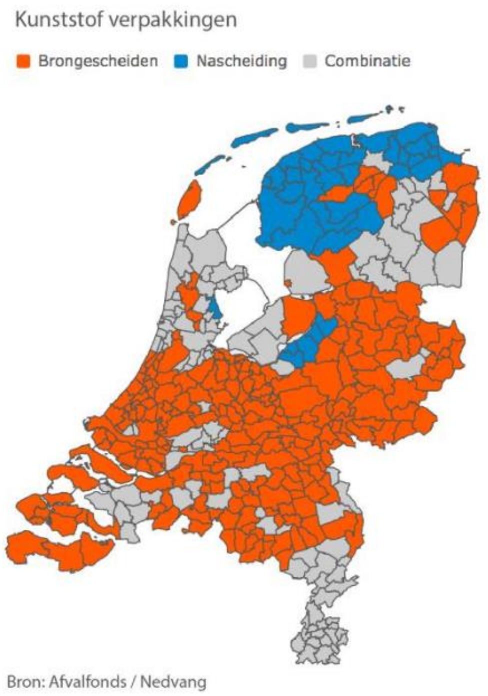


Figure 17. Collection systems in the Netherlands in 2017 [30].

In some municipalities where source separation is in place, incentives are in place to improve the quality of the PMD fraction (diftar) [31]. It is doubtful whether this incentive has the intended effect.

5.1.2.3 Sorting and reprocessing of plastic packaging waste

Table 3 shows the streams on which sorters sort plastic in the Netherlands. It is important to note that these are only the plastic streams. Next to the below mentioned streams there are also other streams, such as (non)-ferrous metals, and beverage cartons. Since this report focuses on plastic, we provide an overview of only the plastic sorting streams. This is also the case for the following countries. Note that beverage carton also contains some PE; they are mostly sorted but not recycled inside The Netherlands as there is no recycling capacity.

Table 3. Sorting streams in the Netherlands.

Sorting streams
Plastic film >A4
Rigid PE
Rigid PP
PET bottles
PET trays
Mixed plastics/ MPO

5.1.2.4 Quotes and Mass Flows

Figure 18 provides an overview of the Dutch plastic market in 2020. Plastics Europe created this complete overview of the plastic market in the Netherlands. As the figure shows, 5.370 kt plastics was produced. Additionally, 2.070 kt plastics were consumed in the Netherlands. In terms of waste, 1.058 kt was collected and sorted. From this, 3 kt ended up in landfill, 537 kt was used for energy recovery, and 478 kt was sent for recycling. The input for Dutch recycling plants was 500 kt. In addition, during the recycling process there were 190 kt in losses and an output of 300 kt recycled plastic. Table 43 in Appendix B also provides an overview of the data.

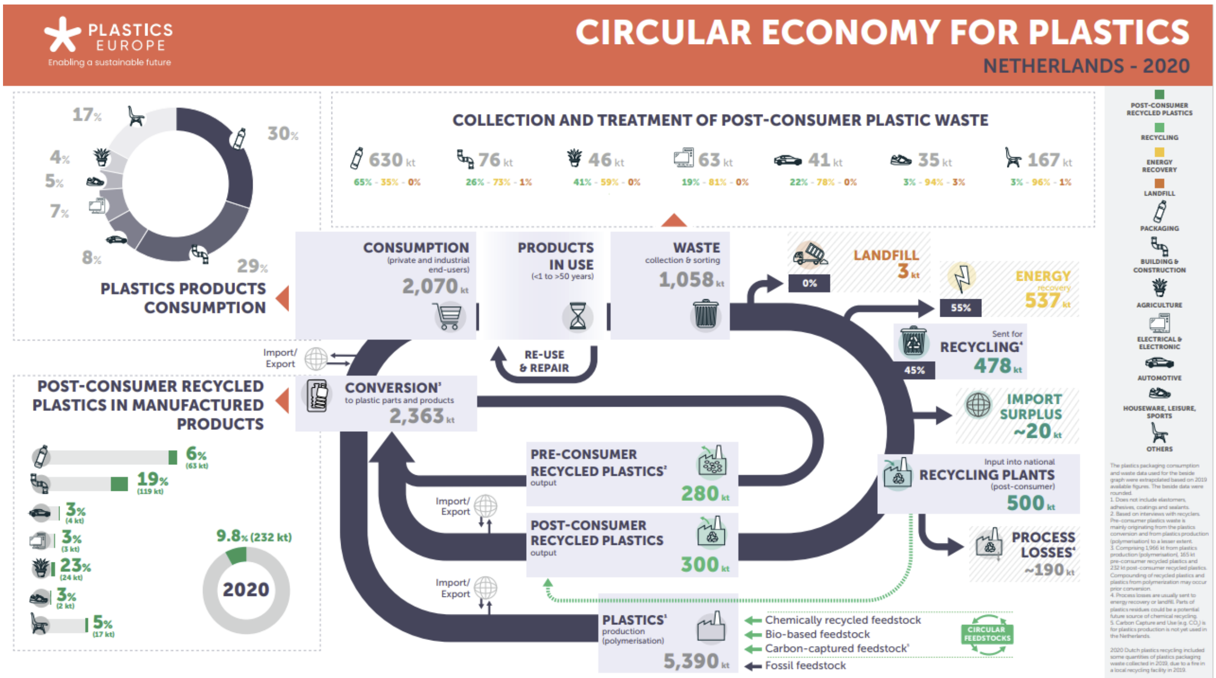


Figure 18. Dutch plastic market [29]. Note, that thickness of the arrows does not represent the stream volumes.

Figure 19 shows the waste division in the Netherlands in 2020. In total municipalities collected 10.137 kt waste. From this waste, 9.112 kt was household waste. Subsequently, 1.228 kt from this household waste was mixed packaging. Here it is important to note that this is a sum of the packaging that Afvalfonds Verpakkingen published in their 'Monitoring Verpakkingen' report. In this report, glass packaging also includes commercial glass packaging (a total of 459 kt glass packaging). From this 1.228 kt mixed packaging, 316 kt is plastic packaging.

Figure 19 Waste data from 2020, based on: [32], [33].

Packaging put on the market in the Netherlands is calculated by adding three separate categories: above threshold, below threshold, and logistic resources. Table 4 provides an overview of the amounts of plastics per category. Companies that put more than 50.000 kg on the market are defined as 'above threshold.' Companies with less than 50.000 kg of their packaging on the market are defined as 'below threshold.' The amount of packaging that comes from below threshold companies is calculated by an independent research centre. The last category, logistic resources, includes packaging that is not taxed. This includes packaging that is used for transporting, such as, pallets, crates, and large boxes [32].

Table 4. Plastic packaging put on market, in kt [32].

Above threshold (plastics)	Below threshold (plastics)	Logistic resources (plastics)	Total put on the market (plastics)
431 kt	41 kt	82 kt	554 kt

According to *Afvalfonds Verpakkingen* the recycling rate of packaging plastics in the Netherlands in 2020 was 66 % [34]. From 2022 the measuring point for recycled waste has been changed. Previously, the measuring point for recycled material was at the entrance of a reprocessing plant, whereas from now on, this measuring point lies at the washed and dried flake in the reprocessing plant. This shift in measuring point is expected to cause a decrease in the recycling numbers. As Table 5 shows, the estimated recycling rate for 2020 according to this new measuring point, again according to Afvalfonds Verpakkingen, is between 46 and 52 % [34]. A detailed formula for calculating recycled packaging can be found in Figure 68 in Appendix C. There is quite some improvement needed since Brouwer *et al.* reported a net recycling rate (new measurement point) for post-consumer plastic packaging of only 26 % in 2017; this is better if one also includes post-industrial plastic packaging: 38 % [35]. Some overestimation of recycling rates seems to be in place. Upon request, we could not receive data for 2021 and 2022 on actual recycling rates.

Table 5. Dutch waste management overview for 2020 according to Afvalfonds Verpakkingen [32].

Production of plastic packaging	Source-separated collection	Post-consumer separated collection	Total collection	Recycling (based on old measuring point)	Recycling rate	Recycling rate estimation for new measuring point
554 kt	395 kt	66 kt	461 kt	368 kt	66 %	46-52 %

5.2 Belgium

5.2.1 Legal Framework

For legislation, Belgium has a Cooperation Agreement. This agreement provides a legal framework on how Belgium will meet the packaging objectives. Additionally it is based upon the EU Directive 94/62/EC [36]. The Cooperation Agreement includes three obligations for businesses that put products on the market:

5.2.1.1 Reporting obligation:

- Company is obliged to annually report the quantity, type, and recycling rate of packaging they put on the market to the Interregional Packaging Commission (IRPC).
- Company can either report via an accredited compliance organisation (PROs Valipac or Fost Plus), or report to the IRPC themselves [37].

5.2.1.2 Take-back obligation:

- Company needs to demonstrate that their packaging has been recycled for the minimum recycling rates if they put more than 300 kg packaging on the market per year.
- Company can either comply by joining an accredited compliance organisation (PROs Valipac or Fost Plus) or reporting to the IRPC themselves [38].

5.2.1.3 Prevention plan:

- Company is obliged to submit a prevention plan every three years if they put more than 300 tonnes of packaging on the market or if they package a minimum of 100 tonnes of goods in Belgium.
- The plan should summarize the 'preventive measures' that a company will take to reduce the quantity of packaging put on the market [39].

5.2.2 Waste Management System

5.2.2.1 EPR scheme

As mentioned above, the share of Belgium in terms of containers and packaging on the market in Europe is 1.7 %. In Belgium's Extended Producer Responsibility system, there are two PROs: Fost Plus and Valipac. While Valipac focuses on commercial waste, Fost Plus focuses on household waste. The tariffs that brand owners have to pay for the packaging they put on the market are based on the green dot tariffs per material. These are not directly related to the level of recyclability but are related to type of polymer and packaging [40].

5.2.2.2 Collection of plastic packaging waste

Plastic is collected by using source-separation with a 'blue bag.' In the past, only plastic bottles, flasks, metal packaging, and drinking cartons were included in the collection system [41]. Now with the implementation of the 'new blue bag' all other plastic packaging is also included in the collection system [42]. Moreover, there is no deposit refund system in Belgium for plastic packaging [43].

5.2.2.3 Sorting and reprocessing of plastic packaging waste

Table 6 shows the streams on which sorters sort plastic in Belgium. As mentioned above, these are only the plastic streams at the sorting facility and do not include other material streams. From a meeting with FostPlus, we acquired an overview of these sorting streams.

Table 6 Sorting streams in Belgium

Sorting streams
PET transparent
PET blue
PET coloured
PET opaque
PET trays transparent
Rigid HDPE
Rigid PP
Rigid PS
Rigid mixed PO
PE film
Other film

5.2.2.4 Quotes and Mass Flows

Plastics Europe created a complete overview of the Belgian market, which can be seen in Figure 20. As the figure shows, 6.820 kt plastics was produced. Additionally, 1.270 kt plastics were consumed in Belgium. In terms of waste, 578 kt was collected and sorted. From this, 10 kt ended up in landfill, 341 kt was used for energy recovery, and 227 kt was sent for recycling. The input for Belgian recycling plants was 210 kt. In addition, during the recycling process there were 70 kt in losses and an output of 140 kt recycled plastic. Table 44 in Appendix B also provides an overview of the data.

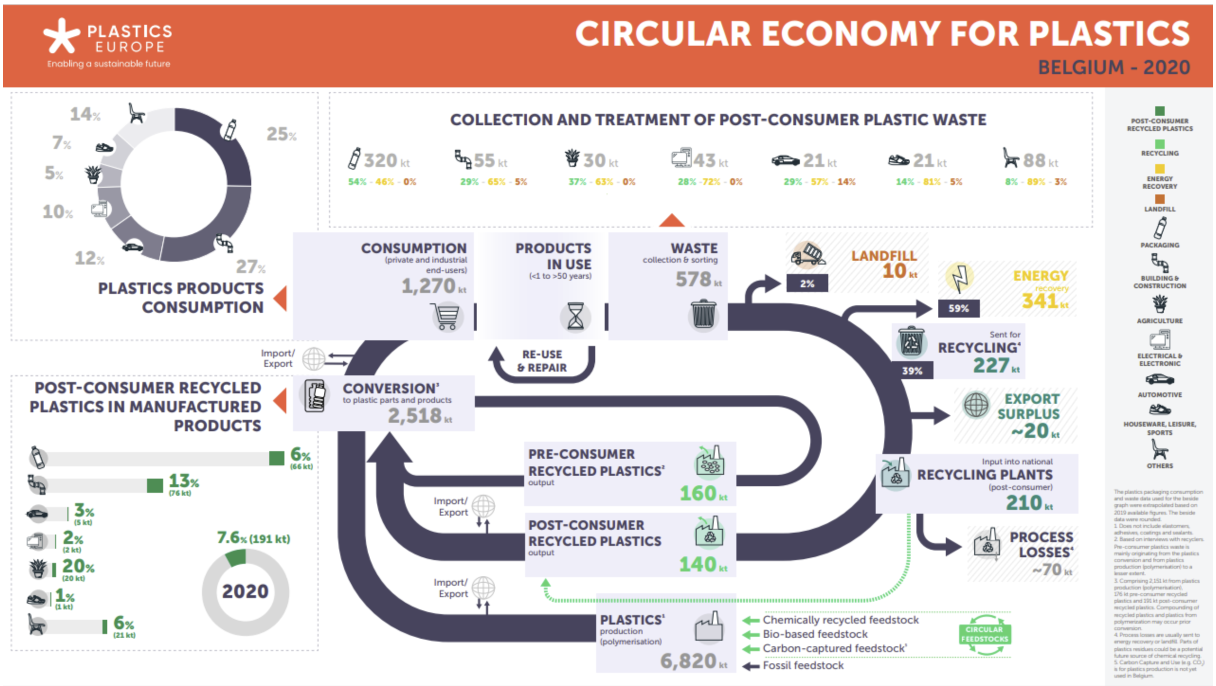


Figure 20. Belgian plastic market [44]. Note, that thickness of the arrows does not represent the stream volumes.

In Belgium, the recycling rate for household plastic packaging in 2020 was 51 % [45]. This means that 107 kt of household plastic packaging was recycled [46]. Overall, 98 % of the PMD waste in Belgium is also recycled in Belgium and neighbouring countries. To be more specific, 79 % of this 98 % is recycled in Belgium [47]. The recycling measuring point did also change in the country, however, there is no data available as to how this change influence the recycling rates for Belgium. In general, there is not much data publicly available on the Belgian plastic packaging market.

5.3 Germany

5.3.1 Legal Framework

The national transposition of the European Waste Framework Directive in Germany is the "Circular Economy Act" or Kreislaufwirtschaftsgesetz (KrWG) last amended in 2021. The KrWG also reflects the requirements of the EU Single-Use Plastics Directive for non-packaging items.

In the KrWG, separate collection of the following household waste flows is required (KrWG §20(2)):

- Biowaste
- Plastics
- Metals
- Paper and cardboard
- Glass
- Textiles (latest 2025)
- Bulky waste
- Hazardous waste

Municipalities are only allowed to differ if they can prove, beside other factors, that the costs are disproportionately high, and the aimed mixture provides the same quality as segregated waste flows and that the potential for reuse, recycling and recovery is not lowered.

Certified waste treatment companies do the collection and treatment. With the regular certification (min. every 18 month) is ensured, that the companies manage the waste in the sense of the KrWG and related legal acts and directives. The certificate displays for example the number and type of treatment sites and the ability of the treatment site, also regarding technical equipment (e.g. sorting technology), to receive and properly treats certain types of waste.

The national transposition of the packaging directive in Germany is the Packaging Act or Verpackungsgesetz (VerpackG), last amended in 2021. The VerpackG replaced in 2019 the former existing German Packaging Ordinance or Verpackungsverordnung (VerpackV).

Packaging is only allowed to enter the German market if licensed by a Producer Responsibility Organisation or similar (§7(7)) ensuring a comprehensive collection all over Germany. Furthermore, the supervision of packaging flows from market to collection to treatment is centralized by the "Zentrale Stelle Verpackungsregister," where all packaging must be registered when entering the market and PROs and similar systems report to validate the efficiency of their waste treatment scheme. The annual reporting of the PROs for household packaging waste displaying the mass flows over the collection and treatment pathway (Mengestromnachweis, §17 VerpackG) is reviewed by sworn experts before reported to the Zentrale Stelle Verpackungsregister. Packaging producers furthermore have to hand in a declaration about the packaging volumes brought on the market (so called Vollständigkeitserklärung following §11 VerpackG).

In §21 of the VerpackG it is stated that the height of the license fee must be rated with regard to the recyclability of packaging and the use of recyclates and sustainable resources to engage producers in Design for recycling. For the evaluation of recyclability the Zentrale Stelle Verpackungsregister published a minimum standard so called Mindeststandard (latest from 2021), to be used as a basis from the PROs. The basic criteria defined are:

- Existing sorting and recycling Infrastructure for high quality material recycling
- Packaging is sortable by the target material component and separable from other packaging components if necessary for high quality material recycling
- None of the packaging components or substances contained in the packaging material may represent recycling incompatibilities that could prevent the recycling success in practice.

In Germany, household packaging waste is to be collected free of charge and separately from other municipal waste following §13-14 VerpackG managed by the PROs.

In contrast to other European countries, there are a number of PROs available in Germany producers can license with, currently 11. To avoid negative impact on recycling efficiency by competition in between the PROs, the Zentrale Stelle Verpackungsregister took over the following responsibilities:

- Splitting of treatment costs according to market share of the systems
- Splitting of supplementary remuneration according to market share of the systems
- Coordination of competition-neutral tenders
- Splitting of costs and coordination of customer information initiatives

Following the waste hierarchy, the VerpackG further defines the following requirements deviating from the EU Packaging directive:

<table>
<tr><td>Prevention</td><td colspan="2">Ban on lightweight carrier bags 15µm -50 µm brought on the market as of 2022.</td></tr>
<tr><td rowspan="2">Preparing for reuse + Recycling</td><td>Recycling targets EU 2025 in mass fraction

– 50 % for plastic packaging

– 70 % for ferrous metals packaging
– 50 % for aluminium packaging
– 75 % for paper + cardboard packaging
– 70 % for glass packaging</td><td>Recycling targets Germany 2022 for household packaging waste in mass fraction
– 70 % for plastic packaging
– 70 % for composite packaging
– 80 % for beverage cartons
– 90 % for ferrous metals packaging
– 90 % for aluminium packaging
– 90 % for paper + cardboard packaging
– 90 % for glass packaging</td></tr>
<tr><td colspan="2">Obligatory participation of all single-use drink bottles 0.1l – 3l in the national deposit system with a deposit value of 0.25€. Excluded are beverage cartons, alcohol, and juices if they are not filled in plastic or metal bottles/cans. Dairy drinks in plastic or metals bottles/can included from 2024 on.</td></tr>
</table>

With the Single-use Plastics ordinance or so-called Einwegkunststoffverbots-Verordnung (EWKVerbotsV) of 2021, the EU Single-use Plastics Directive is transposed into national law.

5.3.2 Waste Management System

In Germany, 11 approved commercial PROs provide the services of Extended Producer Responsibility for packaging producers with market shares in between 0.8 % and 20 %. These are:

- BellandVision GmbH
- Der Grüne Punkt – Duales System Deutschland GmbH
- EKO-Punkt GmbH & Co. KG
- Interseroh+ GmbH
- Landbell AG für Rückholsysteme
- Noventiz Dual GmbH
- PreZero Dual GmbH
- Recycling Dual GmbH
- Reclay Systems GmbH
- Veolia Umweltservice Dual GmbH
- Zentek GmbH & Co. KG [48]

For the treatment of packaging waste from households, the PROs share a similar system as described in the following.

As specified in the VerpackG, household packaging waste is to be collected separately for further treatment to reach the high recycling rates required. At households and comparable sources (e.g. small businesses/offices), plastic packaging waste is collected together with metal packaging, beverage cartons and composite packaging in the yellow bag or bin. The comingled waste is called lightweight packaging waste (LVP). Separate from that, most drink bottles are either collected via the deposit or the re-use system. In some regions, the LVP-collection has been further extended by non-packaging plastics and metals similar in material type to packaging material types. This extended system is the so-called Wertstofftonnecheck.

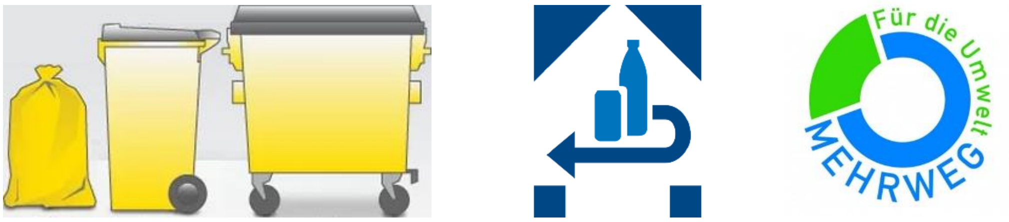


Figure 21. Collection methods in Germany [49].

In 2017, about 30 kg per capita of LVP/Wertstofftonne has been collected in Germany, in total round about 2,66 Mt. Figure 22 shows an exemplary composition of the collected material (waste analysis 2017).

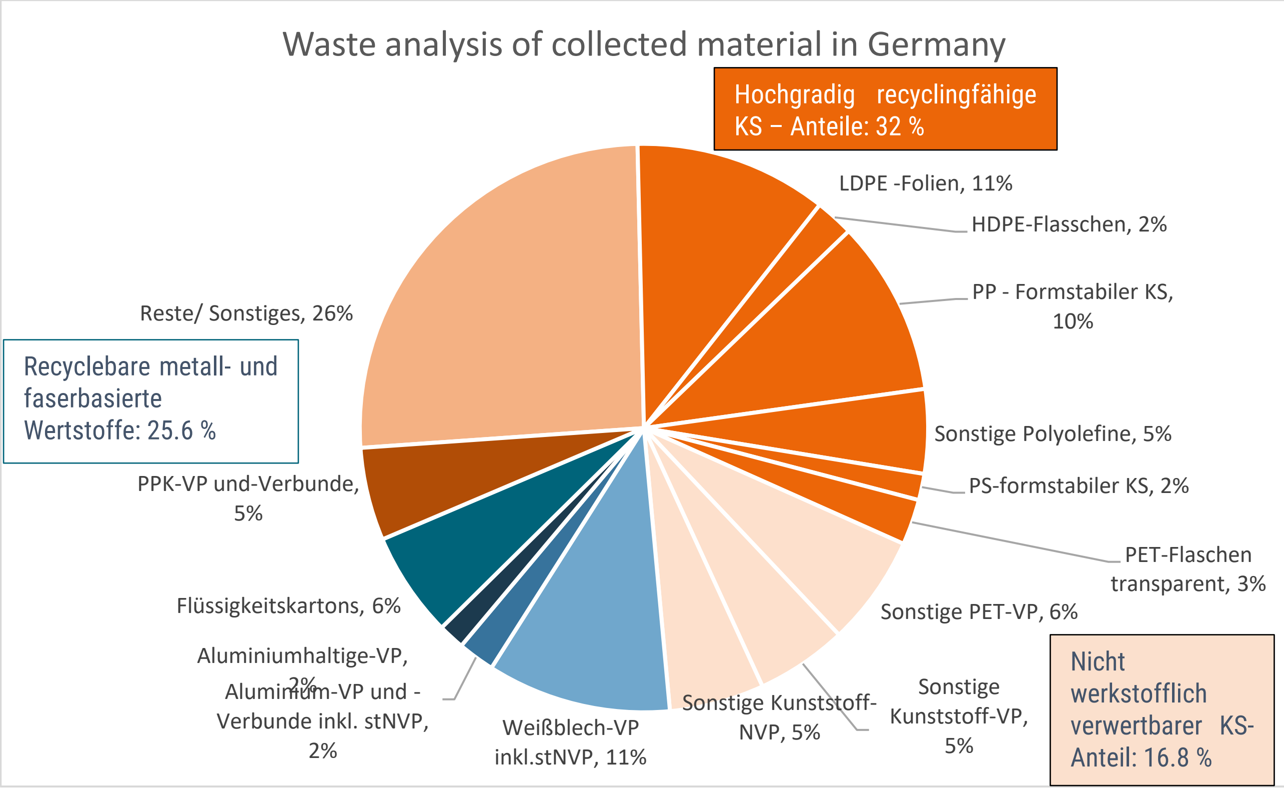


Figure 22. Waste analysis of collected material in Germany, data incorporated from: [50].

It is significant that only about 75 % of the collected amount is identified as recyclable material. Furthermore, about 17 % of the collected amount it rated as not suitable for material recycling due to non-existent recycling pathways and non-sortability and or recyclability of the packaging/item design, leaving a recycling potential in German LVP of about 58 %.

As a next step, the collected LVP is fed to one of about 120 sorting facilities. Figure 23 shows the basic sorting concept.

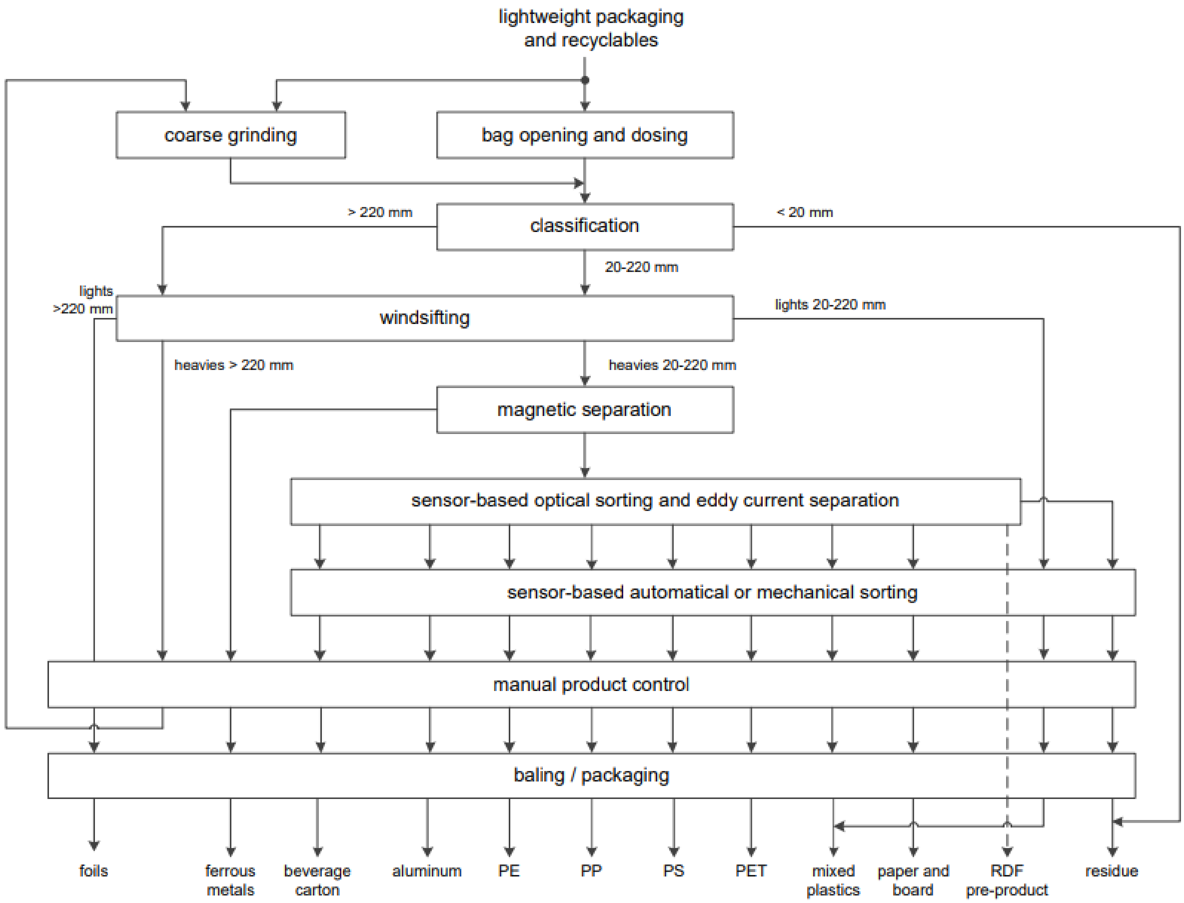


Figure 23. Schematic of the current sorting process [51].

As shown in the flowchart, the listed material types are regained here:

- Film /LDPE
- PET bottles transparent / PET mix
- PET trays / PET mix
- HDPE rigid
- PP rigid
- PS rigid
- Mixed Polyolefins
- Mixed Plastics / RDF
- Beverage cartons
- Paper and paper composites
- Ferrous metals / tinplate
- Aluminium

In terms of sorting streams for plastic in Germany, Table 7 provides a summarizing overview.

Table 7 Sorting streams in Germany

Sorting streams
Film/ LDPE
PET bottles transparent/ PET mix
PET trays/ PET mix
HDPE rigid
PP rigid
PS rigid
Mixed polyolefins and/or Mixed plastics/ RDF

In the past years especially the sorting of film material has been improved in State of the Art sorting facilities, moving from sorting of mixed film to sorting of film by material type.

One of the latest sorting facilities put into operation in 2018 is MEILO GmbH in Gernsheim, Germany. Figure 24 shows the performance of the sorting facility.

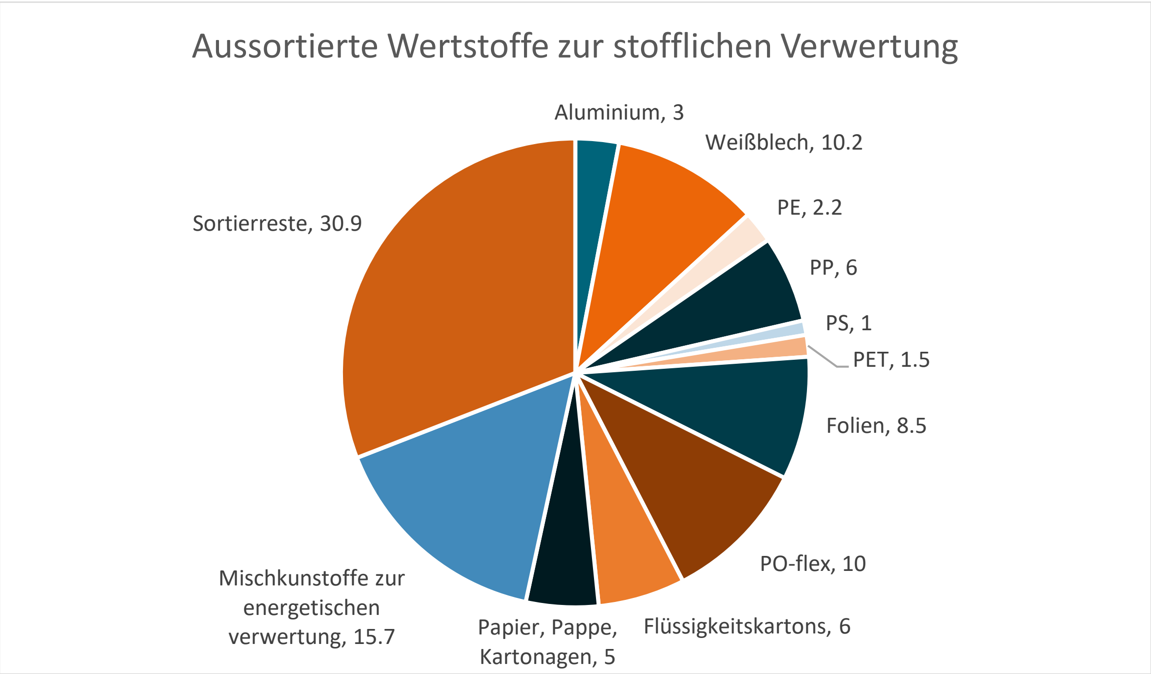


Figure 24. Performance of a German sorting facility, data incorporated from: [52].

Considering the measured recycling potential of German LVP with about 58 %, the efficiency of the MEILO plant with a production of 53.4 % output available for further reprocessing is already high. To regain the lost plastic potential of 17 % in the input and further increase output qualities, innovation in technology and packaging design is required.

In 2020, the PROs reported a total amount of 1.33 Mt of sorted LVP waste as an input into recycling according to VerpackG. With that amount, the target recycling rate of 50 % has not been met failing by 0.02 % with 49.98 %. Following the explanation of the environmental agency, the Zentrale Stelle Verpackungsregister reduced the reported amount of material for recycling due to missing proof of actual recycling of a certain amount [53].

To correctly report the waste mass flows over the complete treatment pathway, the PROs are obliged to hand in the so-called Mengenstromnachweis according to VerpackG. In the associated test guideline, a regular inspection of sorting, reprocessing, and recycling facilities is required to ensure their compliance with the KrWG and VerpackG [54]. Especially at the calculation point of the recycling rate, infeed recycling process, the recycling facilities have to provide a certificate containing information regarding

- the suitability of the process for the received material;
- the design of the process ensuring that recyclables are not systematically removed (hinders polishing of quotes by accepting low qualities at the calculation point to be removed subsequently in the process and actually not recycled); if so, the mass flow is reduced by the removed amount;
- type of product.

The certificate is regularly renewed by registered sworn experts. In the regular inspections, the inspectors verify the data of the certificate e.g. by comparison to current mass balances and visual inspection.

The recycling capacities for sorted plastic packaging waste is limited in Germany. Therefore, volumes are as well exported to other European countries or even outside of Europe.

Considering not only household plastic packaging waste but post-consumer plastic waste from commercial, industrial, and institutional facilities, the following paragraphs discuss the mass flow from post-consumer plastic waste generated in Germany 2019.

Figure 69 in Appendix C provides an overview of the post-consumer plastic mass flow after collection. With a total collected amount of 5.35 Mt, about 38 % is treated in further recycling facilities either in Germany (about 1.3 Mt) or exported to other countries (about 0.7 Mt). With a yield for the reprocessing and recycling process of about 77 % in average, 1.03 Mt of post-consumer plastic waste has been made available as recyclate to be used in plastic production.

Figure 25 provides an overview of the German plastic market in 2020 in total.

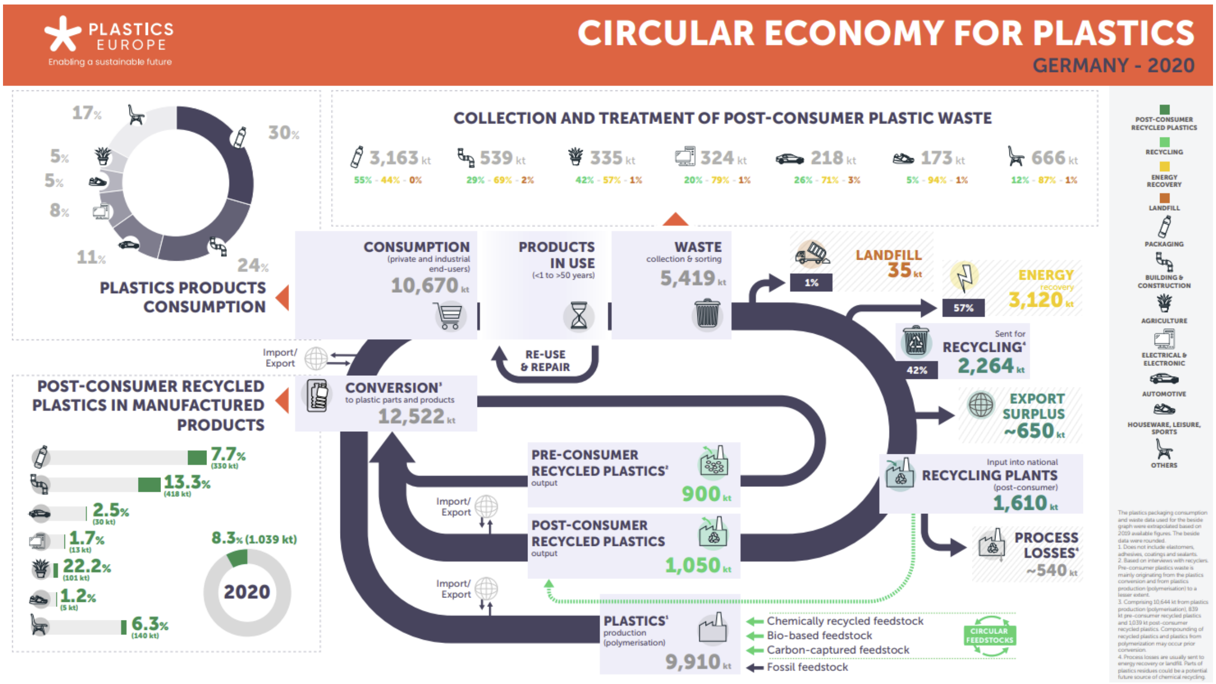


Figure 25. German plastic market [55]. Note, that thickness of the arrows does not represent the stream volumes.

As shown in the figure, about 9.9 Mt of virgin plastics have been produced as raw material to manufacture plastic parts and products. In comparison to that, only about 2 Mt of recycled plastics have been recycled to be used as secondary raw material. From 10.7 Mt plastic parts and products placed on the German market, only about half enter the waste collection and treatment system due to reuse, repair and long-term product life, mainly post-consumer plastic waste. From there on, the figures show a slight increase in volumes for recycling compared to the figures from 2019 discussed earlier.

5.4 France

5.4.1 Legal Framework

The national transposition of the European Waste legislation France is the Environmental code mainly Art. L541, D541 and R541 introducing the Extended producer Responsibility as well as the waste hierarchy aiming for waste prevention and reduction.

Based on the targets of the French roadmap for a circular economy (*feuille de route de l'économie circulaire)* from 2018, the so-called Anti-waste-law or AGEC law (LOI n° 2020-105 du 10 février 2020 relative à la lutte contre le gaspillage et à l'économie circulaire) has been instated in 2020 amending the environmental code. It also transposes the EU Single-use Plastics Directive is into national law. Going a step further with the high focus on prevention and reuse, the Anti-Waste-Law defines the following key goals (non-limitative list):

Prevention	• Reduction of household waste per inhabitant by 15% between 2010 and 2030 • Reduction of industrial waste by 5% between 2010 and 2030 • Reduction of single-use plastic drink bottles by 50% until 2030 • Elimination of single-use plastic packaging by 2040 • Consumers right to be served in their own containers • Price benefit for consumers buying a beverage with own containers • Ban on destruction of unsold non-food products for EPR schemes by 2021, for all other by 2023
Preparing for reuse	Goal of amount of packaging for reuse • By 2023 – 5% • By 2027 – 10% Retailers >400m² must provide reusable containers for products sold in bulk
Recycling	• Reuse packaging shall be recyclable. • Goal of 100% recycling of plastics by 2025 • Collection of all plastic packaging until 2022 for recycling • Collection of plastic drink bottles of 77% by 2025 and 90% by 2029 • Reduction on non-recyclable products by 50% until 2020

On the basis of the defined goals, specific binding targets were enacted:

- Ban on single-use plastic bags since 2016
- Ban on import and production of single-use plastic bags since 2021
- Ban on plastic packaging for fruit and vegetables <1.5kg by 2023
- Ban on single-use plastics for food and drinks in gastronomy by 2023
- Ban on non-recyclable packaging made of styrenic polymers and copolymers by 2025
- Decree 2022-748 on environmental labelling of waste-generating products
  - display or digital information available by latest 2025
  - information for packaging: e.g. compostability, recycled material, reusability, recyclability
- Decree 2022-507 on amount of packaging for reuse -> 5% latest 2026, 10% latest 2027
- Decree 2021-517 on prevention, reuse, and recycling of single-use plastics from 2021-2025
  - reduction of single-use plastic packaging by 20% between 2018 and 2025, thereof 50% by reusable packaging
  - 100% recycling of plastic packaging by proving existing recycling pathways and recyclable design of packaging

Furthermore, specific requirements on the consumer information have been defined *e.g.* prohibiting misleading terms like biodegradable or eco-friendly and informing about recycled content and giving sorting instructions.

To support the economy and create jobs, waste treatment inside of France close to the point of waste generation is induced by the environmental code.

The introduction of a deposit scheme is one of the future goals of the environmental code and connected decrees but not put into operation yet. The evaluation on system integration is currently running, deposit experiments in voluntary regions are encouraged.

5.4.2 Waste Management System

5.4.2.1 EPR scheme

In France there are three approved Producer Responsibility Organisations responsible for the treatment of packaging waste from households:

- CITEO
- Adelphe (part of Citeo) – responsible only for the wine and spirits and pharmaceutical sector, mostly glass
- Léko

For household packaging, CITEO adapted the license fee calculation according to the requirements of the packaging directive by taking as well eco-modulation of packaging and premiums/penalties into account to encourage design for recycling.

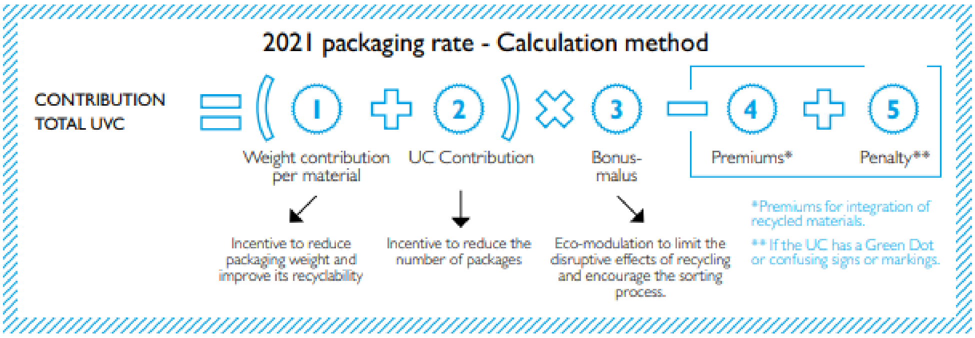


Figure 26. License fee system as used by CITEO (source: CITEO).

Since the collection and treatment of waste is organised by the municipalities, the PROs work closely with the municipalities to set up a wholistic collection and treatment scheme.

5.4.2.2 Collection of plastic packaging waste

The current collection scheme for plastic packaging is a comingled collection of packaging made of paper and carton, plastics, and metals. Previously, only plastic bottles have been collected in the comingled collection. With the extension of the household packaging waste collection scheme to all plastic packaging ongoing, Citeo states in their annual report of 2021 that about 42Mio inhabitants are connected to the extended collection scheme so far (about 2/3 of France).

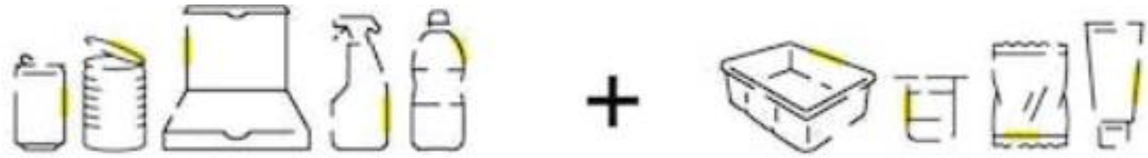


Figure 27: Extension of the household packaging collection (source: CITEO)

This extension already caused and increase of collected plastic packaging waste of 37% from 2020 to 2022. This reflects a collection of 20 kg/capita of collected comingled paper and packaging [56].

In the following, an exemplary composition of the comingled collection waste from households is shown:

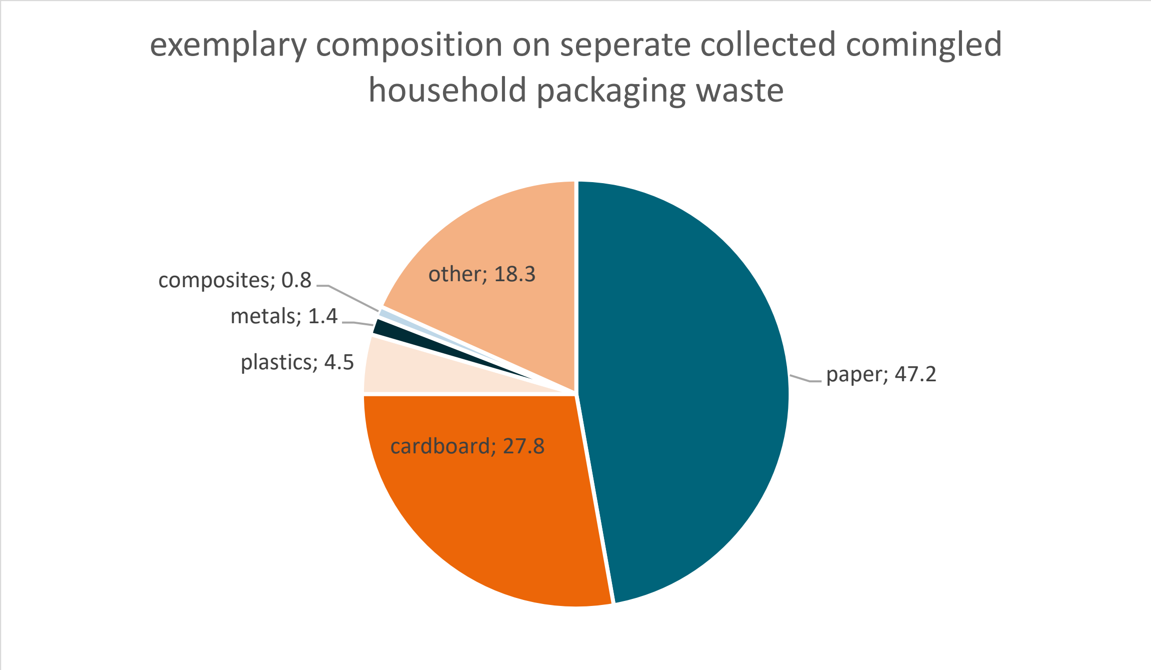


Figure 28. Example composition of comingled waste (source: European Commission).

5.4.2.3 Sorting and reprocessing of plastic packaging waste

With the extension of the collection scheme, the sorting facilities had to be adapted to recover plastic packaging for recycling. So far, about 79 of 163 sorting centres have been modified. With the collected mix, about 65% of plastic packaging is rated as recyclable in the existing treatment structures and sent to reprocessing facilities for further treatment.

In the Figure 29, the basic sorting steps of a French sorting facility for comingled packaging are shown:

STEP 2: SORTING IN SORTING FACILITIES

In France, household waste packaging is sorted in nearly 200 sorting facilites (2019 data) according to their material. Several stages take place in the sorting centers:

– Ballistic separation: packaging is separated according to their shape and size. In this step, packaging with a small size or volume are less extracted (e.g. pods and bottles <20ml or films with size <size A5).

– Metals separation: plastic packaging containing metallic elements (steel or aluminum) can be oriented with plastics or metals according to the quantities of metal and depending on the machine settings (for example: PET jars with a steel hinge or mixed aluminum cans /plastic)

– Optical sorting: with infra-red sorting technologies, plastics can be separated by resin (PET, HDPE, PP, etc.). Some elements may interfere and reduce the efficiency of optical sorting: sleeves made of a material that is different from packaging body, complex trays made of several plastic resins, black packaging, etc.

– Manual sorting: the human eye is still essential to ensure a good quality of materials sorted out of sorting centers.

– Baling: the sorted materials are compacted and baled, then shipped to the regenerators.

Figure 29. Typical sorting steps in French sorting inastallations (source: COTREP).

In terms of sorting streams for plastic in France, Table 8 provides a summarizing overview.

Table 8 Sorting streams in France

Sorting streams
Several qualities of paper and cardboard
Composite paper/Beverage carton
PET bottles clear (+trays where collected)
PET bottles colour (+trays where collected)
HDPE bottles (+other rigids where collected)
PP bottles (+other rigids where collected)
PS rigid
PE-film were collected
Mixed plastics/MPO/RDF

5.4.2.4 Quotes and Mass Flows

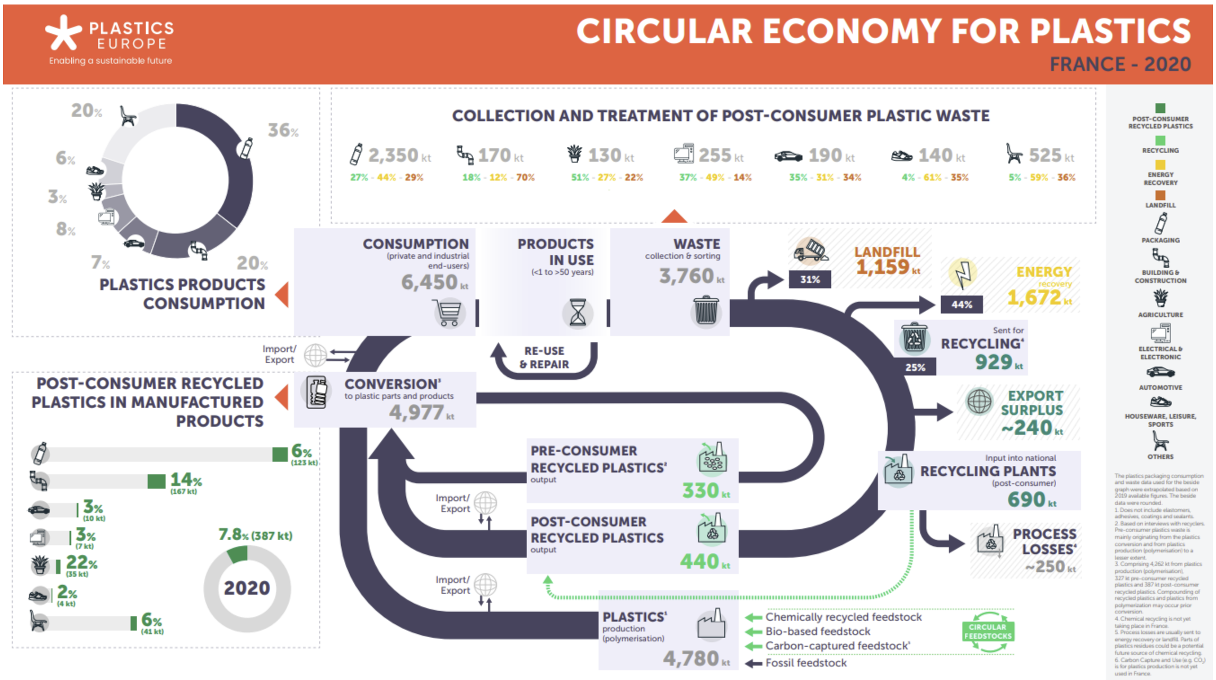


Figure 30. French plastic market [57]. Note, that thickness of the arrows does not represent the stream volumes.

As shown in the Figure 30, about 4.8 Mt of virgin plastics have been produced as raw material to manufacture plastic parts and products. In comparison to that, only about 0.8 Mt of recycled plastics have been recycled to be used as secondary raw material. From about 6.5 Mt plastic parts and products placed on the French market, only about 60% enter the waste collection and treatment system due limited collection, reuse, repair and long-term product life, mainly post-consumer plastic waste. From there on, about 25% are send for recycling either in or out of France. The French plastic recycling facilities are operating at an average efficiency of about 64% leaving much room for technology improvement as well as Design for recycling.

5.5 Interim conclusions

In the previous sections we discussed the plastic packaging waste management system on national level per country. Now we will compare these waste management systems. Table 9 provides an overview of the previously discussed numbers on the market. For Europe, we provide these numbers in Mt, and for the countries we use kt. The percentages in the table are based on the plastic waste in the country (thus including not only packaging but also other plastic waste).

In comparison to the Netherlands, Belgium, Germany, and the European average, France has a relatively high landfill rate. In France 31 % of the collected plastic waste ends up in landfills. Subsequently, their rate for plastic waste sent for recycling is also relatively low: 25 %. In comparison to the other countries, France uses incineration for energy recovery the least with 44 %.

The Netherlands has the lowest landfill rate in comparison to the other countries. However, Belgium and Germany also bring very little plastic waste to landfills. In the Netherlands, Germany, and Belgium, the amount of plastic waste sent for recycling is higher than the European average. Moreover, the input for recycling plants is also higher than the average in the Netherlands and Belgium. In terms of process losses, the Netherlands has the highest rate with 18 %, which is above the European average of 12 %. The other countries are on the average (Belgium), or below the European process loss rate (10 % for Germany, and 7 % for France). Furthermore, the Netherlands has the highest rate of post-consumer recycled plastics from plastic waste with 28 %. Belgium is slightly below with 24 %, and Germany is on the European average with 19 %. France is below the European average for post-consumer recycled plastics with 12 %.

Table 9. Comparison of countries based on waste [44] [57] [55] [58] [6].

	EU in Mt	EU in %	NL in kt	NL in %	BE in kt	BE in %	GE in kt	GE in %	FR in kt	FR in %
Waste	29.5	100	1058	100	578	100	5419	100	3760	100
Landfill	6.9	23	3	0	10	2	35	1	1159	31
Energy	12.4	42	537	51	341	59	3120	58	1672	44
Sent for recycling	10.2	35	478	45	227	39	2264	42	929	25
Export surplus	1	3	20	2	20	3	650	12	240	6
Input into recycling plants	9.1	31	500	47	210	36	1610	30	690	18
Process losses	3.6	12	190	18	70	12	540	10	250	7
Post-consumer recycled plastics	5.5	19	300	28	140	24	1050	19	440	12

Next to the mass flows, we also discussed the sorting streams per country. Table 10 provides an overview of these sorting streams per country. While the Netherlands, Germany, and France sort on plastic film >A4 for flexibles, Belgium has other sorting categories: PE film and other film. For rigid PET, Belgium again has more categories. While Germany and the Netherlands only have a distinction between bottles and trays, Belgium divides PET into transparent, blue, coloured, opaque, and transparent trays. In contrast, France only has one sorting stream for PET. For rigid PE and PP, the sorting streams are similar in the countries. For PS, there is no sorting stream in the Netherlands, while the other countries do have a sorting stream for this. Furthermore, for mixed plastics, there is a distinction between mixed polyolefins and mixed plastics (including also other plastics next to polyolefins). In the Netherlands and Germany it depends per sorting installation and in Belgium sorters sort on rigid MPO. In France, the sorting stream is mixed plastics.

Table 10. Comparison of sorting streams per country.

Plastic type	**Netherlands**	**Belgium**	**Germany**	**France**
Flexibles	Plastic film >A4	PE film	Film/ LDPE	Plastic film >A4
		Other film		
Rigids PET	PET bottles	PET transparent	PET bottles transparent/ PET mix	PET
	PET trays	PET blue	PET trays/ PET mix	
		PET coloured		
		PET opaque		
		PET trays transparent		
Rigid PE	Rigid PE	Rigid HDPE	HDPE rigid	Rigid PE
Rigid PP	Rigid PP	Rigid PP	PP rigid	Rigid PP
Rigid PS		Rigid PS	PS rigid	Rigid PS
Mixed Plastics	Mixed plastics/ MPO	Rigid MPO	Mixed polyolefins	Mixed plastics
			And/ or Mixed plastics/ RDF	

6 Plastic Packaging Waste System - The Netherlands In-Depth

This chapter discusses the plastic packaging waste system for the Netherlands in more detail. We will describe the collection, sorting, reprocessing, and recent developments.

6.1 Collection of Plastic Packaging Waste

Figure 31 provides an overview of the composition of packaging types per type of material of the main component in the Netherlands in 2021. As the figure shows, the largest part of packaging has a main component of PE (28.6 %). Following, 26.7 % of the packaging has PET as the main component, and 26.3 % has PP as the main component of the packaging. Additionally, 7.8 % has multi-material as the main component, and 6.6 % is packaging that has a main component which is not NIR sortable (*i.e.* because carbon black is used). The figure also shows that there is relatively little packaging with a main component of PS (2.0 %), or PVC (0.4 %) [59].

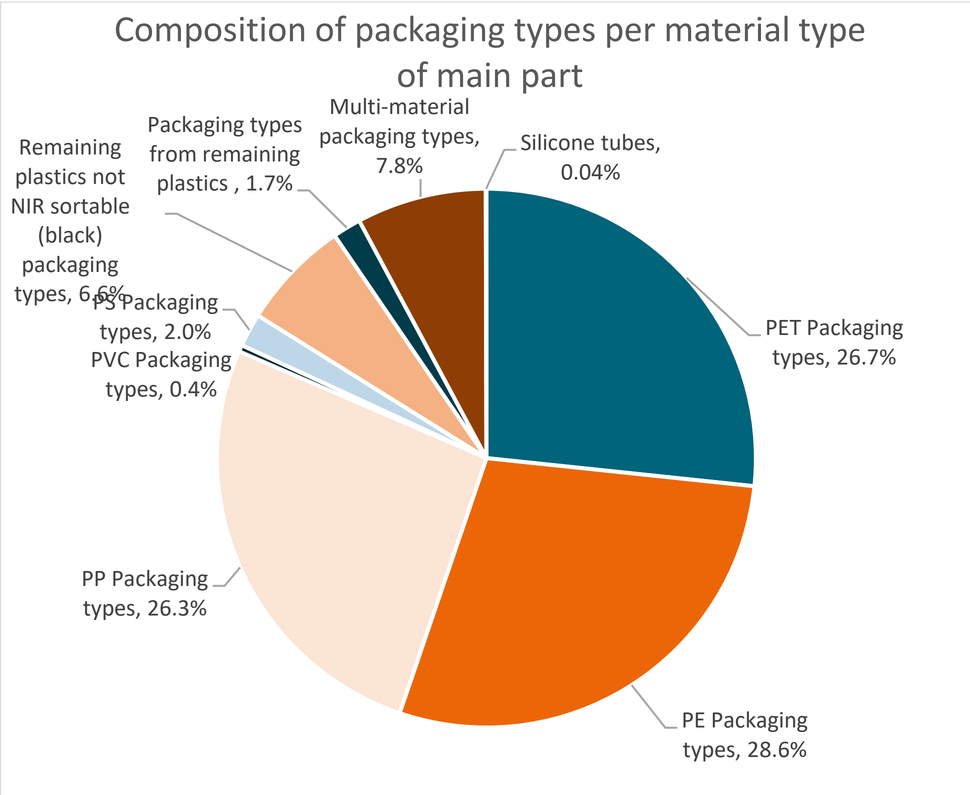
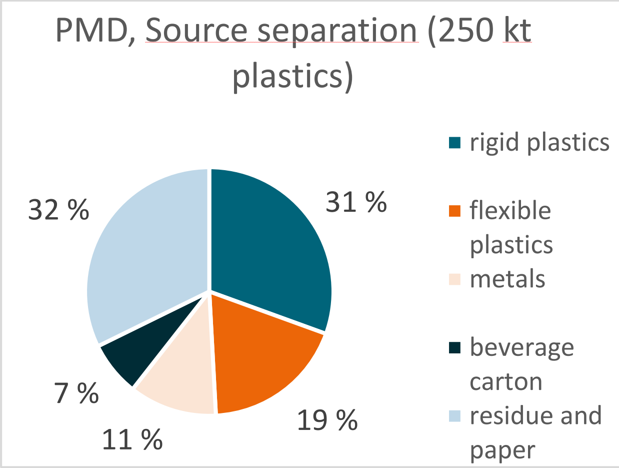


Figure 31. Composition of packaging type per material type of main part, in the Netherlands 2021 [59].

Appendix C also includes a detailed figure that shows the average composition of plastic packaging. Based on a composition analysis of PMD material and residual waste in three municipalities, Brouwer, Velzen and Workala created an overview of the average composition of plastic packaging [59]. Figure 70 in Appendix C provides an overview of this data. The largest categories were:

- PP remaining rigid: 19.3 %
- PET remaining rigid: 17.0 %
- Film PE > A4: 7.2 %
- Film PE < A4: 7.1 %
- Remaining plastics not NIR sortable rigid: 5.3 %
- Film PP < A4: 5.2 %
- PET flacons: 4.5 %
- Aluminium flexible laminate: 4.5 %
- Carrier bags (PE) > A4: 4.0 %
- PE flacons: 3.9 %

As discussed in the previous chapter, there are two types of separation in the Netherlands: source separation and post-consumer separation. Figure 32 provides an overview of the composition of the two different separation methods. For source separated material, the largest part is residue and paper (32 %), which is followed by rigid plastics (31 %). Flexible plastics make up 19 % of the total. Additionally, 11 % is metal and 7 % is beverage carton. On the right, the composition of post-consumer separated plastic shows that 81 % are residue, organics, etc. Here, 9 % is rigid plastics and 4 % flexible plastics. This is followed by also 4 % of metals, and only 1 % of drinking cartons. This means that, in total, 18 % of the post-consumer separated waste is PMD on average.



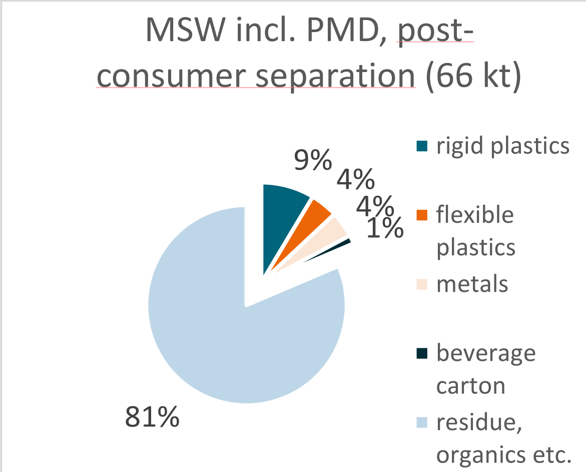


Figure 32. Composition of PMD and post-consumer separated PMD [32] [60].

For the composition of post-consumer separated waste, HVC also includes an overview in their annual report. Figure 33 provides an overview of their data. The figure shows that the largest parts are organic and food waste (32.9 %), and residual waste (26.3 %). The PMD waste makes up 16.8 % of the total. This percentage is slightly different from previously mentioned percentage (18 %).

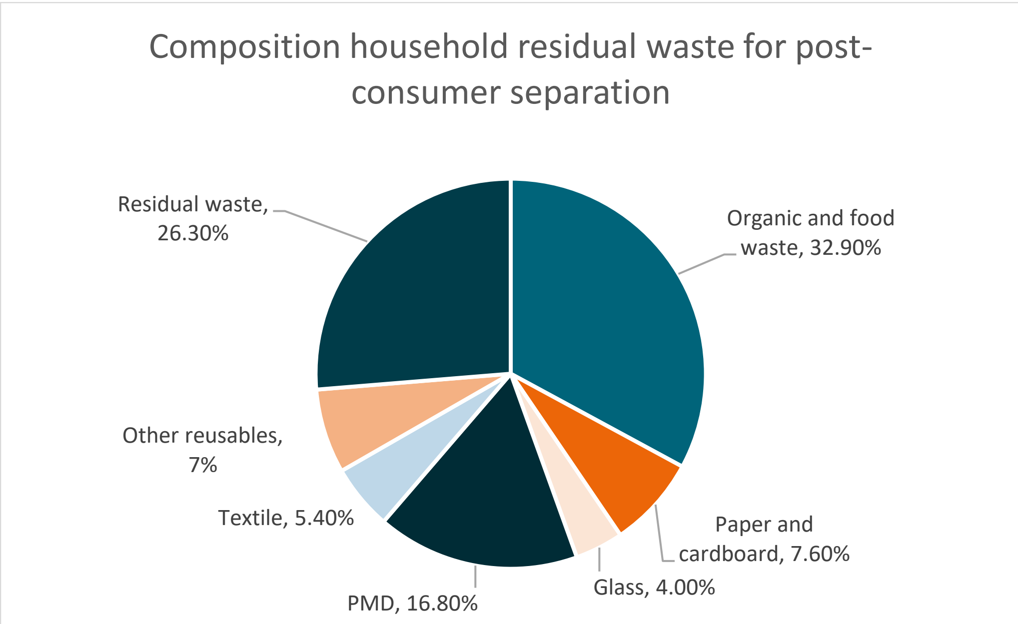


Figure 33. Composition of household residual waste (post-consumer separation) [61].

The above-mentioned composition analyses of post-consumer separation material do not give an indication of the PMD that is actually sorted out in a post-consumer residual waste sorting installation ('nascheidingsinstallatie'). According to AVR, their throughput in the post-consumer residual waste sorting installation is 428.1 kt. Of this 428 kt, the output of plastics is 28.6 kt, which is 6.7 % of the total throughput [62].

6.2 Sorting and Reprocessing of Plastic Packaging Waste

Table 11 provides an overview of the recycling capacity in the Netherlands for PET, HDPE/ PP, and PE film. This overview is based on data from Plastics Recyclers Europe. It is important to note that the recycling capacity for PET (144 kt) is based on the capacity in the Benelux, since there was no available data of the Netherlands on its own. It can be seen that PE film is plastic type with the most recycling capacity in the Netherlands with 192 kt. Additionally, for HDPE/ PP there is a recycling capacity of 120 kt.

Table 11. Recycling capacity Netherlands [12] [13] [14].

Plastic type	Capacity in the Netherlands	% of Europe total
PET	144 kt (Benelux)	6 % (Benelux)
HDPE/ PP	120 kt	8 %
PE film	192 kt	11 %

Overall, there is relatively little data publicly available in terms plastic packaging and the recycling thereof. There are two reasons for this lack in available data. Firstly, in some cases there is just limited data collected. For example, the Dutch EPR Afvalfonds Verpakkingen does not require PI to report on the specific type and material of packaging. They only make a distinction between good recyclable plastic, biodegradable plastic, and 'regular' plastic [63]. Unlike Belgium for example, there are no detailed categories on which PIs need to report. Without this detailed reporting, there is no data collected on type of material entering the market.

Important to mention is that despite the fact that we contacted and interviewed multiple parties that own data on the sorting and reprocessing of plastic packaging waste, they are reluctant to share information. Most parties perceive information as competitively sensitive and are not willing to share this information.

6.3 Recent Developments

As previously mentioned, the deposit refund scheme in the Netherlands extended. Now it includes also smaller PET bottles. This results in a decrease of PET bottles in the collected PMD waste. Additionally, a decrease in litter has been observed because of this deposit refund scheme extension [64].

Next to the extension of the deposit refund scheme, the EPR scheme is also extending. From 2023, the EPR system also includes commercial household-like packaging waste in the Netherlands [65]. Furthermore, in the future, there will be more extensive diversified PRO fees to increase the recyclability of packaging. This means that PIs will not only distinguish between the 'good recyclable' fee and the normal plastic packaging fee, but also distinguish based on polymer and packaging type.

7 Plastic packaging waste treatment – technology scan

7.1 Approach

In this chapter we focus on the existing and upcoming technologies used in the plastic packaging recycling. For the existing technologies we have made use of information publicly available, held interviews with different parties along the plastic recycling chain, and used the experience already gathered by HTP and NTCP in this field.

Using the information from the previous chapters, especially those focussed on The Netherlands, we start with a description of the existing processes and individual technologies that are commonly used in plastics recycling. To put those in perspective we will start with a general view on levels of recycling form closed loop to energy recovery as this distinction plays a leading role in the monetary and environmental value of plastic recycling.

7.2 Levels of recycling

In their study, Hopewell, Dvorak, and Kosoir describe four important types or recycling [66] as listed below. For secondary and tertiary recycling, we added some sub levels to reflect the current situation and view on plastic recycling.

- **Primary recycling** is recycling where plastic is mechanically reprocessed into a product with comparable properties, often called closed loop. This is most convenient when polymer components can be separated from contamination and prevented from degradation during the reprocessing and following usage. Preferably, there is also little variety in polymer grade to facilitate the replacement of virgin sourced material. Pre-consumer plastic waste such as industrial plastic waste is currently more used for primary recycling than post-consumer plastic waste. However, the amount of post-consumer plastic waste is significantly higher than pre-consumer plastic waste. Especially, food packaging is difficult to recycle into new food packaging (food-to-food recycling), because of current legislation. The European Food Safety Authority has published guidelines around the contaminants of the input, the used chemicals in the recycling process and degradation of the products [67]. Currently, only for certain specific applications closed-loop recycling is allowed by EFSA. Examples are PET bottles for beverages and HDPE milk jugs in the UK.
- **Secondary recycling** is the type of recycling that is quite common for household plastic packaging waste: mechanical recycling of plastic streams that have been sorted in sorting facilities. Here the recycled plastic is not put into the same application as it comes from. Two general types of mechanical recycling can be distinguished:
  - **Mechanical recycling** of mono-material sorted streams (e.g. PP rigid) towards new products of that material (typically thicker-walled products). When the material contains little contaminants after the recycling process it can still be used in relatively high-end applications.
  - **Remelting** of mixed plastics or mono-material streams of low quality towards more-or-less solid products using so-called intrusion moulding; this is sometimes referred to as down-cycling or downgrading.
  - **Solvent-based mechanical recycling** of sorted streams specifically dissolves the polymer in a solvent and is recovered as a purer fraction after distillation; this is sometimes ranked under chemical recycling.
- **Tertiary recycling** is recycling of polymers by depolymerising or degrading the plastic from a sorted stream. This is typically done for streams that are difficult to recycle with mechanical recycling. This is defined as chemical or feedstock recycling and can be seen as complementary to mechanical recycling. Two main types can be distinguished:
  - **Thermochemical recycling** or pyrolysis is the process where heating the plastic to 500 – 600°C in a nitrogen atmosphere to retain a so-called pyrolysis oil. This oil, after upgrading, can be used in a steam cracker to produce the base chemicals needed for virgin polymer production. This process is suitable for polyolefins.
  - **Chemical recycling** is the process whereby use of controlled chemical reaction the polymers in the plastic waste stream are depolymerised to monomers or oligomers that, after purification, can be used to produced new virgin polymers. This process can be used for condensation polymers like PET. This is also referred to as solvolysis.
- **Quaternary recycling** can be described as energy recovery. This is applied to products that are not suitable for other types of recycling. Even though it does reduce volumes of landfill, it does not reduce the demand for virgin plastics. Additionally, there are typically also negative environmental and health consequences associated with the emissions. Another term for this type of recycling is valorisation.

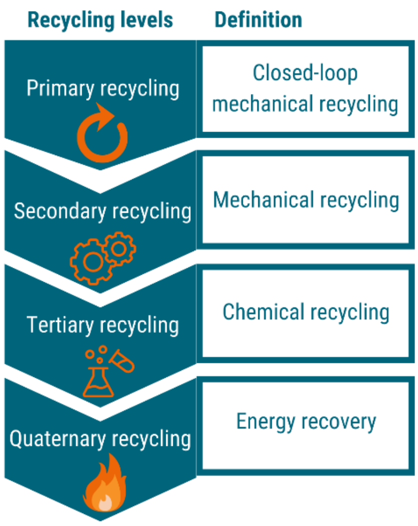


Figure 34. Levels of recycling as defined by Hopewell, Dvorak, and Kosoir [66].

7.3 From plastic packaging waste to new product

The waste management process of plastic packaging consists of various steps which are schematically shown in Figure 35. In chapters 4 to 6. the general waste management in the EU and The Netherlands in particular are described. In this chapter we focus on the technology after waste collection.

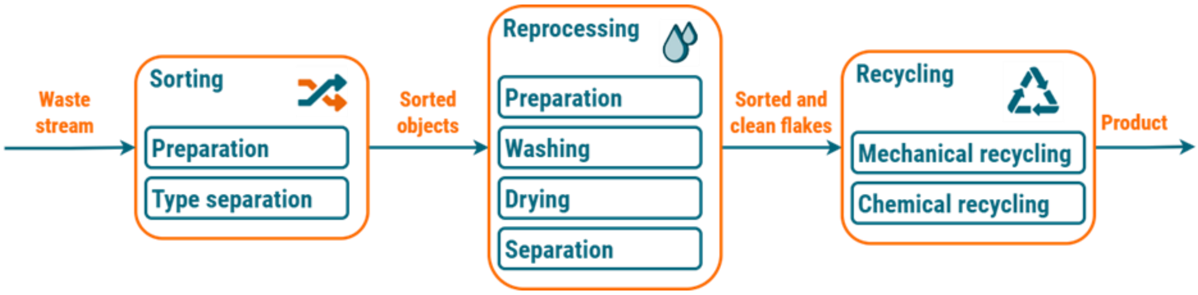


Figure 35. Schematic overview of the waste management process for plastic packaging waste.

The process is divided into three major steps based on the physical appearance of the plastic packaging waste (objects, flakes and finally melt or process fluid). These steps are also often separated by processing facility although some integrated plants are available as well. On a functional level, we describe the steps as follows. The technologies associated to these functionalities are addressed further down in the report.

The focus levels differ per step in the process. In collection and sorting, calculations are based on object level. For reprocessing calculations are based on material level. Figure 36 provides an overview of these levels.

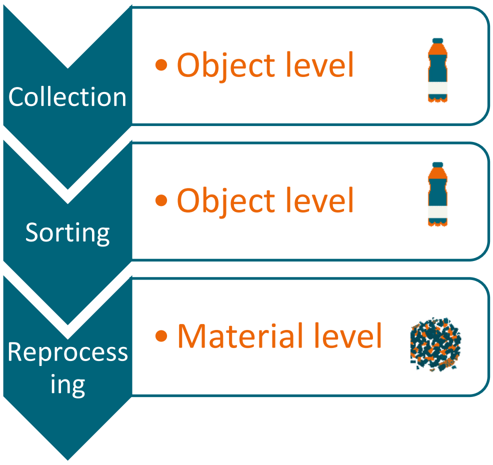


Figure 36. Level per process.

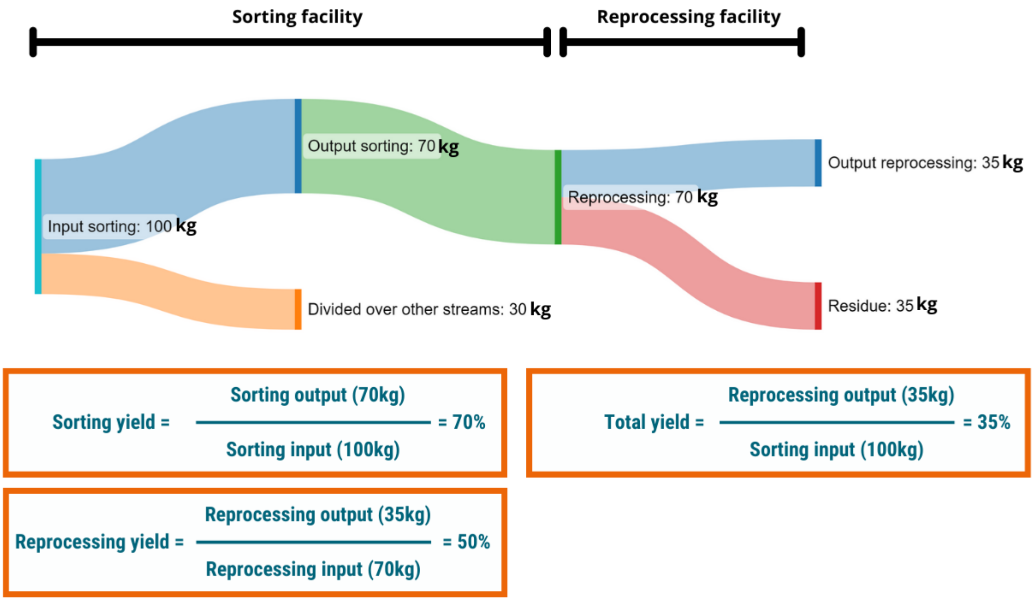


Figure 37. Example of a yield calculation in plastic sorting and reprocessing for PET.

Figure 37 provides an example yield calculation for PET. The figure shows that 100 kg enter the sorting facility, and 70 kg leave the sorting facility as the desired output stream. The yield for sorting is 70 %, since 70 kg out of 100 kg ends in the right output stream. It is important to mention that the sorting output is on object level. This means that the 70 kg objects, of which the main component is PET, ended in the right output stream. Thus, this 70 kg also includes contamination such as other plastics, caps, labels, surface contamination, and moisture (so the purity is not 100 %). Following, this 70 kg (of which the recyclable potential is typically 80 %) then enters reprocessing, of which 35 kg leave as the desired output stream. Here the yield for reprocessing is then 50 % because 35 kg from the 70 kg in reprocessing are output. The total yield of the process (from sorting input to reprocessing output) is 35 % since only 35 kg from the sorting input leaves the reprocessing facility as the desired product.

7.3.1 Sorting

- **Preparation.** The collected household packaging waste, either coming from consumer separation or post-consumer separation, is prepared such that individual objects can enter the sorting process. This means for instance that bags need to be opened.
- **Type separation.** The waste stream is sorted on object level where it is separated by shape (flexible or rigid) and material type. The intended output streams are mostly controlled by the producer responsibility organisations (PROs). In the Netherlands, this currently leads to the output streams: ferrous metals, non-ferrous metals, beverage cartons, PET bottles, PET trays, PP rigid, PE rigid, mixed plastics (2D and 3D), and plastic film.

It should be noted that technically more streams can be produced and that does happen in some facilities both in the Netherlands as abroad. Typical examples of other sorted streams are PS, LDPE film, PP film, PO flex, and clear PET bottles. The sorted streams are mostly baled for further transport unless reprocessing takes place at the same facility.

7.3.2 Reprocessing

- **Preparation.** The received sorted stream is debaled (if necessary) and the objects are reduced in size to enable further processing and remove contaminants embedded in the objects that can be detrimental to the reprocessing steps.
- **Washing.** The first step in washing is a combination of removing coarse surface contamination and a further reduction in flake size. The washing steps should retain clean flakes that can be used in the chosen recycling process. Washing can involve both cold and hot washing steps including the use of chemicals.
- **Wet separation.** Before the flakes are dried, they can be separated on density to separated contaminating polymers from the stream (*e.g.* PP labels in a PET bottle stream).
- **Drying.** Before the final separation steps, the flakes need to be dried.
- **Separation.** The last steps in the reprocessing separate the flakes on type (rigid *vs.* flexible), material and/or colour. The product flakes can be used in a subsequent recycling process and are typically transported in big bags.

7.3.3 Recycling

- **Mechanical recycling.** In mechanical recycling the clean sorted, preferably mono-material, flakes are used as input. The mechanical treatment revolves around an extrusion process where *e.g.* deodorisation and melt filtering are used to remove contaminants that could not be removed in the reprocessing steps. The final product of this step are polymer pellets that can be used at a convertor to produce an end product by *e.g.* thermoforming, injection moulding or film blowing. The recyclate replaces virgin polymers in the final products.
- **Chemical recycling.** In this process the input material are typically flakes that have undergone limited reprocessing and often mixed plastics are involved. The polymers in the streams are depolymerised by either thermal degradation (pyrolysis) or chemical depolymerisation. The output of chemical recycling is a pyrolysis oil or a (solution of) monomers or oligomers. Further processing follows conventional chemical processes to end products. These end products are not necessarily polymers.

7.4 Current technologies

In this section we describe the key technologies that are typically used in current plastic recycling facilities, especially in The Netherlands. The technologies are categorized according to the treatment steps described in the previous section. For each major step, we give a schematic overview of the process followed by the description of the technologies used. In this we focus on the functionality of the steps in the current system, partly dictated by the PROs.

7.4.1 Sorting

Figure 38 shows a schematic overview of the different steps in a typical sorting process for post-consumer plastic packaging waste with the corresponding technologies used, also summarised in Table 12. As mentioned before, the main purpose is to obtain monomaterial sorted plastic streams for further processing. To achieve this a range of technologies is used to sort on size, mass, shape, and material. Additionally, contamination objects and fines are removed as well. Part of the process is a final quality control step that often involves manual labour. Although the technologies used in the sorting process are the same in all European countries, the order in which they are applied and the setting that are used do differ depending on the chosen system and output streams per country or even region.

A simplified example of a Dutch sorting facility is shown in Figure 39. The high-valued sorted streams are indicated in green, whereas the lower valued are indicated light blue. A typical sorting plant in the Netherlands operates fulltime and has a capacity ranging from 60 to 120 ktonne/yr.

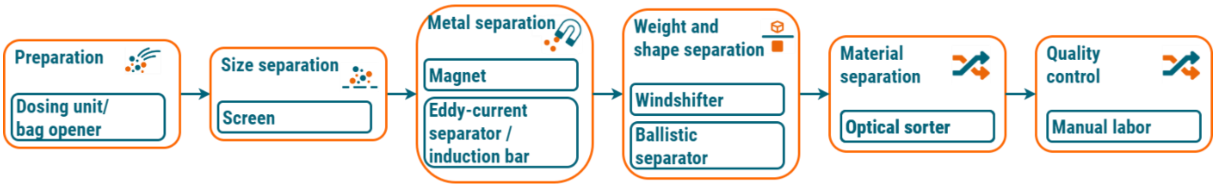


Figure 38. Schematic overview of the steps in the sorting process and the corresponding technologies.

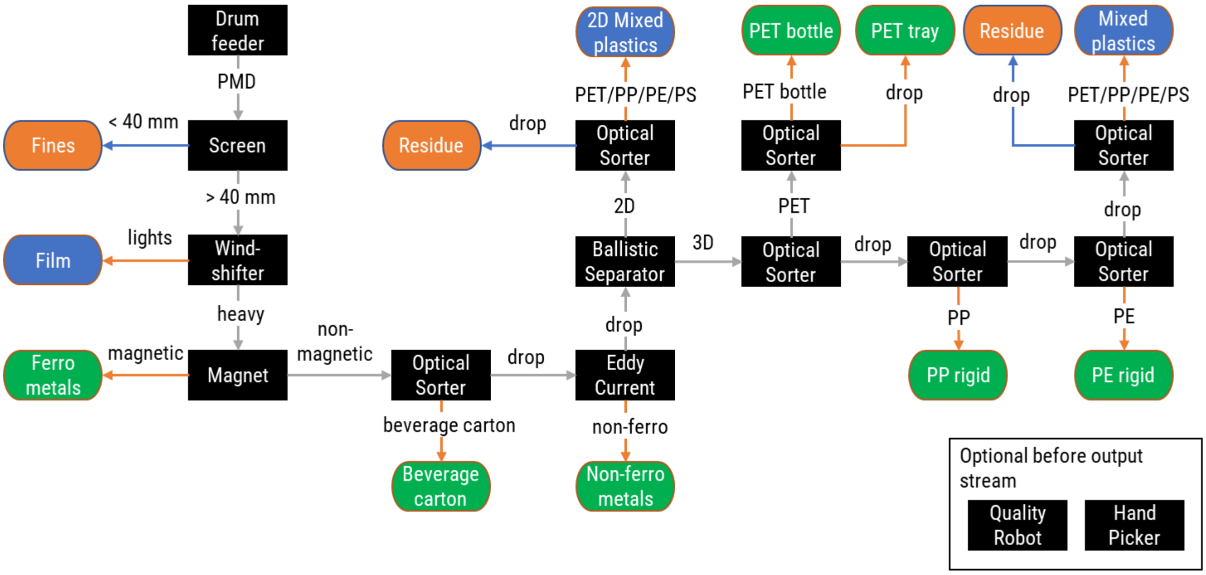


Figure 39. Simplified process flow of a Dutch plastic sorting plant where green streams are considered high value, the light blue ones need further sorting to be useful for proper mechanical recycling, and the orange ones are intended for incineration.

Table 12. Overview of current technologies in sorting.

Process	Function	Technology	Relevant material
Preparation	Prepare waste stream for sorting	Dosing unit / drum feeder	All
		Bag opener	
Size separation	Separating objects by object size	Vibrating screen	All
		Drum screen	All
Mass & shape separation	Separating film material from other material	Windshifter / air classifier	Plastic film
	Separating flexible (2D) and rigid (3D)	Ballistic separator	Flexible packaging material
Metal separation	Sorting out ferrous metals	Magnetic separator	Ferrous metals
	Sorting out non-ferrous metals	Eddy current separator	Non-ferrous metals
		Induction bar with air ejection	Non-ferrous metals
Material separation	Separating objects based on material type	Optical sorter with NIR camera	Plastic types, other material types (*e.g.* beverage carton)
Quality control	Sort out specific items to maintain quality	Manual labour	All (where automated sorting quality is not sufficient)

Below we describe the current technologies that are used in the plastic sorting process in more detail and highlight some of the challenges and weaknesses in the respective technologies.

7.4.1.1 Preparation: dosing unit / bag opener

The main purpose of the preparation step is to transform the collected waste material to individual objects that can be sorted in the subsequent separation process. The major task is to open garbage bags and loosen material such that individual objects are available. Two partly similar technologies are used for this task: a drum feeder or a pre-shredder.

The dosing unit consists of a material buffer with either a conveyor or walking floor at the bottom feeding the waste to a rotating drum equipped with knives to open bags. The gap between the rotating drum and the feeding conveyor belt determines the mass flow into the sorting process. The intention is to fill the conveyor in such a way that subsequent object sorting is possible with an optimized yield-to-throughput ratio. Some dosing unit designs work with a number of discharge screws at the bottom of the buffer simultaneously dosing the material and opening the closed collection bags.

As an alternative or in addition to the dosing unit, a separate bag opener (pre-shredder) can be used. Bag openers consist of either 1 or 2 shafts equipped with knives and a housing with stationary knives to open the bags and at the same time crush oversized objects. An example is shown in Figure 40.

Figure 40. Close-up of a single-shaft bag opener (source: MSW Sorting).

In addition, the preparation process also includes the removal of hazardous objects such as batteries, gas cylinders, and large objects as these might lead to damage of sorting equipment or even fire. This, mostly manual, process is controlled by the operator feeding the line.

Weaknesses / challenges

- Small bags (typically less than 20 l) can pass through the bag opener without being opened due to their size. This hinders the content from being sorted in the subsequent process.
- Films and contaminants like ropes or cassette tapes tend to wrap around the rotating drum / rotating shafts increasing the risk of blockage, reducing the machine performance, and causing a high cleaning and maintenance effort.
- In case of a dosing unit, oversize material can block the dosing unit and, if passing through, might cause blockages in the following process steps. This is also why manual removal of such items is often in place.
- In case of a pre-shredder, not every machine type is able to and set up in a way to crush oversize material + collection bags and let the remaining material pass through undamaged at the same time. An intense crushing process can lead to the production of additional fines, consisting of broken pieces of packaging, not available for sorting and recycling anymore.
- In the dosing unit it is important to have a balance between cutting all the bags open and not ripping up the material. A challenge here is that there are always bags that are not being opened and enter the sorting line. The material within these bags can then not be sorted in the desired streams.
- There is also a risk of ignition in the dosing unit. During the whole sorting process, hazardous objects such as batteries and gas cylinders can cause fire or explosions. This is especially relevant in the dosing unit since this is the first machine where the material enters the sorting line. Moreover, it is also the machine that cuts open bags and thereby has a chance of cutting open gas cylinders, batteries, *etc.* The current mitigation for this is manual removal of such objects by the operator of the infeed of the line.

7.4.1.2 Classification or screening

Using screens, the waste is sorted into specific object size fractions to

- remove small sized objects not suitable for further sorting;
- limit the object size range for more efficient sorting in the subsequent machinery (especially optical sorters);
- enable the use of specific sorting steps for objects in a certain size range, e.g. to produce a stream with large film.

The most common technologies for classification of plastic packaging waste are drum (trommel) screens, vibrating screens, and star screens. Drum screens are most suitable in case multiple size fractions are needed. A recent trend is to use a drum screen in combination with a subsequent vibrating screen for the fine fraction. The smallest fraction from the drum screen would then contain objects smaller than *e.g.* 50 mm which are then further classified to objects between 20 and 50 mm that will still contain valuable plastic objects such as sachets and bottle caps.

Most plastic sorting facilities use a drum screen. In this technology, the material passes through a long horizontal drum (trommel) that is slowly rotating. The drum typically has circular openings of different sizes, starting with small openings at the beginning and increasingly larger openings toward the end of the drum. By this design, several size fractions are created that can be treated differently in subsequent processes.

Figure 41. Example of a trommel screen (source: Stadler).

Vibrating screens transport the waste flow by using vibration over screen decks equipped with holes, to separate items fitting through the holes from those passing over. To increase the efficiency, some vibrating screens are equipped with a flexible instead of a rigid surface oscillating with the vibration. Most designs have multiple steps differing in height to mix the material again making sure small items are screened out and not transported with the other objects.

Figure 42. Example of a vibrating screen (source: MSW Sorting).

Another way to separate fines is the use of a star screen. A large number of parallel shafts with multiple star shaped cogs transport the waste and at the same time separate the fines.

Figure 43. Example of a star screen (source: Bollegraaf).

For all technologies, the sizes of the openings differ per sorter. The smallest size used in sorting plants ranges from 20 to 50 mm. The so-called fines fraction in mostly incinerated.

Weaknesses / challenges

- In a drum screen, its rotation can lead to entanglement of plastic film material leading to improper sorting or clogging of the equipment. The latter would lead to an unplanned maintenance stop of the sorting line.
- A current challenge is to retain as much valuable material as possible especially smaller objects like bottle caps and sachets. Decreasing the smallest hole size, however, also increase the amount of contamination in the sorted stream.
- Another challenge is the separation on size of film material. Film material is mostly not fully extended and might behave as a much smaller object.

7.4.1.3 Windshifter

One way to separate objects by mass and shape is by using a windshifter. The windshifter uses the flow of air to separate light objects with a large surface area from the waste stream. The objects that are not separated by air continue on the sorting line. The windshifter has multiple ways in controlling the air flow that eventually determines the sorting behaviour. The major control is the fan speed, but multiple flaps can be set (manually) to fine tune the equipment. This adjustment is typically performed by an operator based on visual inspection of the two outgoing streams.

In the Netherlands, the separated film material is not separated further but collected in the so-called film stream. This stream mainly consists of LDPE and LLDPE film, a smaller amount of PP film and some PET and multi-material film. Technology does however exist to separate this stream further in PE film, PP film and other film. This is used in some facilities, especially in other countries.

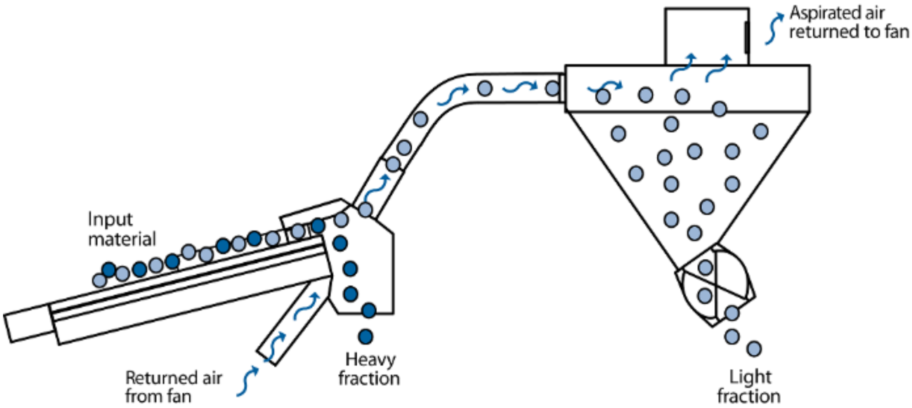


Figure 44. Schematic representation of a windshifter (source: Nihot).

Weaknesses / challenges

- One of the challenges using a windshifter is using the right setting to sort as much large film from the waste stream into the lights fraction without also sorting light rigid plastic objects such as food trays in this stream. As mentioned, this adjustment is manual based on visual inspection; automation of this task is rarely done. Also, with this pure mechanical technology it is inevitable that some film will end up in the heavy stream and light rigid objects will end up in the lights fraction.
- A windshifter is relatively maintenance intensive due to its intrinsic nature. The lights fraction is transported by air through piping that will have multiple bends before it reaches the air separator. As the waste typically is moist and can be sticky, clogging of piping is common in sorting installations. When this happens the light fraction will actually not be sorted until the pipes are cleaned again. This leads to quality issued in the final sorted streams.

7.4.1.4 Magnet

A household packaging waste stream includes steel packaging such as tin cans. A suspension magnet is used to remove ferro-magnetic materials from the sorting stream. An overhead conveyor belt with a magnet inside, attracts the steel packaging and removes it from the main stream. The non-ferrous metals and other materials continue with the main stream. Both permanent as well as electromagnets are used in this step. The strength of the magnetic field at the main conveyor belt determines the sorting efficacy. It can be controlled by the distance of the overhead conveyor or the current when using an electromagnet.

7.4.1.5 Eddy-current separator

Since a packaging waste stream also includes non-ferrous metals like beverage cans and aluminium laminates, there is a sorting step that takes out non-ferrous metals from the stream: the eddy-current separator. This separator uses a rotating drum wrapped with a permanent magnet in the conveyor belt. The produced alternating magnetic field induces an eddy current in metallic objects passing by. The eddy current in its turn generates an alternating magnetic field that is opposite to the one in the rotor resulting in a repulsive force (Lorentz force) on the metallic object. This force is used for the actual separation. The force is proportional to the mass m and conductivity σ of the object and inverse proportional to its density ρ. Different metals have a different $\frac{\sigma}{\rho}$ ratio where aluminium and magnesium have a very high value, whereas brass, lead and nickel have very a value of an order of magnitude lower. Obviously, this makes it an ideal process for the separation of aluminium.

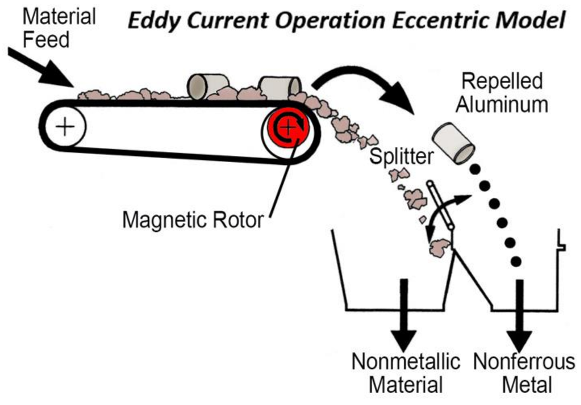


Figure 45. Schematic representation of an eddy current separator (source: Dings)

Weaknesses / challenges

- Aluminium objects that are covered by plastic film will also sort out the plastic film to the aluminium stream which is considered a contaminant.
- Laminate materials containing aluminium and aluminium lidding attached to a light-weight plastic cup will likely be sorted in the aluminium stream. In The Netherlands, beverage cartons (often aluminium laminate) are sorted before the eddy current separator. In some countries the eddy current separator is placed at the end of a sorting line which might lead for the aluminium laminated material to end up in plastic streams.

7.4.1.6 Induction bar separator

As an alternative to an eddy-current separator, an induction bar separator is used to separate non-ferrous metals from the waste stream. An induction bar is placed below the conveyor belt by which metallic objects can be detected. In combination with an air ejection system that is commonly used with optical sorters (see below for details), the metallic object can be sorted. This method is not common in plastic sorting plants but can have an advantage over eddy current sorting when used in cleaning steps of plastic streams.

Weaknesses / challenges

- The challenges are similar to that of an eddy current separator.

7.4.1.7 Ballistic separator

The remaining waste stream after removal of lights and most metallic object, still contains flexible materials. The main purpose of the ballistic separator is to create a rigid (often called 3D) and a flexible (2D) plastic stream. Objects enter a set of parallel inclined screens. The screens (or decks) follow an elliptical movement where neighbouring screens move out-of-phase from each other. This particular movement slowly transports flexible objects upwards, whereas rigid objects due to their ballistic behaviour move downwards. Additionally, fines that have come loose during the previous sorting steps can be separated by the screens.

The operator of the sorting line has the possibility to optimise the sorting behaviour by changing the entry point of the waste, changing the inclination angle of the decks (extremes ranging from 10 to 30°), or changing the rotation speed (not often used). Higher inclination leads to more material going to the 3D fraction. One needs to realise that due to the nature of flexible and rigid objects, the sorting efficiency is far from perfect and an efficiency of 75 % is quite common.

Figure 46. Example of a ballistic separator (source: Recycling Today).

Weaknesses / challenges

- The ballistic separator is a maintenance intensive machine because material compiles in the crank shaft. Approximately every eight hours this machine needs to be cleaned, therefore it is quite labour-intensive.
- There is a chance that objects end up in the wrong stream. Pouches such as cat-food bags can end up in the 3D stream, while it should end up in the 2D fraction., Additionally, flat trays, should end up in 3D, but can end up in the 2D stream.

7.4.1.8 Optical sorter

At the heart of many sorting installations lies a cascade of optical sorters to sort the 3D stream into the relevant materials streams. Additionally, optical sorters are used as clean-up steps of output streams and can also be used in the 2D (currently in the Netherlands only for mixed plastics) and even film stream. These machines separate objects by material type using a near-infrared (NIR) camera. In some cases an additional colour camera is used to sort on colour (*e.g.* for clear PET bottles). The NIR camera is a hyperspectral camera, meaning that for each 'pixel' of an image the NIR reflection spectrum is recorded and can be used for identification purposes. The visual process of this optical sorter consists of various steps:

- **Detection.** If the reflected NIR light is of sufficient intensity a reflection spectrum is recorded for (a part of) an object. Hence, the object is (partly) detected. In case a colour camera is present, this can also be used for object detection.
- **Identification.** For each pixel of the image, the recorded NIR spectrum is compared to a spectrum library with known materials. From that, using proprietary software, a material identification is made. If no proper match is found in the library, the category 'not identified' is applied. In case the reflection to too high (*e.g.* for metallic coatings, no identification can be made). In addition to the NIR reflection identification, the colour can be identified per pixel as well.
- **Classification.** Using internal software programmed based on the sorting requirements, the system attempts to classify a full object for a subsequent decision. The classes in this process are typically agreed with the sorting facility and programmed by the optical sorter supplier.
- **Decision.** Based on the classification image, a decision is made how the mechanical ejection system is triggered. This decision can be both as positive sorting, i.e. triggering the system to eject the intended material such as PET bottles. This is typically done in the major optical sorting steps. Additionally, negative sorting can be used to remove contaminating objects from a stream. This is typically done in a mono-material stream before it reaches quality control. The ejected material might be fed back into the overall sorting process or go to a residue stream.

The mechanical sorting process connected to the vision system is pneumatic. Based on the decision by the vision system, for each object of the programmed class an attempt is made to eject it in the so-called positive stream, whereas the rest will drop down into the negative stream. A typical valve block contains 80 air nozzles per meter conveyor belt width; this means an object resolution of approx. 12 mm. The nozzles are individually triggered for a certain duration depending on the size of the object to be ejected. More nozzles can be opened for a longer time than the object size would imply; in that case the yield of the material goes up, while the quality of the sorted stream goes down as unintended objects might also be sorted. If one does the reverse, the quality goes up, while the yield goes down. This is the balance a sorting facility has to deal with. Typical sorting efficiencies for good sortable objects are close to 90 %.

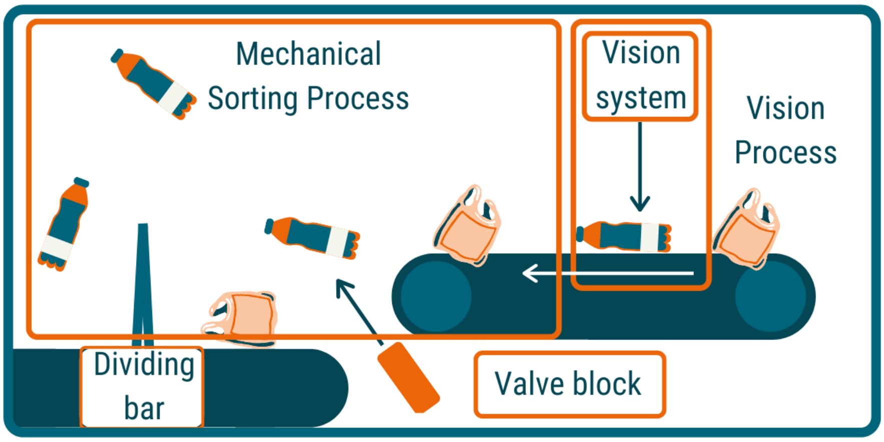


Figure 47. Schematic representation of an optical sorter.

Weaknesses / challenges

- Packaging consisting of multiple layers of different materials can be hard to identify due to combined NIR spectra.
- Carbon-black pigmented packaging is not detected due to high absorption of NIR light. Some NIR-detectable pigments and dyes are available on the market. Also using MIR is an option but is a more expensive solution.
- Packaging that is clogged (stuffed together with other packaging) cannot be classified properly. Either it is classified as the outside material leading to contamination of that material's stream or it ends up in a residue stream, leading to loss of valuable material. This problem needs to be tackled earlier in the process.
- Packaging that is stacked together (*e.g.* flower trays stacked on top of each other) might be classified correctly but might not be shot over the division bar because of its high mass.
- Packaging that has the tendency to roll on flat surfaces, like small round object, might not be sorted because its speed is not equal to that of the conveyor belt and hence does not reach the valve block at the expected time.
- Product residue inside of the packaging might influence the identification by NIR. This is for instance the case by sticky honey in a transparent PET flask: the NIR spectrum no longer resembles that of PET.
- Heavy packaging might not be 'shot' over the division bar because of the mass; this can be caused by residual product.
- Flexible packaging may have the tendency to be dragged by the friction between air and object at high conveyor belt speed and hence not stay in place on the conveyor belt. Solutions where the conveyor belt is in an enclosed space where a forced laminar air flow at the same speed of the conveyor belt is applied are available on the market.
- Strongly reflective packaging (*e.g.* metallised) might end up in the wrong stream because it is difficult to classify due to high direct reflection of light for detection.

7.4.1.9 Baling press

Figure 48. Typical baling press used in plastic packaging waste sorting (source: Bollegraaf).

Although not really a sorting step, as reprocessing typically takes place at a different facility, the sorted material is compressed into a bale before transporting. The most commonly used presses are horizontal presses that allow a semi-continuous stream of material.

Weaknesses / challenges

- The baling process adds steel wire to the material that needs to be removed during the reprocessing.
- The material is strongly compacted that make reprocessing more difficult.

7.4.2 Reprocessing

The sorted streams from the sorting process typically are transported as bales to specific reprocessing facilities for each polymer type. During reprocessing the aim is to create flakes that are suitable for further processing in the actual recycling process. Currently the majority will go to mechanical recycling, but (thermo)chemical recycling is an upcoming process for the recycling of plastics from household waste.

The reprocessing process is schematically illustrated in Figure 49 and summarised in Table 13. We need to mention that certain steps are optional depending on the polymer type and intended quality of the end product. In the dry preparation step the optical sorting is similar to that in the sorting process and is typically applied if the quality of the input material on object level is too low for the intended end product quality.

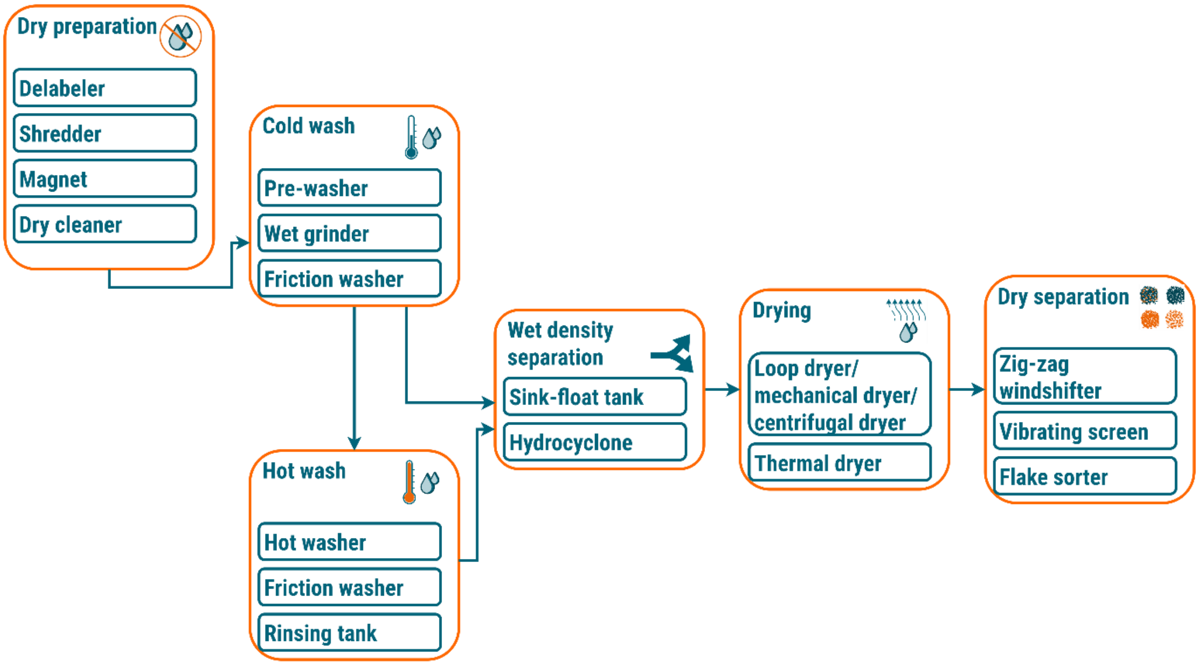


Figure 49. Schematic overview of the steps in the reprocessing process and the corresponding technologies.

*Table 13. Process steps and corresponding function and used technologies for the reprocessing process. Technologies marked with a * are optional and only used in specific plants.*

Process	Function	Technology	Comments
Dry preparation	Removing labels and sleeves	Delabeler*	Useful for bottles (typically PET)
	Reducing size of the material to 50 – 80 mm	Shredder	
	Removing ferro-magnetic material	Magnet	
	Removing excess dirt	Dry wash*	Especially for film
Cold wash	Removing initial part of contamination, including sand, stones, paper, and metal fines	Wet pre-washer	
	Reduce size of the material to 10 – 20 mm	Wet granulator	
	Remove contaminants such as fine particles and product residue from the flakes	Friction washer	
	Separate the product flakes from the smaller solid objects	Sieve	
Hot wash	Taking out difficult removable contaminants such as, oil, adhesives, and odour at elevated temperature in an aqueous solution of caustic soda and detergents	Friction washer*	Used for PET and recently also for PE and PP
		High speed washer*	
		Rotary washer*	
	Removing caustic soda from the plastic with clean water	Rinsing unit*	
	Separate the product flakes from the smaller solid objects	Sieve	
Wet separation	Removing high density material from low density material. Relevant to remove polyolefin labels from a PET stream or PET sleeves from a PE stream.	Float-sink tank	
Drying	Mechanically reducing moisture level of stream	Loop dryer	
		Mechanical dryer	
		Centrifugal dryer	
		Step dryer	
		Screw compactor	
	Thermally reducing moisture level of stream to a level suitable for extrusion	Thermal drying	
Dry separation	Separating rigid from flexible flakes	Zigzag windshifter	
	Separating flakes on colour and/or material type	Optical flake sorter	
	Separating flakes based on size needed for downstream processing	Screen	

The processes currently used in reprocessing facilities are describes in more detail below including typical challenges and weaknesses if any.

7.4.2.1 Delabeler

Especially for (PET) bottle streams, labels and sleeves can be removed by a delabeler. In this way the label and sleeve material will disturb the recycling process less. In a rotor-stator setup with knives on either side with a substantial gap tears sleeves and labels from bottles. Subsequently, an air flow is used to separate the film material from the rigid material.

Figure 50. Close-up of the rotor-stator setup of a delabeler (source: Stadler).

Weaknesses / challenges

- During the process fines can be generated from bottles that also get cut to some extend.
- The process is not really suitable for other rigid plastics than bottles.

7.4.2.2 Shredder

The initial shredding step in reprocessing (also called pre-shredding) is to unclog all material, release metallic parts from compound packaging, and get the material in a suitable size for further processing. A typical size after shredding is 50 mm. The equipment's working principle is a rotor-stator setup with knives on either side with a small gap and, hence cutting the material. Underneath this setup a basket screen is placed to retain the intended size flakes.

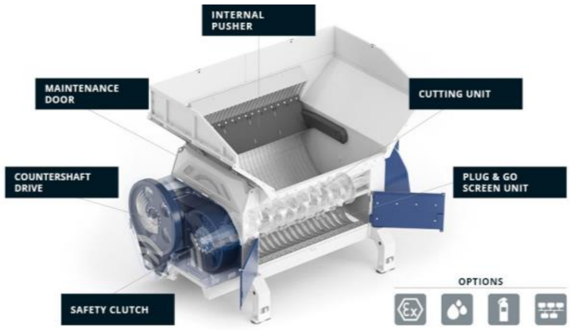


Figure 51. Typical shredder used in reprocessing of plastics (source Linder).

Weaknesses / challenges

- The cutting process can generate heat which in the presence of hazardous materials in waste stream (batteries, gas canisters) could lead to hazardous situations.
- The equipment is typically noisy and fine particles are generated that could become airborne.
- Because of the presence of sand and other harder particles, the shredder knives wear relatively quick.

7.4.2.3 Magnet

Although there is already a magnet in the sorting step that removes the ferro-magnetic objects from the waste stream, not all the ferrous metals are removed during this process. This could occur because it is contained in the packaging material and is only released after shredding. Therefore, there is another magnet in the beginning of the washing process, to remove the ferro-magnetic metals from the shredded material. The setup is essentially the same as in the sorting process.

7.4.2.4 Dry washer

The dry wash step removes a part of the contamination that is adhering to the shredded material. The centrifugal motion and baffles in the rotating drum lead to removal of dry surface contamination. This contamination includes organic residue, paper, and fines such as stones, metals, and glass. The losses that occur in this process are the losses of the small particles of the product material. Not all the organic residue is removed in this step and thus continues as contaminant with the product stream to the next step. A combination of a dry washer and a zigzag windshifter (discussed later) can be a reprocessing process that does not involve the use of any water and could be sufficient for certain recycling processes.

Figure 52. Opened dry washer for plastic reprocessing (source B+B).

Weaknesses / challenges

- Depending on the exact design fine particles are generated that could become airborne.
- For brittle materials like PET, material losses can be significant.
- If the material contains too much moisture, the efficiency might be low.

7.4.2.5 Pre-washer or rafter

In the wet pre-wash process, flakes are washed to remove excessive dirt from highly contaminated pre-shredded plastics (mainly polyolefins). The process uses slow rotation for gentle processing and relies on sedimentation of sand, metal, and glass. The contaminants are removed by a chain type conveyor

Figure 53. Pre-wash setup for plastic reprocessing (source Lindner Washtech).

Weaknesses / challenges

- Loss of heavier plastics like PET.
- Water becomes heavily contaminated. Cross flow is often used with other washing steps where the pre-wash receives the dirtiest water.

7.4.2.6 Wet granulator

The purpose of the wet granulator is to create plastic flakes in a size that is needed for the chosen recycling process. Typically flake size ranges from 6 to 20 mm. The design of the granulator is a rotor with multiple knives (~5) and 1 or 2 counter knives on the housing (stator). Typical rotation speeds are 400 to 600 rpm. A basket screen is available in different sizes to get the correct size. Injection of water is used to wash of contaminants and solved paper, flush the material out of the grinder and cool the material.

Figure 54. Wet granulator for plastic reprocessing (source [Lindner Washtech](#)).

Weaknesses / challenges
- As in all grinding process, fines could be generated that lead to product loss and emissions.
- A granulator wears due to the cutting actions leading to frequent maintenance.

7.4.2.7 Friction washer

The purpose of a friction washer is to remove surface contamination and detach plastic labels *etc.* Later in the process these labels can be removed from the main product by separation steps like float-sink, zigzag windshifter or flake sorter. Paper labels typically disintegrate and are separated from the washing water. A friction washer is designed with a fast-rotating rotor with attached inclined paddles that induces friction on the flakes and at the same time transports the flakes upwards. Water jets on the rotor function as a washing medium and the amount also controls the friction. Fines, water, and other contamination is separated from the flakes through the perforated screen cage surrounding the shaft.

Figure 55. Friction washer for plastic reprocessing (source [Lindner Washtech](#)).

Weaknesses / challenges
- Because of the high friction and use of water, energy and water use can be high.
- Contaminant that are migrated into the plastic will not be removed.

7.4.2.8 Hot washer

The function of the hot washer is to perform high level cleaning of plastic flakes with removal of adhesives, inks, organic residue, *etc.* A hot washer is often an integrated system containing a hot-wash reactor (commonly as batch reactors (tanks with stirrers) with defined retention time) and friction wash (see before). The process is performed at elevated temperature (85°C) with the use of caustic soda (surface treatment of PET), and detergents (often nonionic formulations). A rinsing step is typically the last step in the hot washing process to remove caustic soda and detergents.

The hot wash step is not used in every washing process for plastic waste. Typically, it is not used cleaning for PE and PP, although this leads to a lower quality recyclate. Since there is a still a market for this lower quality product, recyclers choose to avoid the additional costs of hot washing. As mentioned earlier the demand for high quality PP and PE recyclate is growing, hence some recyclers have already chosen to use a hot-wash step for

Figure 56. Integrated hot-wash setup for plastic reprocessing (source [Lindner Washtech](#)).

Weaknesses / challenges

- Obviously due to the higher temperatures, energy consumption is increased
- Demand for fresh water is higher in this step than for instance in the pre-wash step. As mentioned, cross flow use of water is often applied.
- The water from this step will not only contain the contaminants from the waste stream but also added caustic soda and detergent that needs to be treated. The effort for recovery of treatment chemicals is high.

7.4.2.9 Float-sink separator

In a float-sink separator the aim is to separate low density (polyolefins) from high density (PET, PVC, ABS) plastics. This is typically applied to remove labels from a PET stream or PET sleeves from a HDPE stream.

The principle of the process is using the difference in density of a plastic to that of water (density adjustment possible with salt although not often used). The floating fraction can be removed from the top, whereas the sinking fraction can be removed with a chain conveyor from the bottom trough of the machine. Either stream can be considered as product but as a reprocessing line is typically designed for one polymer type, one stream is chosen upfront.

Figure 57. Float sink setup for plastic reprocessing (source [Lindner Washtech](#)).

Weaknesses / challenges

- This is the last step of the cleaning process; hence the water cleanliness is important, but it is not acceptable to continuously supply fresh water. Proper water treatment needs to be in place.
- Foamed materials will have a different density than the polymer itself. Foamed PET (sometimes used in sleeves) will float which is acceptable in a PET stream but unwanted in a polyolefin stream.
- Density separation in a single batch will not allow the separation of PP from PE.

7.4.2.10 Loop dryer / mechanical dryer / step dryer

Different mechanical dryers all have the goal to remove excess water from a flake stream. You may find this step at distinct stages of reprocessing. A loop dryer uses the centrifugal force to remove water (and possibly some remaining contaminants) to dry the flake stream. The dryer spins at high velocity, whereby the plastic flakes are contained in the drum and the water plus some remaining contaminants are removed through a surrounding screen. A mechanical dryer can have either a horizontal or vertical orientation. A variation on this technology is the step dryer. In this dryer, the material and water stream enter from the bottom and the water is removed in multiple stages. Each stage is associated with an increase of diameter, thereby gradually increasing the centrifugal force on the stream.

Figure 58. Mechanical dryer for plastic reprocessing (source Lindner Washtech).

Weaknesses / challenges

- During centrifugation small particles could be generated.

7.4.2.11 Thermal dryer

Thermal dryers use hot air to dry the flake stream coming from the mechanical dryer to reduce its moisture contents to very low levels. The flake stream mixes with the hot air and is dried continuously during this contact. After this, the stream typically enters a cyclone, where cool air is added to remove more moisture and possibly some remaining dust and fine particles.

Figure 59. Thermal dryer for plastic reprocessing (source Lindner Washtech).

Weaknesses / challenges

- The main drawback of a thermal dryer is the high energy use.

7.4.2.12 Zigzag windshifter

In one of the last steps of the reprocessing step, film flakes are separated from rigid flakes because most mechanical recycling extruders are designed either for a rigid or for a film flake input due to the flow properties of the materials. In the zigzag windshifter an airflow is directed upwards in a zigzag channel to separate light from heavy flakes. Gravity will transport rigid flakes down, whereas the air flow takes film flakes up. The zigzag layout prevents film flakes to fall down.

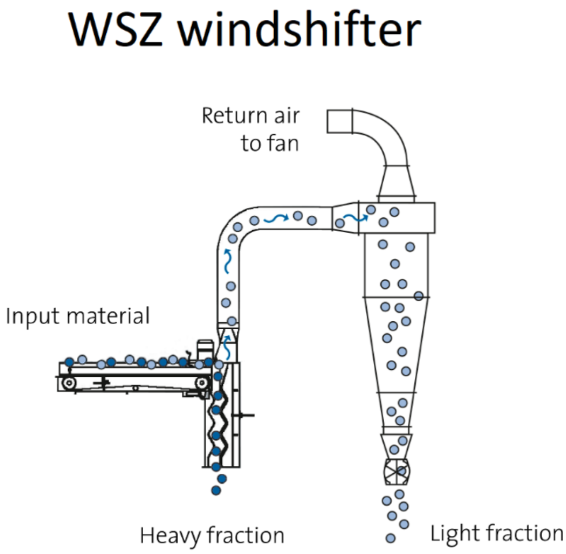


Figure 60. Schematic representation of a zigzag windshifter used in plastic reprocessing (source Nihot).

Weaknesses / challenges

- Material loss in either stream.
- In this process there are no emissions, however, small particles of targeted material can be lost.

7.4.2.13 Optical flake sorter (NIR/ RGB)

As last step in the reprocessing, flakes can be sorted on colour and/or material in multiples streams or a simple product and reject stream. This step enables different grades of output material and increased purity. As in an optical sorter in the sorting process, an RGB camera is used for detection of colour and some non-product materials like wood and metal, whereas NIR is used for material detection. Separation can be either from a belt (comparable to object sorting) or falling flakes. Both work with compressed air. In industry often either a colour sorter or a NIR sorter is used, although some combined machines exist.

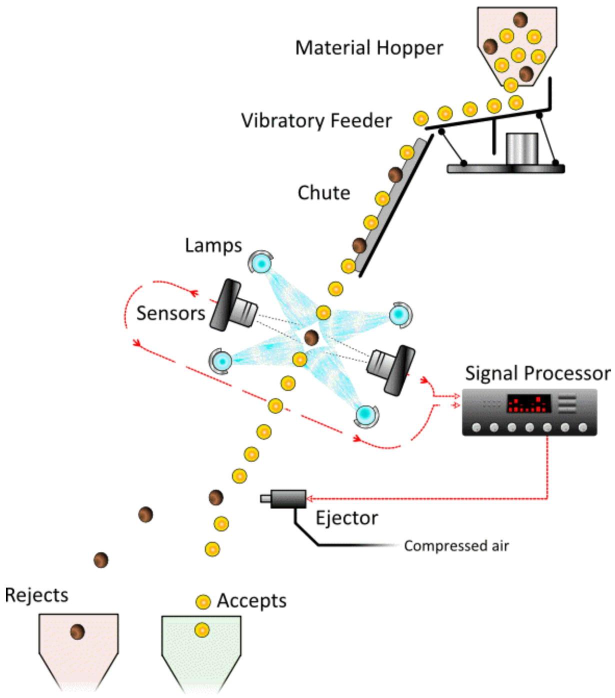


Figure 61. Schematic representation of a flake sorter.

Weaknesses / challenges

- Depending on the reprocessing facility only colour or material sorting is used.
- The reject stream can contain a substantial amount of product as the ejection of small flakes always leads to ejection of surrounding flakes.

7.4.3 Recycling

The term recycling is often used for the complete process of converting plastic waste into new plastic. However, in the context of this report, recycling refers to the conversion of a prepared (*i.e.* clean, sorted, and/or shredded) plastic waste stream into an end-product (pellet) for the production of new plastic products (mechanical recycling or dissolution) or semi-product that can be used for the production of polymers or other chemicals (chemical recycling).

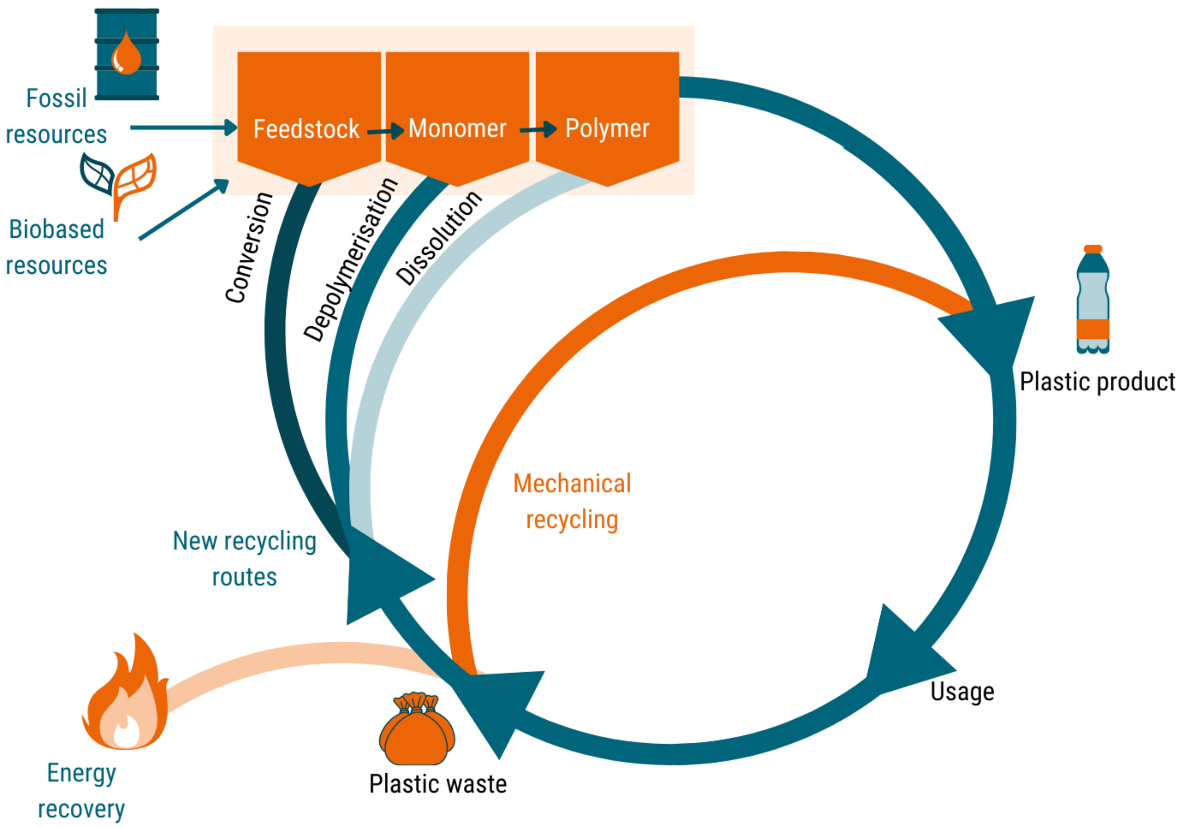


Figure 62. Schematic representation of the different recycling routes.

In this part of the report we only discuss established mechanical recycling, whereas chemical recycling and dissolution are addressed in section 7.5.

7.4.4 Mechanical recycling

As in the reprocessing step, the mechanical recycling step is designed for a specific product type (both polymer and flexible or rigid). The washed and dry flakes from the reprocessing step serve as feedstock and the end product if the mechanical recycling step described below is a pellet, the so-called post-consumer recyclate (PCR), that can be used as feedstock for film blowing, injection moulding, *etc.*

The most part of the mechanical recycling step is mostly integrated in an integrated piece of equipment. An example of such integrated extruder is shown in Figure 63. This is a typical design for a thermoplastic recycling machine where the input are flakes and the output pellets. It includes the following functional parts:

1. Feeding system for the flakes; the design depends on the type of flakes being used.
2. Preconditioning unit where material can be cut, heated, dried, compacted and buffered. The exact design also depends on the polymer type and shape (rigid or flexible). Typically a temperature gradient is applied (cooler at the top). The material is fed pre-compacted and pre-heated to the extruder screw.
3. In the screw the polymer is plasticised and homogenised supported by the screw design where transport and kneading sections are present.
4. Degassing takes place to remove any volatiles that might still be present in the material that was not removed in the reprocessing step or in the preconditioning unit.
5. A melt filtration unit (different designs exist) removes any solid not melted parts from the plastic. This could be fillers that were present in the flakes.
6. At the exit of the extruder the melt is conveyed at low pressure to mostly a pelletiser.

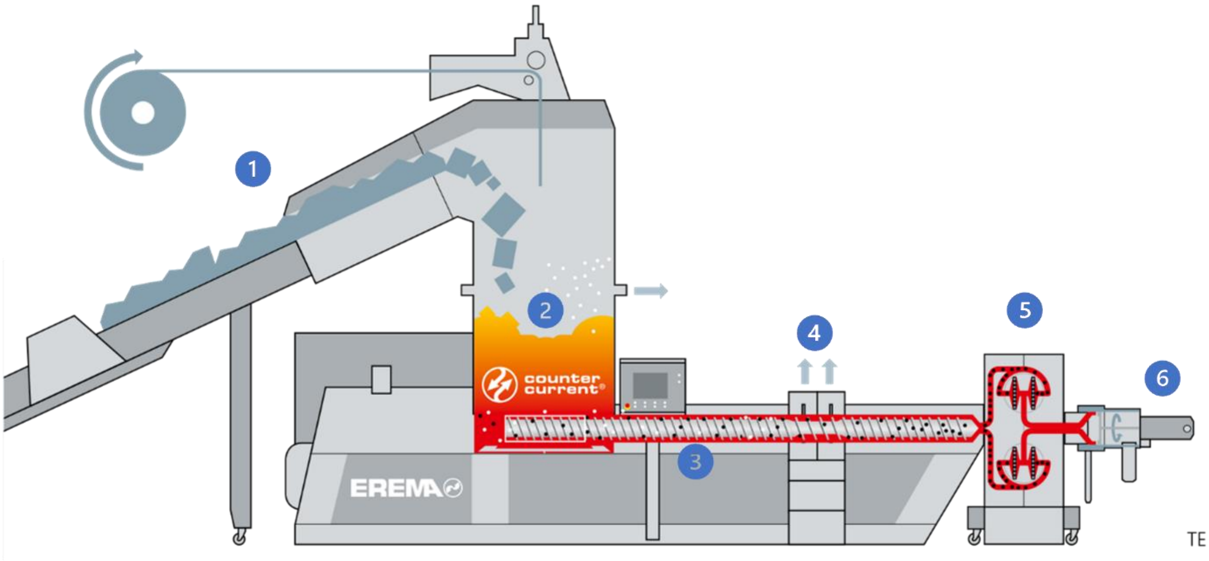


Figure 63. Integrated film recycling extruder (source: Erema).

After this extrusion process different downstream processes can be applied to increase the quality of the recyclate. For condensation polymers like PET it is possible to apply so-called post-condensation under vacuum in the absence of oxygen to increase the molecular weight of the polymer. One could call this rejuvenation of PET.

Before the pellets can be used for the conversion into new product, often compounding is applied to add dyes, pigments, antioxidants, and other additives.

Weaknesses / challenges

- Due to the elevated temperature in the extruder and viscous shear, some depolymerisation can take place that will reduce the quality of the recyclate. As mentioned before for PET post-condensation (in melt or solid state) can be applied. For polyolefins this is less easy; use of organic peroxides is possible to change the molecular structure as well [68].
- Melting of polymers obviously requires high temperatures and hence high energy use. Similarly, the shear friction increases the energy use.

7.5 Upcoming technologies

In the sections below we will focus on technologies that are in an early phase of implementation in plastic packaging sorting, reprocessing, and recycling. The technologies as such are mostly not new but are not yet used broadly in plastic waste management. We will place the technologies into the context as described above on the present systems.

7.5.1 Sensor technologies

7.5.1.1 Context

In the current sorting process, NIR and RGB sensors are typically used to classify material based on their material type or colour. By coupling these sensors to fast working air jets, material can be sorted fast and relatively accurately. To extend the capabilities with respect to detection and classification, other sensor technologies can be considered. Some of developments work by analysing a different or wider range of the electromagnetic spectrum, while others excite the molecules of the materials and analyse the response. In this way more information on the objects and material can be gathered that would enable sorting on other attributes than currently is done. Important considerations for the evaluation of sensors technologies are costs, sensor speed, and online or offline applicability. Fast online measurements allow for a real-time monitoring of the process, while slower and/or offline measurements can only give delayed or batch-wise information.

7.5.1.2 Technical description

There are several developments in the sensor technology used in the plastic sorting process where the details and applicable area are dependent on the type of sensor. An overview of newer sensor technologies for identification and classification is listed in Table 14. For a more detailed overview, the interested reader is referred to the REMIX Final Report [69].

Table 14. Variations in sensor technology types for the identification and classification of plastic waste [69].

Type	Description
Laser induced breakdown spectroscopy (LIBS)	LIBS is a chemical analysis tool which can be used to do a multi-elemental analysis of solid samples. Short laser pulses are used to create a micro-plasma on the sample surface. The light emitted from the plasma contains relevant spectra coming from the atoms and ions contained in the material. **Application**: LIBS could be used to detect specific metal parts in packaging; it is likely more suitable for the aluminium stream than for the plastics streams. **Strengths**: The method itself is quite fast and is used in aluminium sorting up to 5 tons/h. **Weaknesses**: LIBS is a single point measurement technique and requires the material stream to be object by object. For high mass material this might be feasible, but not so much for plastics and thin aluminium objects.
Mid infrared (MIR) spectroscopy	In reflection spectroscopy in the MIR range more detailed chemical information can be deduced from the sample (fingerprint) than in the NIR range. It can be use, like NIR, for material identification. It is less prone to full absorption by carbon black (still used in packaging) than NIR. **Application**: MIR spectroscopy can be used as a drop-in replacement of a NIR optical sorter where carbon black is expected to be an issue. **Strengths**: Much less absorption by carbon black and hence the possibility to identify the material type of objects that contain carbon black pigments. **Weaknesses**: The sensor needed for MIR is a factor three more expensive than that for NIR. The amount of heat generated by the lamps is higher than with NIR and hence a higher risk of fire.
Raman spectroscopy	Raman spectroscopy is a vibrational spectroscopy technique for the analysis of materials. It provides detailed information about its molecular structure. A sample is excited by a monochromatic light, usually emitted from a laser, and the scattered light is analysed where the wavelength of the laser itself is filtered out (Raman shift). **Application**: The method could be combined with a NIR optical sorter to identify more detailed compositional information about surface treatment (print, coating) of objects. This can add value in streams where hazardous substances are expected (typically not in household waste). **Strengths**: Detailed molecular information about coatings and materials. **Weaknesses**: The commonly used green laser may induce fluorescence in many plastics that makes the Raman spectrum useless. A possible solution is using a DUV laser.
Terahertz (THz) spectroscopy	THz spectroscopy uses the portion of the electromagnetic spectrum between the microwave and the infrared region (0.3 – 10 THz). With its high penetration depth (millimetres) and the sensitivity for the presence of plasticisers and inorganic fillers in plastics it can perform a more detailed classification on polymer type and grade [70]. **Application**: Could be used to sort a specific plastic stream into specific polymer grades.

	Strengths: Reveals more detailed information about polymers than NIR does; it can be used in combination. **Weaknesses**: The THz source (pulsed laser) is rather expensive.
Energy dispersive X-ray fluorescence (XRF)	Using XRF, the heavy elemental composition of materials can be determined in a quick and non-destructive way. This is determined by measuring the spectrum of the characteristic fluorescence emitted by the different elements in the sample when it is illuminated by high-energy X-rays. It works for elements with higher mass; typically one can detect elements starting from Na (Z=11). **Application**: XRF would be useful in quality control to check whether heavy metals, chlorine or bromine are present in the plastics. It is not useful for polymer detection as H, C, N, and O are not or hardly detectable by XRF. **Strengths**: Element specific detection method. **Weaknesses**: The method uses X-rays, so shielding is required. Also, the method is not fast enough to use in most sorting steps.
X-ray transmission imaging (XRT)	A radiation source emits X-rays which penetrate the sample, and the residual radiation is registered by a detector. How much radiation is absorbed depends on the atomic density and the thickness of the material, so this technology can be used to identify different materials based on their atomic density (as long as there is not much variation in thickness). **Application**: The technique can be used at the entrance of a sorting or reprocessing line to detect the presence of hazardous objects such as gas cylinders and batteries. **Strengths**: Capable of quickly detecting metals in a plastic stream even when they are overlapping. **Weaknesses**: X-rays are used, hence proper safety precautions are needed.

Although the application areas and strengths / weaknesses depend on the specific sensor (already described in the table above), the evaluation of developments in sensor technology can also be discussed in more general terms, as described below.

7.5.1.3 Application

- **Optical sorting.** Some of the sensor technologies described can be used in the optical sorting step to improve the identification and classification of materials, or even identify material on other properties than are available in the current process.
- **Quality control**. Some techniques can be used to detect contaminants, additives, or polymer grade; this can be used in quality control of flakes and/or object streams

7.5.1.4 Competitive Technologies

- **Optical sensors.** The most used sensors in current facilities are NIR and RGB. These sensors have a fast response time and give good accuracy for the determination of the material and colour of the objects. Innovative technology should be able to extend the functionality, while preferably maintaining a fast response time with continuous output.

7.5.1.5 Strengths

The specific strengths per technology were already listed above. Added value to existing technologies could be:

- **Enhanced identification and classification**. By using a wider/different range of the electromagnetic spectrum or by exciting molecules, additional information on the material in the waste stream can be obtained. This allows for more sophisticated methods for identification and classification of the objects.
- **Automatic and online measurement.** Preferably the measurements should be taken automatically and online so that the waste stream can be continuously monitored and there is no need to manually takes samples. However, not all sensors are suitable for this, either due to their inherent process or due to slow measurement times.

7.5.1.6 Weaknesses

- **High costs.** Although it depends on the specific technology, most technologies come at a higher cost than the current optical systems. This mean that the increased benefit of introducing new sensor technology should outweigh the added costs before it will be implemented.
- **Low scale / robustness / maturity level.** Some of the sensor technologies are still in the development phase when it comes to use in sorting, reprocessing, or recycling process. Since a waste sorting facility is a high-throughput and contaminated environment, there is a risk that not all technologies will function in these harsh conditions.
- **Response time.** Again, this depends on the sensors itself, but in most cases the sensors have a slower response time than the sensors that are currently in use in waste sorting and reprocessing facilities.

7.5.1.7 Technology evaluation sensor technologies

Based on the description and analysis above we give a global evaluation of the sensor technologies.

Table 15. Laser induced breakdown spectroscopy (LIBS) – Technology evaluation.

Laser induced breakdown spectroscopy (LIBS)		
Overall	**-**	
Maturity	+/-	Mature in metal recycling but not in plastic recycling
Costs	+/-	
Implementation effort	-	Single object detection in contrast to the multiple object approach in plastic sorting. Requires complex engineering.
Potential	-	Only limited added value for streams containing metals.

Table 16. Mid infrared (MIR) spectroscopy – Technology evaluation.

Mid infrared (MIR) spectroscopy		
Overall	**+/-**	
Maturity	++	Is available for plastic sorting.
Costs	-	2 – 3 times more expensive than NIR.
Implementation effort	++	Similar footprint as conventional optical sorter.
Potential	+/-	Black plastics can also be solved in the design. Furthermore black plastics can typically not be used for high quality recyclate unless you are able to remove the carbon black.

Table 17. Raman spectroscopy – Technology evaluation.

Raman spectroscopy		
Overall	**-**	
Maturity	-	Although Raman spectroscopy is established, it is not for fast moving objects.
Costs	+/-	
Implementation effort	-	From a single spot detection to high throughput streams requires quite some effort still.
Potential	+/-	Might be suitable in some quality control environments.

Table 18. Terahertz (THz) spectroscopy – Technology evaluation.

Terahertz (THz) spectroscopy		
Overall	**+/-**	
Maturity	+	Examples of real time detection are available.
Costs	-	Higher costs than NIR.
Implementation effort	+	The principle is comparable to NIR and hence should not be too difficult.
Potential	+/-	Could be useful in final steps of sorting or in safety measures at the start of a sorting line.

Table 19. Energy dispersive X-ray fluorescence (XRF) – Technology evaluation.

Energy dispersive X-ray fluorescence (XRF)		
Overall	**-**	
Maturity	-	Used as handheld gun, but not really in inline applications.
Costs	-	Both detection and X-ray source are expensive.
Implementation effort	-	Needs development to make it suitable in waste treatment at high throughput.
Potential	-	Only suitable for heavier elements; niche applications.

Table 20. X-ray transmission imaging (XRT) – Technology evaluation.

X-ray transmission imaging (XRT)		
Overall	**+/-**	
Maturity	++	Used in different recycling processes (not so much in plastics).
Costs	-	X-ray sources are not cheap.
Implementation effort	-	Safety measures are needed including shielding of the source. Also source and detection are on different sides. Not just plug-and-play.
Potential	+	Detection of metal objects covered by plastics (*e.g.* at start of line).

7.5.2 AI detection and classification

7.5.2.1 Context

As discussed in the previous section, in the current plastic sorting and reprocessing processes, optical sensors (typically NIR and/or RGB) are used to identify objects by comparing the recorded spectrum to known spectra in a database, so that they can be classified and sorted based on their material properties and/or colour. In some cases one would like to be able to classify on other packaging attributes than material and colour alone. Examples of that is material shape and previous use of the packaging. This could enable application-based sorting such as sorting food packaging to be recycled to pellets for food packaging again.

As the demand for high-quality, sorted plastic streams increases, continuous improvement and extension of systems for identifying and classifying the plastic in the waste stream is necessary. Not only to ensure high-purity output, but also to be able to continuously monitor streams throughout the facilities. Using artificial intelligence (AI) systems, more sophisticated decision models are available for identifying and classifying the objects. These systems also allow the coupling of different sensors to enhance decision-making.

7.5.2.2 Technical description

AI systems work by processing copious amounts of labelled training data, which are analysed to establish correlations and patterns used to predict future states. Although AI is a broad term that encompasses many techniques and disciplines, within the plastic sorting domain it typically means that machine learning algorithms are used to feed a neural network using the data from one or multiple sensors. A variety of these AI systems is already commercially available from the large equipment providers. For example, the use of AI models for enhanced sorting in current optical sorting systems is already standard practice for the large equipment manufacturers; the quality of these models is not always clear though. Other AI systems, that are now gradually introduced in plastic sorting facilities, combine a vision system with AI to characterize objects based on image recognition, of which an example is shown in Figure 64. This allows for characterization on other properties than material and/or colour, such as food-grade packaging.

Figure 64. Vision and AI system that identifies food and non-food grade packaging

The performance level of an AI system is typically expressed in terms of accuracy, which is the sum of true positives and true negatives divided by the sum of true positives, true negatives, false positives, and false negatives. This means that the accuracy is based only on the objects that are recognized by the system and if objects are not recognized, they are dismissed and not represented in the accuracy value. Therefore, to be able to evaluate such a system for practical use, it is not only necessary to know the size of the dataset, but also to have an indication of how well the dataset reflects the actual input data (in this case packaging waste). Additionally, it is important to know performance speed of the system, as this will give an indication of the maximum belt speed. The performance speed will be dependent on the hardware requirements, which in turn influence the cost of the system. Since there is currently no industry standard or benchmark it is difficult to compare the different systems with each other.

7.5.2.3 Applications

- **Optical sorting**. An AI system can be used in combination with the conventional air jets for more sophisticated sorting using one or multiple sensors. These systems are already available from the large equipment manufacturers.
- **Quality control.** In conventional sorting facilities, the last step in the process is the quality control, where manual labour is used to check the final stream and remove unwanted contaminants and objects, typically at a speed

of 30 to 40 picks per minute. Image recognition and AI coupled to a mechanical sorting solution (*e.g.* a robot arm) could substitute this task at (claimed) higher speeds (60 to 80 picks per minute) and more consistent quality. Several companies offer a commercial product, although implementation in sorting facilities is still in the initial phase.
- **Stream analysis.** Using a vision system in the sorting line allows for online and automatic stream analysis that can give a real-time analysis of the composition of the waste stream. Several companies offer a commercial product, but the implementation is still in the initial phase.
- **Process control and optimization.** One step further is the combining of the AI system with different sensors to generate autonomous decisions that actively control and optimize the process. An example is to use the stream analysis to modify the belt speed. In modern facilities, this principle is sometimes applied for a limited number of unit operations.

7.5.2.4 Competitive Technologies

- **Optical sorting – conventional NIR / RGB.** The main advantage of the current NIR / RGB systems is their performance speed. These systems can identify objects based on material property or colour in hundreds of milliseconds, thereby reaching picking speeds up to 1000 – 2000 picks per minute.
- **Quality control – manual labour.** For quality control, the alternative is to use workers to sort out the unwanted objects. The best option mainly depends on the availability and costs of the manual labour (mostly region-defined).

7.5.2.5 Strengths

- **Extended and flexible identification and classification.** AI systems depend on specific input data and as such are not limited by the sensors used, as long it is trained with the corresponding data. This makes it a flexible system which can do sophisticated sorting and allows for sorting on other properties than material, shape, or colour, such as the intended-use specification of the object (e.g., food-grade packaging).
- **Performance speed.** The main advantage of the current optical systems is that they have high performance speeds, allowing for fast sorting in combination with air ejectors. The processing of additional data in AI systems could lead to slower performance speed, possibly leading to slower sorting. However, compared to the decision speed of manual labour in the quality control, AI systems could significantly improve the performance speed.

7.5.2.6 Weaknesses

- **High costs.** The processing of large amounts of data demand high hardware requirement and combined with the possible use of a vision system, leads to a high-cost system.
- **Training and ownership of dataset.** For good performance, AI systems need to recognize all objects of interest (in this case packaging waste). This means that the system needs to be trained with all relevant packaging and if new packaging is introduced, it should be added to the dataset. Another important consideration is the question of data ownership.

•

7.5.2.7 Technology evaluation

Table 21. AI detection and classification – Technology evaluation.

AI detection and classification		
Overall	**+**	**The use of AI for detection and classification – either using existing sensors or image recognition – can significantly improve and extend the existing technologies.**
Maturity	+/−	Several large and small suppliers exist that offer systems with AI functionality, specifically targeted at waste streams. Commercial systems are already employed in existing facilities at varying degrees of success.
Costs	+	The prices for standalone AI systems are relatively modest. Higher costs are involved when the AI systems are sold in combination with mechanical systems, such as robotic arms.
Implementation effort	+/−	Low implementation effort of the machine since a unit can easily be added to existing facilities. For image recognition, the main challenge is having a comprehensive and up-to-date database that can recognize all relevant packaging.
Potential	++	Combining sensors with AI based decision models gives a great opportunity for enhanced sorting. Through image recognition, it also allows sorting on other attributes than material or colour. Additionally, the system provides possibilities for automatic stream analysis and improved quality control (in combination with a robotic arm).

7.5.3 Robotic sorting

7.5.3.1 Context

At the end of the mechanical sorting process, optical sorters are used in combination with air ejectors to sort the streams based on material type and/or colour. Although this system works fast, each optical sorting step is a binary process. Based on the settings in the sorter, the material is considered negative or positive, which decides if it gets ejected or not. This means that for each distinction, an optical sorter and air ejector system is necessary. Therefore, in practice, facilities are equipped with a succession of many optical sorters for sorting the different plastic product streams. The optical sorting step is followed by the quality control step, where, typically, operators are standing next to the belt to do the final sorting. Their job is to remove unwanted contaminants or to recover valuable items, after which the stream is conveyed to a bunker from which it is baled. Depending on the region, it might be costly or difficult to employ high-quality manual labour for this final separation step. For this, a robotic sorter might offer the same flexibility and adaptive qualities as operators. And compared to an optical sorter, a robotic sorter has the potential to sort out a larger variety of products, albeit at a much lower throughput.

7.5.3.2 Technical description

Robotic sorters use a mechanical system coupled to sensors for the removal of the object of interest. Typically, robotic sorters are coupled to a vision system with AI for real-time object detection and classification of objects, but these systems are also combined with other sensors, such as NIR or height sensors. The most common type is the pick and place robot, which has one or more robotic arms that are equipped with a gripper. Variations for the gripper include a vacuum gripper that uses suction to grab an object, a magnetic gripper, or a mechanical gripper that clamps the object.

Robotic sorters are commercially available from large equipment manufacturers as well as dedicated smaller companies that purchase the robots from external parties. These sorters are implemented in new waste sorting facilities and also introduced and evaluated for existing waste sorting facilities. Manufacturers claim a speed of 60 to 80 picks per minute for each robotic arm and accuracies between 90 and 99 %.

7.5.3.3 Application

- **Quality control.** Although robotic sorters are not fast enough to compete with optical sorters combined with air jets, the speed is comparable or higher (60 – 80 picks/minute) than manual labour (30 – 40 picks/minute). Therefore, robotic sorters could serve as an addition or replacement for manual labour in the quality control.
- **Rescue line.** Similar to the quality control, the robotic arm can be employed in the rescue line for the recovery of valuable materials.

7.5.3.4 Competitive Technologies

- **Manual Sorting.** Currently, the robotic sorters only compete with manual sorting due to the sorting speed. Depending on the local conditions for labour, this could be beneficial when operators are costly, not available, or provide insufficient quality output.

7.5.3.5 Strengths

- **High and consistent quality.** Manufacturers claim high accuracies which should give the robotic sorter a high-quality output. Considering that the sorter performs at a comparable level throughout its lifetime, its output quality is consistent. In practice, the accuracy that is claimed by the manufacturers, is not always reached due to mechanical issues (*e.g.* gripper loses item) or difficulties with the recognition of packaging items.
- **Availability and flexibility.** Since the availability of the machine depends on the manufacturer and not on the local labour pool, it might be easier to replace or add capacity. Robotic sorters can be programmed and trained to identify a variety of objects, giving them flexibility. However, this also means that the sorter needs to be retrained for each new object that needs to be identified (if combined with a vision system).
- **Safety.** Since a robotic sorter replaces manual labour on the line, it means that the employer contact with the line is reduced. This minimizes contact with moving objects and contaminated waste, thereby increasing safety.
- **Sorting of more type of objects in one step.** In the current optical sorters with air ejectors, items are separated on a binary basis. Even though a robotic sorter operates at a much lower speed than these systems, it is able to sort out a much wider range of objects in one sorting step.

7.5.3.6 Weaknesses

- **Sorting speed.** Depending on the application, the sorting speed can be a negative aspect. Currently robotic sorters are not able to compete with the speed that air jets offer, but they are in par with manual sorting.
- **Operational costs.** The operational costs of the robot depend on the electricity and maintenance cost, while the operational costs for manual sorting are directly related to the wages. Therefore, it depends on the geographical region, whether the robotic sorter has lower or higher operational costs.
- **Operational issues.** One point of concern is the wear of the gripper; it needs frequent replacement, and a non-functioning gripper will lead to no sorting. Also, the gripping of objects is less accurate than by humans. This is related to the used vision system as well to determine where a gripper needs to pick an object.
- **High investment costs.** In comparison to manual labour, the investment costs are significantly higher since a new machine must be acquired. However, training overhead is lower if the robotic sorter is replaced, as the new sorter does not have to be retrained.
- **Robustness / exchangeability.** Commercial systems of robotic sorters, specifically designed for waste sorting, are already available on the market. However, not all systems are currently robust enough to function in a waste sorting facility, requiring regular maintenance or product up-dates to function properly. Related to this is the exchangeability of a robotic sorter If a robotic sorter breaks down, it might be much more difficult or costly to replace than an operator, who are typically available from a pool of manual labour.
- **Quick adaptation.** Although robotic sorters are potentially quite flexible, there are specific situations in which quick adaptation is necessary. An example of this is the removal of a new type of packaging item. When an operator is shown this specific item, it knows what to remove from the stream. A robotic sorter needs to be retrained, which could take significantly more time.

7.5.3.7 Technology Evaluation

Table 22: Robotic sorting – Technology evaluation.

Robotic sorting		
Overall	**+**	**Robotic sorting for quality control has the potential to deliver a more consistent and higher quality output stream. The potential is highest, when availability of manual labour is low, and its costs are high.**
Maturity	+/−	A pick-and-place robot is used in many applications and is, therefore, well-established technology. Several companies deliver commercial robots in combination with AI systems for specific use in waste sorting. Several new and existing facilities employ robotic arms. The gripper durability and the picking accuracy in waste is not yet optimal.
Costs	+/−	Although investment costs are considerably higher than the initial training costs of manual labour, operational costs could be significantly lower depending on the cost of manual labour.
Implementation effort	+	In existing facilities, the robot can be placed at the location where the operator for quality control is normally located. In new facilities, the system can be specifically designed to incorporate one or more robotic arms. Either way, the implementation effort is relatively low.
Potential	+	Robotic arms have the possibility to improve the quality and consistency of the output stream but cannot replace the – much faster – existing air ejection systems. Their main potential lies in quality control or the rescue line, especially considering that a single robotic arm can operate faster than an operator.

7.5.4 Tracer technology

7.5.4.1 Context

The current approaches in sorting only focus on specific properties or parts of an item for separation into a specific product, like windshifters using shape and weight to separate film or optical detection devices, screening an item surface to decide on material type and colour. Because the specific properties do not only apply to the target items but also to contaminants like paper with windshifting or packaging with recycling-harming residual content (*e.g.* cartridges) in optical detection, a number of sorting steps in a row as well as manual sorting is currently necessary to reach a certain level of purity for a sorting product.

Using tracers, all relevant packaging properties can be given at once including information not available at all with current sorting technologies but critical for high-quality recycling like food/non-food application, composition of a multilayer packaging, hazardous content or melt flow range (MFR). For certain tracer technologies, a database is needed to process the tracer code.

7.5.4.2 Technical Description

Tracer-based sorting is an optical identification of a tracer carried by a packaging item giving the relevant information, not about a part or surface but about the whole item for sorting into the correct recycling path.

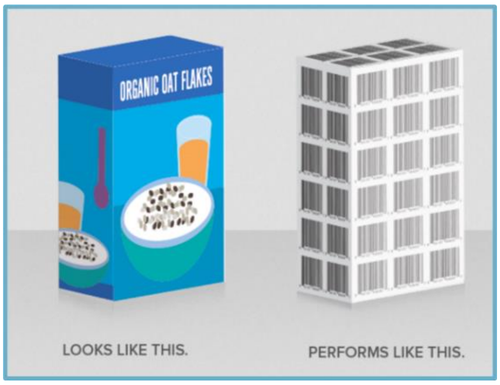


Figure 65. Left: Example of packaging with fluorescent marker as tracer. Right: Example of a readable code (digital watermark) on the packaging surface as tracer.

Tracers can be implemented or applied to the packaging in the following variants:

Type	Description
Fluorescent markers	A fluorescent tracer substance is applied to plastic packaging and or plastic labels marking the item with a specific colour recognizable by optical detection. The colour carries relevant packaging properties enabling the allocation of the item to a specific recycling path.
Curve codes	A specific sequence of dots is embossed, matted, or printed on a packaging and or label surface recognizable by optical detection. The code carries relevant packaging properties enabling the allocation of the item to a specific recycling path. The optical detection unit needs access to the database to correlate code and information.
Digital watermark	A barcode or QR code is embossed or printed on a packaging and or label surface recognizable by optical detection. The code carries relevant packaging properties enabling the allocation of the item to a specific recycling path. The optical detection unit needs access to the database to correlate code and information.

7.5.4.3 Application

Curve codes and digital watermarks can only work on object level so an application in a sorting facility or at the pre-sorting step upfront a grinder in reprocessing is possible. The recognition technology can either be installed as an add-on to an existing optical sorter or as a new optical sorter similar in design and size to the established optical sorting machinery. So far, the technology has been evaluated successfully on pilot scale with chosen marked plastic packaging.

7.5.4.4 Competitive Technologies

Competitive technologies are optical sorting technologies with artificial intelligence with the prospects as described in the respective chapter of this report.

7.5.4.5 Strengths

- **High yield and quality of the sorting product**. With the clear identification of the decisive recycling properties of a packaging, non-sortable plastics (e.g. black plastics) can be recovered for recycling and only plastics recyclable via the sorted fraction are part of the product.
- **Easy trackability of packaging per producer.** Reliable data collection for mass flow supervision of packaging regarding collection and sorting/input reprocessing.

7.5.4.6 Weaknesses

- **High implementation rate required.** For an economically balanced sorting by tracer technology, nearly all packaging of the target type must be marked to produce a fraction of a certain amount worth handling.
- **High effort for brand owners / producers**. Al involved brand owners/producers must agree to adapt their packaging design and change the relevant production steps to implement the marker. Furthermore, the recycling relevant data per packaging must be included in a database and regularly updated.

- **Only on object level for curve codes and digital watermarks.** Reprocessing is still necessary to remove labels, caps, etc.
- **Fluorescent markers**. Spillage into regranulate unclear.

7.5.4.7 Technology evaluation

Table 23. Tracer technology – Technology evaluation.

Tracer technology		
Overall	**+/-**	Potential to sort high-quality recyclable sorting fractions shaped to the demands of the market (food/non-food/MRF level etc) but the commitment required from each producer is critical.
Maturity	+/-	The recognition is tested successfully but the database development is still under development.
Costs	+/-	The costs for changing the packaging production are not clear. The technology implementation costs will be comparable with the invest for optical sorters.
Implementation effort	+/-	The nation-wide implementation into sorting facilities will be high effort due to the number of facilities. The implementation into the pre-sorting of reprocessing facilities will be lower effort due to the limited number of reprocessors.
Potential	+	Technology with high potential regarding quality and yield improvement.

7.5.5 Deinking

7.5.5.1 Context

Another important topic is the production of high-quality flakes to meet the requirements that are posed on the final product. For example, the strict requirements on food-grade packaging make it difficult to use recyclate for the production of new packaging, where ink can be a significant source of contamination. Another important consideration is the value of transparent and white flakes. Since these represent the most valuable plastics for recycling, it is important that these plastics retain their colour. However, even when the plastic itself is white or transparent, the presence of ink can cause the final product to be colorized.

During the washing process, inks can be a significant disturbance, either by ink bleeding – where the released ink discolours the washing water – or as a direct source of contamination. To facilitate a high-quality product, inks must be removed down to an exceptionally low level. Inks that remain in the recycled material can alter the colour and/or the transparency of the material, create defects on the final product and degrade to form odour, gassing, or migratable species [71]. Therefore, an important development is the removal of ink from the plastics in the waste stream by deinking. However, in practice, completely deinking plastic packaging remains difficult.

7.5.5.2 Technical Description

Almost all plastic packaging contains printing ink, either directly printed on the packaging or on the corresponding label. Ink is used for marketing purposes and to convey information about the product, such as composition, nutritional values, or the presence of allergens. The main constituents of printing inks are resins, solvents, dyes, pigments, and additives, where the composition depends on the printing process and the substrate [72]. Currently, deinking in plastic recycling is a hot washing process, using a caustic aqueous solution with detergent, where the ink layers are removed from the plastic material. The ink that is washed off builds small particles. The coarser plastic material can be easily separated with a sieve and the smaller ink residue particles can be filtered off [73]. It is difficult to design a single solution for deinking due to large variety in ink composition, printing method, and ink type such as water-based inks, solvent-based inks, and UV-inks.

Newly developed technology allows the removal of the ink from the shredded film before the material is fed into the recycling extruder. Recently developed technology, which is commercially available, focus on the use of surfactants to effectively remove printing ink from the plastic packaging. Other technology involves the deinking of multilayer packaging by adding a deinking primer. This primer dissolves during the hot wash which makes the different polymer layers easier to separate. This allows for the deinking of the separated polymer layer that contains the ink during the washing process [74]. Technology is also available in the form of brushes that mechanically remove the ink from the surface.

7.5.5.3 Application

- **Hot washing.** The ink is typically removed from the flakes done during the hot-wash step in the plastic recycling process. It can be an addition to an already existing washing setup.

7.5.5.4 Strengths

- **Reduction of contaminants / higher quality product.** Ink introduces contaminants into the final product stream. Subsequently, these contaminants are either (partly) removed during the extrusion product or are still contained in the final product. Thus, removing the ink leads to less contaminants in the product stream leading a higher quality product available for extrusion.
- **Decoloured product.** The presence of ink could lead to coloration of the product stream, resulting in brownish or black colour which can only be used in downcycled products. By successfully deinking the product stream, the ink no longer influences the coloration.

7.5.5.5 Weaknesses

- **Introduction of additional chemicals.** The removal of ink could lead to the introduction of more or other chemical additives in the washing process, which will end in the washing water. The use of environmentally hazardous chemicals should be avoided.

7.5.5.6 Technology Evaluation

Table 24: Deinking – Technology evaluation.

Deinking		
Overall	**+**	**Essential for high quality recyclate**
Maturity	++	Deinking processes are already available but not implemented widely.
Costs	-	Hot-wash steps naturally come with a cost.
Implementation effort	+/-	Depending on the available space it is more or less easy.
Potential	++	Essential for circularity of plastics.

7.5.6 Delamination

7.5.6.1 Context

Multilayer plastic packaging consists of different polymer (and sometimes aluminium) layers, sometimes using tie-layers, to obtain superior physicochemical properties, such as sealing properties or UV protection. Although the combination of different polymer layers broadens the functionality and application area of plastic packaging, the recyclability decreases [75]. Multilayer packaging materials are difficult to recycle using mechanical recycling technologies due to the chemical incompatibility of the different layers. For effective recycling, multilayer plastic would need to be partially or fully deconstructed into their constituent material layers [76]. It should be noted that in order to make delamination useful, the sorting process needs to be adjusted that the multilayer material is separated.

7.5.6.2 *Technical Description*

Several methods for delamination of plastic packaging are listed in Table 25.

Table 25. Methods for delamination of multi-layer plastic packaging.

Type	Description
Selective decomposition of polymer layers	A useable material stream from multilayer packaging can be obtained by decomposition (or degradation) of one or multiple layers of the packaging that are not the target material. Although the results of chemical decomposition are promising in terms of recovery, degradation products remain as impurities in the solution affect the recovery of the medium adversely [75].
Selective dissolution of polymer layers	In this process, the solvent and process conditions are chosen selectively so that only the target polymer is dissolved, and all the other undissolved components can be removed from the solution by means of separation, resulting in high-quality recyclate. However, the selection of a suitable solvent, the need for the addition of substantial amounts of anti-solvent, as well as the drying of the recovered polymers are drawbacks of this process [77].
Selective dissolution of tie-layers	Instead of dissolving the polymer layers itself, another option to selectively dissolve the tie layers used to laminate dissimilar polymer layers by either using solvents or acids. These tie-layers could be specifically developed to allow for easy separation during the hot wash [75].
Acidic separation of aluminium and PE	In beverage carton recycling the PE can be delaminated from aluminium by acidic means. Most of the plants that used this process in Europe stopped using it.

Other commercial activities include separation of multi-layer PET, the use of delamination primers, and the separation of plastic from metal layers.

7.5.6.3 *Application*

- **Washing.** Delamination occurs during the washing process during reprocessing.

7.5.6.4 *Competitive Technologies*

- **Multilayer to monolayer.** Instead of separating the different layers of multilayer packaging, another possibility is to design the packaging in such a way that only one material is used in either one or multiple layers. In practice, it might prove difficult to replace multilayer packaging with one single material due to the packaging requirements. This can still be multi-layered material, but all layers of the same polymer (in different grades).
- **Compatibilizers.** In the current mechanical recycling process, compatibilizers are used to increase the miscibility of the polymer blends. This only works for small amounts of non-target product.
- **Chemical recycling.** For certain material combinations, pyrolysis (mixed polyolefins) or chemical recycling (condensation polymers) can be used. This is not frequently done yet.

7.5.6.5 *Strengths*

- **Recycling of multilayer packaging.** Currently, most multilayer material is incinerated since the occurrence of multiple materials in the product stream cannot be effectively recycled. Separating this packaging into their constituent plastics would allow for the recycling of the separate material streams.

7.5.6.6 *Weaknesses*

- **High energy use.** The separation and recovering of the separate plastics are energy-intensive processes.
- **Maturity.** Although there is commercial activity for this technology and many large companies are involved, this technology is currently mostly still in development.

7.5.6.7 Technology Evaluation

Table 26: Delamination – Technology evaluation.

Delamination		
Overall	**+/-**	
Maturity	-	Most techniques are in an early stage of development.
Costs	+/-	The cost will depend on the required chemicals and temperatures.
Implementation effort	+/-	The required processes are similar to the ones used in washing and hence do not require large development and engineering efforts.
Potential	+	Multi-material materials are expected to remain on the market for quite some time; techniques to delaminate the materials are valuable.

7.5.7 Deodorization

7.5.7.1 Context

One of the key issues towards high-end recycling of plastics is the presence of odorous constituents, which is especially problematic in polyolefins due to their open molecular structure. Because of the persistent odour that remains after washing, much of the recycled plastic packaging is currently only suitable for lower grade applications [72]. Since there is large variety in volatile organic components (VOCs), it is difficult to address this issue effectively. Although some odorous constituents are removed with hot washing or the detergents, completely removing the odour remains challenging due to large variety of VOCs and the fact that many are of apolar nature and hence will not migrate to an aqueous phase during washing.

7.5.7.2 Technical Description

Several developments to address this are listed in Table 27.

Table 27. Different methods for the removal of odour in plastic packaging [72].

Type	Description
Adsorbents / additives	One option to remove VOCs from plastic waste is the addition of specific surface adsorbents during the extrusion process. A similar more recent development is the addition of additives that react with the functional groups of odour-causing substances converting them into non-volatile components.
Degassing	Removal of the gases during the extrusion process can contribute to the removal of odour. Several technologies are available to make this process more effective, including vacuum, thermal, and ultrasound degassing.
Probiotic bacteria	The use of a probiotic bacteria solution can also help to minimize odour on post-consumer plastic packaging waste. These bacteria react with the volatile contaminants to reduce the intensity of the odour.
Refreshing	Extruded pellets can be refreshed by directly applying steam or air to strip the material of the contaminants. Applying hot air or steam for some hours can significantly reduce the VOCs and corresponding odour intensity.
Solvents	If odours are not sufficiently removed during the washing with water, an alternative is the use of solvents to remove the constituents that are not taken out by water. Combining functions such as delamination or deinking with odour removal might prove interesting.

7.5.7.3 Application

- **Reprocessing.** A logical place in the process for the introduction of additional adsorbents, additives, or solvents for deodorization is during the reprocessing process. These components can be introduced during one of the washing steps and specifically target the odorous components.
- **During extrusion.** The gases that are formed during the extrusion can be removed to reduce the odour intensity of the final product.
- **After extrusion.** Refreshing of the final product occurs after extrusion.

7.5.7.4 Strengths.

- **Higher quality recyclate.** Intensive odour on the final product, prevents the use of recyclate in many consumer products. Therefore, by effectively removing odour, the quality of the final product improves and there might be no need to use the recyclate in downcycled applications.

7.5.7.5 Weaknesses.

- **Increased costs.** Adding equipment that specifically targets the odorous components adds to investment costs as well the operational costs.

7.5.7.6 Technology Evaluation

Table 28: Deodorization – Technology evaluation

Deodorization		
Overall	**+**	
Maturity	+	Some technologies are already applied and ready for use, especially during the extrusion step.
Costs	+/-	Some extra cost but higher value of end product.
Implementation effort	-	It does require modification of existing equipment or use of chemicals that are not common in the facility.
Potential	++	Increase the value of the recyclate.

7.5.8 Magnetic density separation

7.5.8.1 Context

The recovery of plastic packaging waste requires the sorting of at 3 different steps over the waste pathway,

1. Sorting at the consumer into the correct collection system
2. Sorting at the sorting facility by material type (object level)
3. Sorting at the reprocessing material type (flake level)

This causes a high economic effort involving personnel, energy, machinery, and space leading to relevant emissions. Furthermore, the multistep approach bears high potential for material losses and technical failure, *e.g.* with limited sorting efficiency in sorting facilities.

With the magnetic density separation, the functions of sorting at the sorting facility and sorting at the reprocessing facility shall be combined in one step to simplify the treatment pathway for plastic packaging waste and reduce the losses of recyclables caused by the multistep sorting.

7.5.8.2 Technical description

The magnetic density separation follows the basic concept of a float-sink-separation, which is standard in most plastic reprocessing facilities. In the standard application the shredded plastics are fed to a tank of water and either swim or sink according to their density, a separation into two fractions is enabled. With this method, high-density plastics like PET or PVC > 1 g/cm³ are separated as sink material from low density plastics < 1 g/m³ like HDPE and PP as floating material. The float-sink separation is however not able to separate in between material types due to only one density split level.

With magnetic density separation, this process shall be improved creating a density gradient in the liquid and hence the ability to separate more than two streams. The principle is shown in Figure 66.

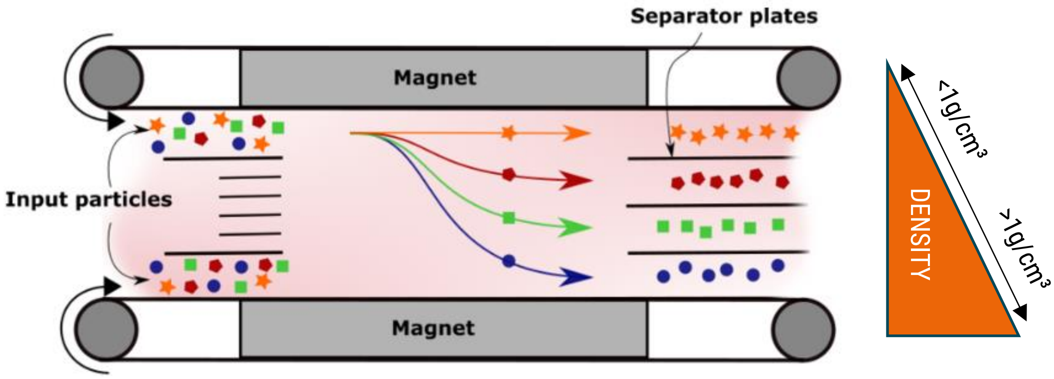


Figure 66. Schematic principle of magnetic density separation (source: [TUe](TUe)).

Having a magnet on opposite sides of the magnetic-fluid-filled separation tank, a magnetic field is induced changing the hydrostatic pressure and creating a gradient of apparent mass density in the fluid. The plastics passing through the fluid stay in their corresponding density level and can be discharged from the tank separately.

7.5.8.3 Application

On industrial scale, one facility operated by the Dutch Company Urban Mining Corp (Umincorp) is known so far.

7.5.8.4 Competitive technologies

Competitive technologies are all sorting technologies able to sort by material type.

Optical sorters and robots use near-infrared technology to detect the plastic type by screening of the product surface. The detected plastics are then separated by air blow (object or flake level) or robot arm (only object level). The efficiency of this technology is currently further developed using artificial intelligence and object recognition. Disadvantage of this technology is the necessity to use one machine per material type instead of sorting several plastic types at once.

The tracer technology currently developed can even go further than magnetic density separation and optical sorting by identifying the recycling capabilities of a packaging in total not just delivering the information of material type.

As a drawback of these competitive technologies it has to mentioned that they are currently implemented to sort on object level. Composites or combinations of material (bottle/cap) cannot be separated.

Looking especially at the position in the chain where the MDS is implemented, another competitive technology is sorting by material-type on flake level by means of optical-sorters (colour and material type). These flake-sorters however do not work very efficiently in terms of yield.

7.5.8.5 Technology evaluation

Table 29. Magnetic density separation – Technology evaluation.

Magnetic density separation		
Overall	**+**	Magnetic density separation is able to separate multiple types of plastics by density in one operation step reducing the effort of current multi-step waste sorting.
	–	The purity of the output fractions is limited to the purity and material density properties of the input material. Due to modifications of the plastic properties during production, overlapping of density ranges in between different plastic types is a risk.
Maturity	+	The technical readiness level (TRL) is for post- consumer material at 8 to 9*, the present installation is on industrial scale operating and as well testing with different plastic fractions.
Costs	+	The costs are estimated to be on a low-middle range for they are connected to a stand-alone machine with slightly higher process effort than a swim-sink separation. However, the effort of cleaning and recovery of the magnetic fluid is unclear to the author.
Implementation effort	-	Magnetic density separation is a standalone process for pre-sorted plastic waste. The applied standards comply with those of the current recycling industry. If implemented at reprocessing sites, the mechanical implementation effort is relatively low due to existing wastewater treatment. Nevertheless, when creating multiple plastic fractions, an increased handling effort is to be regarded which is no standard in reprocessing facilities normally focused on only one or two plastic types. Potential effort of re-looping density fluid needs to be assessed
Potential	+/-	Reducing the effort for sorting of plastics is beneficial from an economic and ecological point of view. The quality level reachable with this technology needs to be evaluated.

7.5.9 Flake sorting and analysis

7.5.9.1 Context

To ensure high-quality products, it is necessary to achieve a good separation of the flakes in terms of material and colour. Related to this is the ability to assess the quality using flake analysis. Currently available technologies can already deliver a high-quality flake stream, but improvements are still possible.

7.5.9.2 Technical description

In addition to the existing technologies to sort flakes based on density, material, colour, size, and shape as described in section 7.4.2, either replacing technologies or additional technologies are considered. For the determination of the quality of flakes, typically, a small batch of material is taken from the stream and tested using manual, visual, and thermal sample analyses. Several companies now offer the possibility to do this automatically. Technologies for the sorting and analysis of flakes are listed in Table 30.

Table 30. Variations of flake sorting and analysis technologies.

Type	Description
Tribo-electrostatic separation	Electrostatic separation is the principle of charging small-size particles of plastic through surface friction. Since different plastics have different electrical permeabilities, either negative or positive charges accumulate on the surface. Using a strong electrostatic field, the differently charged particles can then be separated [78]. For this method, the particles must be dry, and this method works best for a binary and homogeneous mixture. Commercial separators are sold, but this method is not widely used in industry.
Hydrocyclone	A hydrocyclone works according to the same principle as a (air) cyclone, but the flakes are suspended in an aqueous solution instead of air. The goal is to obtain a cost-efficient, high-throughput device to separate the material based on density differences. Although not widely implemented in waste sorting facilities, this technology is commercially available.
Flake analyser	Technologies have been developed that use multiple sensors (including colour, NIR, and 3DI) for an AI supported estimation of the flake stream composition. Since this process takes only a few minutes to complete and is automatic, it has the potential to improve the monitoring of flake quality at the end of the reprocessing of plastics.

7.5.9.3 Application

- **Reprocessing.** Flake sorting and/or analysis is used as intermediate or ultimate step in the reprocessing.

7.5.9.4 Competitive technologies

- **Float-sink tank / air cyclone.** The traditional technologies for density-based separation perform well if there are big differences in density. However, separating plastics with similar densities remains challenging and cannot be performed with density-based separation technologies.
- **Optical flake sorter.** The current optical flake sorters that work with NIR or RGB perform quite well for the separation on material type and/or colour, although it remains challenging to get very high efficiencies due to small size of the particles. Often this should be considered as a complementary technique.
- **Magnetic density separation (MDS).** For MDS, instead of a sorted object stream, A waste stream of shredded particles containing a mixture of plastics. This technology will be treated in more detail in section 7.5.8.

7.5.9.5 Technology evaluation

Table 31: Flake sorting– Technology evaluation

Flake sorting by hydrocyclone or tribo-electric		
Overall	**+/-**	
Maturity	++	Methods are available on the market.
Costs	+/-	Similar cost to other sorting equipment.
Implementation effort	+	
Potential	-	The added value of these techniques is limited and would still require the other sorting steps to be in place.

Table 32: Flake analysis– Technology evaluation

Flake analysis		
Overall	**+**	
Maturity	+/-	Two suppliers have at line equipment available but not widely spread yet.
Costs	-	The use of NIR hyperspectral camera and AI makes the equipment rather costly.
Implementation effort	++	Standalone machine with a small footprint.
Potential	++	The added value of these techniques is high as it will give direct information relevant to the flake quality.

7.5.10 Solvent-based recycling

7.5.10.1 Context

Solvent-based processes find their position between mechanical and chemical recycling. By means of solvent-based processes especially material composites and multilayer packaging can be decomposed, keeping the molecular structure of the components unchanged. Due to the usage of liquid organic solvents and dissolvents and the high effort of cleaning and recuperation of the solvents, the number of impurities being acceptable is limited. Therefore, a pre-treatment by sorting and (wet)-cleaning as conditioning stages is mandatory.

As a result of the solvent-based process the target component or all main components can be processed in subsequent mechanical recycling to high quality PCR with comparable properties as virgin material.

7.5.10.2 Technical description

The infeed of the solvent bases process has to be tailored to the optimal process requirements and, as a minimum, needs a pre-treatment by sorting according to material type, dry and wet cleaning, grainsize reduction and drying. Which is similar or comes close to the quality requirements related to material properties of mechanical recycling entering the final extrusion stage.

The first stage is the selective solving step in which the target component is dissolved and carried over with the liquid phase to the cleaning/filtration stage.

In the cleaning stage impurities and other undissolved components of the feedstock are mechanically removed *e.g.* by filtration or sedimentation units. Further on dissolved non-target components can be removed by specific cleaning stages from the liquid phase if needed.

Subsequent to this, the dissolvement of the target component is done by means of precipitation. The target polymer is dried and extruded to the final PCR with material properties being comparable to the virgin polymer.

Purification of the solvent coming from the different process stages is done by distillation or comparable processes to enable a frequent usage in the sense of re-looping the solvent or the solvent components of the solvent-mixture used in the process.

Process parameters of the solvent processes vary but have all in common the usage of organic solvents like toluene or acetone as single solvent or -in most cases- as mixtures. This requires process and equipment standards used in chemical industry, being much higher than in recycling industry.

For this reason, these processes target on materials that are difficult to recycle like composites made of different plastic layers or multilayer structures of which one layer or the tie-layer is plastics.

7.5.10.3 Application

Several applications are built and are currently operated on pilot scale for the recovery of composite or multilayer plastic materials not only deriving from the packaging sector or household waste collection schemes. Examples are the recovery of the inner layers of beverage cartons coming as a reject from specialized papermills or separate collected or sorted pouches from waste.

Plants and Projects to be mentioned are:

- IVV Frauenhofer
    - Creasolve, pilot plant Unilever Indonesia, recycling of multilayer pouches
    - Creacycle
    - Polystyrene loop, pilot plant Terneuzen NL, recycling of EPS from demolition debris
- APK, Newcycling, pilot plant Merseburg; operational, large scale post-consumer material test outstanding
- Purecycle, (P&G), Orlando US; industrial scale planned for end 2022

7.5.10.4 Competitive Technologies

As alternative technologies chemical and mechanical recycling are to be mentioned.

Pending on the material structure of the pre- sorted and reprocessed multilayer or composite structures – by dry or wet cleaning – the material, mainly made of polyolefins, can be recycled in a mixture with other polyolefins into intrusion products with lower quality requirements of the PCR and thus replace virgin material.

Chemical recycling processes such as pyrolysis or gasification, that brake down the polymeric structure of the plastic material widely, are more robust against variations in material properties, being typical for composites and multilayer structures. However, energy efficiency and yield are lower compared to mechanical recycling or solvent based treatment.

7.5.10.5 Strengths

- **High quality** recycling especially for composites (multilayer)
- **Food grade** applications seem to be feasible
- **Selective dissolution** of specific polymers
- **Molecular structure preservation** of target component

7.5.10.6 Weaknesses

- **High effort** in pre-treatment requested for post-consumer material
- **Challenging process** of cleaning and re-looping of solvents
- **Sensitive** against impurities
- **TRL 5-6** for post-consumer material*

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7.5.10.7 Technology Evaluation

Table 33: Solvent based process – Technology evaluation

Solvent based process		
Overall	**+**	Solvent based processes are able to decompose multilayer material and composites and recover the target component or all components for high quality recycling
Maturity	-	The technology readiness level (TRL) is for post- consumer material at 5 to 6[1]*, present installations are on pilot scale. Larger tests with multilayer material deriving from waste schemes are currently executed or planned for the near future.
Costs	+/-	Due to the maturity level the cost situation cannot be realistically determined. As the process effort -especially for the solvent circle- is high, the costs can be estimated to be at higher range.
Implementation effort	-	Solvent based processes are standalone processes for specific well defined input materials. Process conditions are sensitive, and robustness is low. The applied standards comply with chemical industry rather than recycling industry. As a result, the implementation effort is relatively high.
Potential	+	Related to waste derived materials in the sense of composites and multilayer materials, solvent based processes can be an effective solution to recover the target components on high quality level with good yield. Even food grade applications seem to be feasible. Reliability and robustness need to be improved.

7.5.11 Chemical recycling

7.5.11.1 Context

In mechanical recycling of plastics the molecular structure of the polymers is hardly changes. In chemical recycling on the other hand, the polymers are broken down either thermally (thermochemical) or by controlled depolymerisation (chemically). The objective of (thermos)chemical recycling of plastics is to retain a semi-product that can be used in chemical industry to eventually create new products. This is not restricted to polymers but can be all kind of chemicals and will strongly depend on available feedstock, processes and demands. One persistent myth is that chemical recycling can be easily used on streams that are not suitable for mechanical recycling. In chemical recycling efficient, it is still necessary to sort and clean the input product (like in mechanical recycling), but the focus is on different kind of contaminants than in mechanical recycling. Below we will give some of the background on this.

We expect that there will be a role for chemical recycling of plastics in the future. The main issue with mechanical recycling is that a virgin-like product cannot be achieved, since the input material contains contaminants that cannot be removed, the polymers have degraded, mixed polymers are used, and different polymer grades are not separated. By breaking down the polymers to much smaller molecules, typical chemical separation and upgrading techniques can be used.

7.5.11.2 Technical description

Chemical recycling is characterized by the destruction of the chemical structure of the polymer. This means the polymer is broken down into its monomers (depolymerization) or to more short-chain hydrocarbons or gases (pyrolysis or gasification). Although solvent-based recycling (or dissolution) is sometimes categorized as chemical recycling, it is technically not chemical recycling since the polymer structure is not broken down into smaller parts and is, therefore, discussed in another section of this report (7.5.10).

Depolymerisation

In the depolymerisation process, combinations of chemistry, solvents, and heat are used to break down polymer chains into their constituent monomers or oligomers. The contaminants are removed from the mixture using

[1] TRL 6 for Creacycle

conventional chemical separation techniques and the monomers or oligomers can be used for re-polymerisation, resulting in plastics of similar quality to virgin plastics. In some cases the monomers are used to produce different polymers than the polymer in the feedstock. The target feedstock for this recycling method are mainly polycondensates – which includes polyesters (PET), polyamides (PA), and polyurethanes – as they have a relatively low heat of depolymerization [79].

Globally, several pilot plants and initial commercial activities exist, with the focus of these activities on the depolymerization of PET [80]. In the Netherlands, there are several pilot plants (for example for PET and EPS depolymerization) with plans for upscaling in the coming years [81]. In their Circular Economy scenario for 2050, TNO estimates that 5 % (80 ktonne) of the total plastic waste in the Netherlands will be recycled through depolymerization [82]. The main challenges for this recycling technology are that there are strict requirements on the quality of the input feed, and it is a costly process. But, although it is an energy-intensive process, depolymerisation of polycondensates typically requires less energy than the two alternatives described below.

Pyrolysis
Pyrolysis occurs at moderate to high temperatures (300 – 500 °C) in the absence of oxygen. The elevated temperatures allow the breakdown of the macrostructure of the polymer to form smaller molecules [83]. Plastic pyrolysis is particularly suitable to process polyolefins. It produces oil (which cannot be used directly as feedstock for cracking) and an oil that is more aromatic when the feed is contaminated with other polymers such as PS, PET, and PA [79]. The products include a range of basic hydrocarbons as a mixture of gases, oils, and waxes [84].

Pyrolysis has also been explored for processing plastic waste by major chemical producers for more than 30 years. Although technically successful, these technologies were not commercialized because they could not compete with cheap crude oil, although rising oil prices have renewed the interest [79]. According to their Circular Economy scenario, TNO estimates that more than 7 % (120 ktonne) of the plastic waste in the Netherlands could be recycled using pyrolysis in 2050 [82].

Pyrolysis oil of high quality could serve as feedstock for steam cracking after upgrading where molecular and elemental contaminants are removed. The base chemicals produced in steam cracking can be used for a large variety of chemicals, including polymers.

Gasification
Gasification is a process where waste materials are heated to an extremely high temperature (~1000 – 1500 °C) with a limited amount of oxygen. This breaks down the molecules and produces syngas, which is a stream made up of mainly hydrogen, carbon monoxide, carbon dioxide, methane, and nitrogen [84]. In principle, there are no strict requirements on the quality of the input stream. In practice, however, a highly contaminated input stream means that many purification steps are necessary, adding to the cost, energy demand, and complexity of the system.

In comparison to the two other chemical recycling methods, gasification is the most energy-intensive process. Even though gasification requires much energy and many process steps, the polymers are converted into basic feedstock. This allows the production of different chemicals (e.g., methanol, hydrocarbons, or ammonia) which in turn can be used to make a variety of products such as plastics, fuels, or fertiliser [84]. Combined with the low requirements on the input quality, gasification is a very flexible method for recycling. Since syngas is already commonly used to produce different chemicals, gasification is seen as an interesting option from the perspective of the chemical industry. TNO estimates, in their Circular Economy scenario for 2050 [82], that more than 30 % (540 ktonne) of the plastic waste will be converted using gasification.

7.5.11.3 Applications

- **Recycling.** The chemical recycling process recycles sorted and washed waste streams into feedstock for petrochemical processing. But, although chemical recycling can generally work with any feedstock that is provided for other recycling methods, it is a costly process, both in economic and energetic terms. Chemical recycling should therefore be avoided if a less energetic recycling method (re-use, mechanical recycling, or solvent-based recycling) can be employed.

7.5.11.4 Competitive technologies

- **Re-use.** Using a closed loop, products can be directly re-used without the necessity to recycle. This requires the least amount of energy and material, but there should be a separate system in place to allow for this.
- **Mechanical recycling.** In the mechanical recycling process, the polymers are not broken down into smaller chemical parts, therefore requiring less energy and process steps than the chemical recycling process. However, some plastics demand more strict requirements (e.g., food-grade packaging) than is currently achievable with

mechanical recycling. Furthermore, every time a plastic product is used and recycled, thermal and other stresses lead to degradation of the material, so that it is only possible to recycle a product a limited number of times using mechanical recycling. Chemical recycling can then be used to bring the plastic to virgin-like quality again.
- **Solvent-based recycling.** This recycling process also leaves the polymers intact but requires solvents to separate them. These solvents target specific plastic types which are not available for all materials. Furthermore, solvent-based recycling introduces new substances that require filtering and processing, which could be undesirable.

7.5.11.5 Strengths

- **Virgin-like quality.** By breaking down the polymers to oligomers, monomers or even smaller molecules, the quality of plastic that can be obtained can match the quality of virgin plastics. Another advantage of this is that the plastic can be recycled an indefinite number of times.
- **Flexibility in input and output.** Chemical recycling is flexible with regards to the input, since the requirements for input quality are generally lower than for the other recycling processes, although this does not mean there are no requirements on the input quality. Additionally, the breaking down the polymers give the possibility for the production of chemical compounds other than plastics, thus adding flexibility in the output.

7.5.11.6 Weaknesses

- **Purification of feedstock.** Although chemical recycling could potentially work with contaminated streams, having a highly contaminated stream can lead to a costly and high energy-consuming purification process. Therefore, it is important that input streams for the chemical recycling route are also properly sorted and cleaned, where the amount of purification is dependent on the chemical process.
- **Availability of feedstock material.** The quantity of available feedstock might be insufficient if the chemical recycling process are upscaled. Improving the yield would mean less feedstock for the same amount of output, possibly mitigating this issue.
- **High energy use.** All chemical recycling processes are associated with high energy use, where, typically, the smaller the molecule that is produced, the more energy that is needed.
- **Low yield.** Currently, the yield of these chemical recycling process is low. Improving the yield is critical for improving the cost-effectiveness of the technology.
- **High costs.** At this stage, most chemical recycling technologies are associated with excessive costs. However, as technologies are more intensively employed and new developments introduced, economies of scale and technological improvements could reduce these costs.

7.5.11.7 Technology evaluation

Table 34: Chemical Recycling – Technology Evaluation

Chemical Recycling		
Overall	**+/−**	
Maturity	+/−	Maturity of processes (pyrolysis and gasification) is high. Lack of experience in converting plastic waste into the right feedstock for
Costs	−	High energy and investment costs.
Implementation effort	−	The full recycling chain becomes much longer.
Potential	+	(Thermo)chemical recycling is one of the few routes to convert plastics that cannot be mechanically recycled into a valuable product

7.5.12 Process monitoring and control

7.5.12.1 Context

Within the plastics recycling industry there is a growing interest for improved process monitoring and control, as is already the standard in many other industries (*e.g.* chemical process industry). In traditional sorting or reprocessing facilities, only basic sensors (for example a weigh bridge for the input material) and video cameras are used to monitor the process in real-time. Evaluation is based on internal collection and processing of data, often done manually and not automated. An example of this is the collection of purity of a product stream from a sorting facility, which is typically determined using manual characterization.

The main difficulty of monitoring of a waste stream is that the stream is not a coherent and uniform stream. The waste stream can be dependent on the type of material, the application area, the origin of the waste, the season, and many more factors. It is, therefore, challenging to find a single method for accurate monitoring and control. However, driven by the demands for higher yield and product purity combined with availability of newly developed technology and practices, modern methods and technologies for process monitoring and control are increasingly employed in recycling facilities. This includes the use of process engineers to optimize the process, the introduction of robots for automatic sorting, and the collection and visualization of available data from the facility using cloud-based services. New facilities are equipped with more advanced sensor technology that can automatically monitor and control various parts of the steps in the process.

7.5.12.2 Technical description

Data from sensors can be used to monitor, but also to control processes (*e.g.* belt speed or screen angles) for optimization of the productivity and output quality. For example, optical sensors are not only used as input for the sorting, but also to monitor and provide statistics of the characteristics or composition of the stream. Other examples include the use of smart algorithms to separate different plastic types from one input stream by looping the output stream or the continuous quality monitoring of colour and melt flow rate during extrusion. Another possibility is to using cameras coupled to AI systems to automatically monitor product quality and throughput. Some of the technologies described above can be used in this process.

7.5.12.3 Application

- **Quality control.** Using the combined data from different sensors to provide information of the output quality is not only relevant for internal use but can also be used to provide information to external parties.
- **Process monitoring.** Information from sensors can be used to provide information of different steps in the process. This information can either be used directly – for example, an alarm for the operator that there are too many flexibles in the stream – or aggregated to provide statistics.
- **Automated process control.** One step further, is to use the available data to automatically control the process. New recycle plants exist that automatically adapt machine settings based on the output quality of the process.

7.5.12.4 Strengths

- **Real-time information.** Knowing the characteristics of waste streams real-time, enables process control to increase both yield and quality.

7.5.12.5 Weaknesses

- **Current manual control.** Current mechanical equipment in most sorting and reprocessing installations is not fully controlled by an HMI. Many settings are adjusted manually. Introducing process analytics also means adjustments of existing machinery.
- **Change of mindset.** Introducing full process control in plastic recycling requires a change in mindset of the operators.

7.5.12.6 Technology evaluation

Table 35: Process Monitoring and Control – Technology Evaluation

Process Monitoring and Control		
Overall	**+**	
Maturity	+/-	Process analysis in waste management is still in an early stage of development.
Costs	+	Process adjustments do not involve high-tech machinery.
Implementation effort	-	Adjustments are necessary at most machines.
Potential	+	Real-time process control will increase both yield and quality. The principles are known from other industries.

8 Reflections

The previous chapters provided an overview of the current situation for plastic packaging, and future developments in terms of legislation, mass balance, and technologies. In this chapter, we summarize these trends and future developments.

In terms of packaging development Chapter 4 discussed various trends that we noticed in the plastic packaging market.

- A decrease in unit mass is observed linked to the focus on plastic reduction for packaging. As a consequence this leads to an increased use of flexible packaging, and subsequently, a higher demand for high barrier (multilayer) and composite materials. These multilayer and composite materials ensure that the packaging maintains the right properties. However, they also require different sorting, reprocessing, and recycling technologies.
- An overall increase in the use of packaging. An example of this is the increase in packaging used in e-commerce.
- An increase in the use of paper composites. While perceived as 'sustainable' by some, these composites are troublesome in sorting, reprocessing, and recycling.
- Bio-based and bio-degradable plastics volumes are increasing. Some bio-based polymers can be used as a drop-in replacement for virgin plastics. These polymers are not distinguishable from virgin, thus, good for maintaining a circular value chain. However, there are also bio-based polymers that are technically sortable, but still too low in volume and therefore not sorted (and recycled). Bio-degradable polymers are not circular since the idea is that they degrade.
- An increase in producer awareness of the usage of recycled plastics in their packaging. For example, producers choose polymers that are available as high-quality recyclates such as PET packaging in cleaning or dairy products. This could however have a negative effect on PET streams when no deposit refund scheme is in place.

Next to packaging developments, we also discussed developments on a market level.

- An increase in the use of reusable packaging. Examples of this are refill stations at supermarkets, to-go cups, and take-away food.
- Vertical integration in the market. Here companies such as packaging producers and retailers vertically integrate with companies on the 'other side' of the value chain such as recyclers (*e.g.* Schwarz Group).
- As a consequence of stricter export regulations, there has been a decrease in the transport of plastic packaging waste to countries outside of the EU. Next, in general, the capacity for reprocessing and recycling has been increasing, as well as the demand for more high-end recyclate. As mentioned above, there has been an increase in producer awareness. This relates to brand owners also taking more responsibility by for example joining pre-competitive consortia. In collaboration with other brand owners (and other stakeholders in the value chain) these consortia work on increasing the circularity and sustainability of the plastic packaging value chain.
- Newly built sorting facilities typically create more valuable output streams (especially PE flexibles).
- In order to meet the recycling targets, the collection schemes have been extended. For example in Belgium, they extended their packaging waste collection from certain plastic packaging to all plastic packaging. On a country level, in the Netherlands, there has been a decrease in litter due to the extension of the deposit refund scheme.

On legislation and guidelines, there have also been developments on both European and Dutch levels.

- On European level, there has been a change of measurement point with respect to what is called recycled material.
- The targets of the use of post-consumer recyclate in packaging products have been increased.
- Improvements in recycle checks are in place, which enable brand owners to check their packaging on recyclability. In the Netherlands, the deposit refund scheme extended to also include smaller PET bottles. In addition, there is also an extension of the EPR scheme to also include commercial household-like packaging waste.
- In the near future more extensive diversified PRO fees to increase the recyclability of packaging are expected.
- With respect to food safety EFSA is setting stricter requirements for the use of recycled plastics in food packaging materials. In this report we have not focused on this specific topic, but it will have an effect on the use of recycled plastics in food packaging.

The upcoming technologies we described are also an important part of the future outlook.

- Hot-wash development, designed to acquire high-quality recyclate, in the reprocessing step for polyolefins is gaining momentum.
- To improve the quality of recyclate there are also other developments such as extended deodorization, refreshing, and deinking.
- Artificial intelligence is getting attention in the industry. AI vision systems can be used to analyse waste streams or to assist in sorting.
- Other developments in sorting are the use of markers to sort packaging and the replacement of hand pickers in the quality line with robots. In general, there is an increase in automation in sorting and reprocessing steps.
- Different recycling technologies such as solvent-based mechanical recycling and depolymerization are being explored in addition to conventional mechanical recycling.
- Use of pyrolysis as a recycling technology for polyolefins has received more attention and is being scaled up. For this, there is a demand for polyolefins as feedstock, which could be in competition with mechanical recycling.

9 Conclusion

Our study indicates that the plastic recycling in Europe is complex: the market is not open but regulated by varying EPR schemes, no standard for input or output of treatment facilities and no clear preference yet for recycling routes. As such, it is very difficult to clearly identify the best technologies from a technological point of view. This is because the performance of these technologies

a) is depending on the system they will be deployed in, which are largely dominated by legislation that varies between countries, and
b) should be evaluated from its impact on the entire chain. For example, a very efficient technology may result in a very small high value-stream but may leave an exceptionally large low-value stream that ends up in the incinerator. Overall, application of this technology may therefore have a limited or even negative impact on sustainability criteria (use of fossil resources, CO_2 emission, *etc.*).

Both the system and the technologies that are operated in the system are currently in full and rapid development and are interdependent. We conclude that the system is still diverging with many innovative technologies being developed and it seems premature to clearly prioritize any at this point. On the short term, while the system is diverging, there is probably a benefit to support as much technology developments and as many initiatives as possible, but with the awareness that a selection of prospective technologies is expected once the system settles down and starts converging. For new technologies to be applicable in the (future) system, the following drivers are deducted from this study:

- demand for higher recycling rate to meet European recycling targets;
- application driven quality requirements to the recyclate;
- increased use of plastic packaging, in particular of flexible materials;
- stringent legislation regarding food-contact materials;
- increased use of bio-based (non-biodegradable) polymers.

This implies that not all technologies will prevail, which may be a consequence of legislative and other choices rather than technological performance. It is highly likely that successful technologies will be those that can combine high technological performance with a perfect fit to the system that it has to operate in, and maybe even those that are able to fit the system to their technology. In order to support and advise on the system choices that have to be made to get to a convergence of the system, it is recommended to set-up technology evaluation procedures that will not only consider technical and financial performance but also qualitatively and/or quantitively considers the impact of the technology on the entire chain. Thus, it is recommended to set-up performance indicators that consider the full chain, which will require a thorough understanding of the plastic recycling chain, and to challenge technology developers to quantify their impact on the entire chain rather than the technological performance alone.

References

[1] European Commission, "Waste framework directive 2008/98/EC; article 3, 2b(a)".

[2] Umwelt Bundesamt, "Aufkommen und verwertung von verpackungsabfällen in Deutschland im Jahr 2019," 2021.

[3] Ellen MacArthur Foundation, "Global commitment," [Online]. Available: https://ellenmacarthurfoundation.org/global-commitment/overview. [Accessed 29 September 2022].

[4] European Plastics Pact, "Targets," [Online]. Available: https://europeanplasticspact.org/targets/. [Accessed 21 July 2022].

[5] European Food Safety Authority, "EFSA - Food contact materials," 2022. [Online]. Available: https://www.efsa.europa.eu/en/topics/topic/food-contact-materials. [Accessed 25 10 2022].

[6] Plastics Europe, "The circular economy for plastics - a European overview," 2022.

[7] MarketLine, "Containers & packaging in Europe," MarketLine, 2021.

[8] MarketLine, "Containers & packaging in the Netherlands," MarketLine, 2021.

[9] Plastics Europe, "Plastics - the facts," 2021.

[10] Eurostat, "Packaging waste statistics," 25 March 2022. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics. [Accessed 29 September 2022].

[11] C. Cimpan, E. L. Bjelle and A. H. Stromman, "Plastic packaging flows in Europe - a hybrid input-output approach," *Journal of Industrial Ecology,* pp. 1572-1587, 2021.

[12] Plastics Recyclers Europe, "Flexible films market in Europe - state of play," 2020.

[13] Plastics Recyclers Europe, "HDPE & PP market in Europe - state of play," 2020.

[14] Plastics Recyclers Europe, "PET market in Europe - state of play," 2022.

[15] European Commission, "Assessment report of the voluntary pledges udner Annex III of the European strategy for plastics in a circular economy," Brussels, 2019.

[16] Inspectie Leefomgeving en Transport, "Wijziging classificatie kunststofafval per 1 januari 2021," [Online]. Available: https://www.ilent.nl/onderwerpen/afvaltransport-evoa/wijziging-classificatie-kunststofafval-per-1-januari-2021. [Accessed 21 July 2022].

[17] G. Bishop, D. Styles and P. N. Lens, "Recyclign of European plastic is a pathway for plastic debris in the ocean," *Environment International,* vol. 142, 2020.

[18] SYSTEMIQ, "Reshaping plastics: pathways to a circular, climate netural plastics system in Europe," 2022.

[19] European Commission, "Effectiveness of the essential requirement for packaging and packaging waste and proposals for reinforcement," 2020.

[20] U. Thoden van Velzen, M. Brouwer, M. Paillart and E. Westra, "Recyclebare mono-barrière-folies kunnen houdbaarheid grofweg halveren," 19 September 2022. [Online]. Available: https://www.vmt.nl/58059/recyclebare-mono-barriere-folies-kunnen-houdbaarheid-grofweg-halveren?giftCode=ACneOClZXZQ4upNyWbyGfYsGJvfs3nURciOS7_dKaRSD2oZP58EY4SDPn4WrMgns&social=copy. [Accessed 20 September 2022].

[21] PreZero, "About PreZero," 20 September 2022. [Online]. Available: https://prezero.de/en/about-prezero.

[22] IKEA, "What is IKEA doing about sustainability?," [Online]. Available: https://www.ikea.com/nl/en/this-is-ikea/sustainable-everyday/what-is-ikea-doing-about-sustainability-pub440e8b11. [Accessed 20 September 2022].

[23] CMS, "Plastics and packaging laws in the Netherlands," 30 June 2021. [Online]. Available: https://cms.law/en/int/expert-guides/plastics-and-packaging-laws/the-netherlands. [Accessed 21 July 2022].

[24] Rijksoverheid, "Nieuwe regels over wegwerpplastic," [Online]. Available: https://www.rijksoverheid.nl/onderwerpen/afval/regels-voor-wegwerpplastic. [Accessed 21 July 2021].

[25] Staatsblad 2020, 375, "Besluit regeling voor uitgebreide producentverantwoordelijkheid," [Online].

[26] KIDV, "Besluit beheer verpakkingen 2014," [Online]. Available: https://kidv.nl/besluit-beheer-verpakkingen. [Accessed 21 July 2022].

[27] Rijksoverheid, "Besluit maatregelen kunststof drankflessen," 24 April 2020. [Online]. Available: https://www.rijksoverheid.nl/documenten/besluiten/2020/04/24/bijlage-1-besluit-maatregelen-kunststof-drankflessen. [Accessed 21 July 2022].

[28] Afvalfonds Verpakkingen, "Wij zijn stichting afvalfonds verpakkingen," [Online]. Available: https://www.afvalfondsverpakkingen.nl/nl/wij-zijn-stichting-afvalfonds-verpakkingen. [Accessed 25 July 2022].

[29] KIDV, "Inzameling en recycling," [Online]. Available: https://kidv.nl/inzameling-en-recycling. [Accessed 25 July 2022].

[30] De Afvalspiegel, "Notitie: Bron- en nascheiding in opdracht van CAW," 2019.

[31] CPB, "Diftar in Nederland: verschillen tussen oost en west," September 2019. [Online]. Available: https://www.cpb.nl/sites/default/files/omnidownload/cpb-achtergronddocument-diftar-in-nederland-verschillen-tussen-oost%20en%20west.pdf. [Accessed 2 August 2022].

[32] Afvalfonds Verpakkingen, "Monitoring verpakkingen," Afvalfonds Verpakkingen, Leidschendam, 2021.

[33] CBS, "Gemeentelijke afvalstoffen; hoeveelheden," 14 July 2022. [Online]. Available: https://opendata.cbs.nl/statline/?ts=1565096216320#/CBS/nl/dataset/83558NED/table. [Accessed 2 August 2022].

[34] Afvalfonds Verpakkingen, "Onze recycleresultaten," 2020. [Online]. Available: https://www.afvalfondsverpakkingen.nl/nl/onze-recycleresultaten. [Accessed 25 July 202].

[35] M. T. Brouwer, E. U. Thoden van Velzen, K. Ragaert and R. ten Klooster, "Technical Limits in Circularity for Plastic Packages," *Sustainability,* vol. 12, 2020.

[36] IVCIE, "The cooperation agreement," [Online]. Available: https://www.ivcie.be/en/the-cooperation-agreement/. [Accessed 25 July 2022].

[37] IVCIE, "Reporting obligation," [Online]. Available: https://www.ivcie.be/en/obligations/reporting-obligation/. [Accessed 25 July 2022].

[38] IVCIE, "Take-back obligation," [Online]. Available: https://www.ivcie.be/en/obligations/take-back-obligation/. [Accessed 25 July 2022].

[39] IVCIE, "Prevention plan," [Online]. Available: https://www.ivcie.be/en/obligations/prevention-plan/. [Accessed 25 July 2022].

[40] Fost Plus, "De groene punt tarieven," 2022. [Online]. Available: https://www.fostplus.be/nl/leden/de-groene-punt-tarieven. [Accessed 26 July 2022].

[41] M. Roosen, N. Mys, K. Kleinhans, I. S. Lase, S. Huysveld, M. Brouwer, E. U. T. v. Velzen, K. M. V. Geem, J. Dewulf, K. Ragaert, A. Dumoulin and S. d. Meester, "Expanding the collection portfolio of plastic packaging: Impact on quantity," *Resources, Conservation & Recycling,* vol. 178, 2022.

[42] Fost Plus, "Next milestone for the new blue bag," 1 April 2021. [Online]. Available: https://www.fostplus.be/en/blog/next-milestone-for-new-blue-bag. [Accessed 25 July 2022].

[43] Recycling Netwerk, "De statiegelddiscussie in België," [Online]. Available: https://recyclingnetwerk.org/themas/statiegeld/de-statiegelddiscussie-in-belgie/. [Accessed 25 July 2022].

[44] Plastics Europe, "Circular economy for plastics - Belgium - 2020," 2022.

[45] Fost Plus, "Belgium exceeds European plastic recycling requirements," 2 August 2021. [Online]. Available: https://www.fostplus.be/en/blog/belgium-exceeds-european-plastic-recycling-requirements. [Accessed 25 July 2022].

[46] Fost Plus, "Recycling household packaging in Belgium," 2022. [Online]. Available: https://assets.foleon.com/eu-west-2/uploads-7e3kk3/252/220215_fost_plus_materiaalfiche_en.0c8f7bee38da.pdf. [Accessed 25 July 2022].

[47] Fostplus, "Activity report," 2021. [Online]. Available: https://com.fostplus.be/activityreport2021en/. [Accessed 20 September 2022].

[48] Stiftung Zentrale Stelle, "Vorläufig zuzuordnende marktanteile der systeme für das 4. quartal 2022," 2022. [Online]. Available: https://www.verpackungsregister.org/fileadmin/files/Marktanteile/Vorlaeufige_Marktanteile_der_Systeme_fuer_das_vierte_Quartal_2022.pdf.

[49] Umwelt Bundesamt, "Verpackungen," 17 November 2021. [Online]. Available: https://www.umweltbundesamt.de/themen/abfall-ressourcen/produktverantwortung-in-der-abfallwirtschaft/verpackungen/versandverpackungen%23leitfaden-des-umweltbundesamtes-fur-umweltgerechte-versandverpackungen-im-versand-und-onlinehandel-. [Accessed 29 September 2022].

[50] J. Christiani and S. Berckamp, "Was können die mechanische Aufbereitung von Kunststoffen," 2020.

[51] Institute Cyclos HTP , "Verification and examination of recyclability," 14 September 2021. [Online]. Available: https://www.cyclos-htp.de/publications/r-a-catalogue/.

[52] BVSE, "Statusbericht der deutschen kreislaufwirtschaft," 2020. [Online]. Available: https://www.bvse.de/dateien2020/2-PDF/01-Nachrichten/01-bvse/2020/November/Statusbericht_der_deutschen_Kreislaufwirtschaft_2020.pdf.

[53] Umwelt Bundesamt, "Verpackungsabfälle," 22 February 2022. [Online]. Available: https://www.umweltbundesamt.de/daten/ressourcen-abfall/verwertung-entsorgung-ausgewaehlter-abfallarten/verpackungsabfaelle#verpackungen-uberall. [Accessed 29 September 2022].

[54] Verpackungs Register, "Prüfleitlinien mengenstromnachweis systeme," 15 December 2020. [Online]. Available: https://www.verpackungsregister.org/fileadmin/files/Pruefleitlinien/Pruefleitlinien_Mengenstromnachweis_Systeme_2020.pdf.

[55] Plastics Europe, "Circular economy for plastics - Germany - 2020," 2022.

[56] CITEO, "CITEO annual report 2021-2022," 2022.

[57] Plastics Europe, "Circular economy for plastics - France - 2020," 2022.

[58] Plastics Europe, "Circular economy for plastics - Netherlands - 2020," 2022. [Online]. Available: https://plasticseurope.org/knowledge-hub/circular-economy-for-plastics-netherlands-2020/.

[59] M. Brouwer, U. T. v. Velzen and Y. Workala, "Recyclebaarheid van Nederlandse kunststofverpakkingen," Wageningen Food & Biobased Research, 2021.

[60] "HTP internal figures".

[61] HVC, "Jaarverslag 2020," 2020.

[62] AVR, "Jaarbericht 2021," 2021.

[63] Afvalfonds Verpakkingen, "Tarieven," 2022. [Online]. Available: https://www.afvalfondsverpakkingen.nl/nl/tarieven. [Accessed 20 September 2022].

[64] D. Groot, "Zwerfinator ziet sterke afname plastic flesjes in zwerfafval," 4 February 2022. [Online]. Available: https://zwerfinator.nl/zwerfinator-ziet-sterke-afname-plastic-flesjes-in-zwerfafval/. [Accessed 27 September 2022].

[65] KIDV, "Aanvullende wetgeving voor verpakkingen (2023)," 14 September 2022. [Online]. Available: https://kidv.nl/aanvullende-wetgeving-voor-verpakkingen-2023. [Accessed 27 September 2022].

[66] J. Hopewell, R. Dvorak and E. Kosior, "Plastics recycling: challenges and opportunities," *Philosophical Transactions of the Royal Society,* vol. 364, pp. 2115-2126, 2009.

[67] EFSA, "Guidelines on submission of a dossier for safety evaluation by the EFSA of a recycling process to produce recycled plastics intended to be used for manufacture of materials and articles in contact with food," *The EFSA Journal,* p. 717, 2008.

[68] B. Fischer, "Rheology for polypropylene recycling with organic peroxides," *The Catalyst Review,* vol. March, p. 1, 2022.

[69] PEP, EUPC and EUPR, "REMIX - Final Report," 2015.

[70] G. Pastorelli, T. Trafela, P. F. Taday, A. Portieri, D. Lowe, K. Fukunaga and M. Strlič, "Characterisation of historic plastics using terahertz time-domain spectroscopy and pulsed imaging," *Anal. Bioanal. Chem.,* vol. 403, no. 5, pp. 1405-1414, 2012.

[71] Recyling Inside, "Ink Removal in Plastics Recycling Plants," [Online]. Available: https://recyclinginside.com/plastic-recycling/sorema-previero-ink-removal-in-plastics-recycling-plants/. [Accessed 2022-08-25].

[72] R. Kol, M. Roosen, S. Ügdüler, K. M. V. Geem, K. Ragaert, D. S. Achilias and S. D. Meester, "Recent Advances in Pre-Treatment of Plastic Packaging Waste," in *Waste Material Recycling in the Circular Economy - Challenges and Developments*, 2022.

[73] Packaging Europe, "Closing the loop with deinking," 2022. [Online]. Available: https://packagingeurope.com/features/closing-the-loop-with-deinking/8251.article. [Accessed 2022-08-25].

[74] KIDV, "Fact Sheet - Inks - Printing on Packaging," 2021.

[75] S. Ügdüler, T. D. Somer, K. M. V. Geem, M. Roosen, A. Kulawig, R. Leineweber and S. D. Meester, "Towards a Better Understanding of Delamination of Multilayer Flexible Packaging Films by Carboxylic Acids," *ChemSusChem,* 2021.

[76] T. W. Walker, N. Frelka, Z. Shen, A. K. Chew, Jesse Banick, S. Grey, M. S. Kim, J. A. Dumesic, R. C. V. Lehn and G. W. Huber, "Recycling of multilayer plastic packaging materials by solvent-targeted recovery and precipitation," *Sci. Adv.,* 2020.

[77] S. Ügdüler, T. D. Somer, K. M. V. Geem, J. D. Wilde, M. Roosen, B. Deprez and S. D. Meester, "Analysis of the kinetics, energy balance and carbon footprint of the delamination of multilayer flexible packaging films via carboxylic acids," *Resources, Conservation and Recycling,* 2022.

[78] W. Lyskawinski, M. Baranski, C. Jedryczka, J. Mikolajewicz, R. Regulski, D. Sedziak, K. Netter, D. Rybarczyk, D. Czarnecka-Komorowska and M. Barczewski, "Tribo-Electrostatic Separation Analysis of a Beneficial Solution in the Recycling of Mixed Poly(Ethylene Terephthalate) and High-Density Polyethylene," *Energies,* vol. 14, 2021.

[79] J.-P. Lange, "Managing Plastic Waste—Sorting, Recycling, Disposal, and Product Redesign," *CS Sustainable Chem. Eng.,* vol. 9, 2021.

[80] H. Mangold and B. v. Vacano , "The Frontier of Plastics Recycling: Rethinking Waste as a Resource for High-Value Applications," *Macromol. Chem. Phys.,* vol. 223.

[81] KIDV, "Chemical recycling of plastic packaging materials. Analysis and opportunities for upscaling," 2018.

[82] TNO, "Verspil het niet! Pak de schaduwzijde van plastics met urgentie aan," 2020.

[83] K. Van Geem , L. Delva and K. Ragaert , "Mechanical and chemical recycling of solid plastic waste," *Waste Management,* 2017.

[84] BPF, "Chemical Recycling 101," [Online]. Available: https://www.bpf.co.uk/plastipedia/chemical-recycling-101.aspx. [Accessed 2022-08-19].

[85] Conversio, "Stoffstrombild kunststoffe in Deutschland 2019," August 2020. [Online]. Available: https://www.vci.de/ergaenzende-downloads/kurzfassung-stoffstrombild-kunststoffe-2019.pdf.

[86] Statista, "Plastics industry in Europe," 2020.

[87] Directive 94/62/EC, [Online].

[88] Rebelgroup, "Haalbaar recyclingpercentage kunststof verpakkingsafval voor 2025," Rebelgroup, Rotterdam, 2019.

[89] M. Brouwer, I. W. Smeding and E. Thoden van Velzen, "Verkenning effect verschuiven meetpunt recycling kunststofverpakkingen," Wageningen Food & Biobased Research, Wageningen, 2019.

Appendix A List of figures

Appendix B Additional tables

Table 36. European plastic market [6].

	Europe
Production	47.5 Mt
Conversion	53.9 Mt
Consumption	53.6 Mt
Waste	29.5 Mt
Landfill	6.9 Mt
Energy	12.4 Mt
Sent for recycling	10.2 Mt
Export surplus	1.0 Mt
Input into recycling plants	9.1 Mt
Process losses	3.6 Mt
Post-consumer recycled plastics	5.5 Mt
Pre-consumer recycled plastics	3.6 Mt

Table 37. Division of packaging materials in the European market, adopted from [7].

Category	Market Volume [MT]	%
Paper	56.2 Mt	49.2 %
Plastic	25.7 Mt	22.5 %
Glass	25.0 Mt	21.9 %
Metal	7.2 Mt	6.3 %
Total	114.1 Mt	99.9 %

Table 38. Containers and packaging market geography segmentation: % share, by value, 2021 (MarketLine, 2021).

Geography	$ billion USD		%
Germany	52.0		15.5 %
France	36.3		10.8 %
Netherlands	8.6		2.6 %
Belgium	5.7		1.7 %
Rest of Europe	232.8		69.4 %
Total	335.4		100 %

Table 39. Destination per polymer type of generated pre- and postconsumer packaging waste in kt [11].

	Total collected	%	Recyclate to packaging	%	Recyclate to other sectors	%	Export sorted plastics	%	Incineration	%	Landfill	%
PE-LD	5805	100 %	182	3 %	468	8 %	729	13 %	2538	44 %	1888	33 %
PE-HD	3350	100 %	143	4 %	428	13 %	628	19 %	1251	37 %	899	27 %
PP	3808	100 %	69	2 %	317	8 %	43	1 %	1932	51 %	1447	38 %
PS	682	100 %	0	0 %	17	2 %	17	2 %	365	53 %	283	42 %
PS-E	244	100 %	0	0 %	27	11 %	27	11 %	110	45 %	80	33 %
PVC	391	100 %	0	0 %	0	0 %	0	0 %	219	56 %	172	44 %
PET	3332	100 %	443	13 %	283	8 %	735	22 %	1127	34 %	744	22 %
OTHER	456	100 %	0	0 %	0	0 %	0	0 %	256	56 %	201	44 %

Table 40. Converters demand per segment [9].

Converters demand	Mt	%
Packaging	19.9 Mt	40.5 %
Building & construction	10.0 Mt	20.4 %
Automotive	4.3 Mt	8.8 %
Electrical & electronics	3.0 Mt	6.2 %
Household, leisure, sports	2.1 Mt	4.3 %
Agriculture	1.6 Mt	3.2 %
Other	8.2 Mt	16.7 %
Total	49.1 Mt	100 %

Table 41. Converters demand by country, shown in percentages for a total of 49.1 Mt [9].

Country	Converters demand in 2020	%
Germany	11.4 Mt	23.3 %
France	4.6 Mt	9.3 %
Belgium & Luxembourg	2.3 Mt	4.7 %
Netherlands	2.1 Mt	4.3 %
Total	49.1 Mt	100 %

Table 42. Plastic converter demand by polymer type in 2020 (Plastics Europe, 2021).

Converter demand by polymer	Mt	%
PP	9.7	19.7 %
LDPE, LLDPE	8.57	17.4 %
HDPE	6.32	12.9 %
PVC	4.7	9.6 %
PET	4.14	8.4 %
PUR	3.81	7.8 %
PS, EPS	2.98	6.1 %
Others	8.93	18.1 %

Table 43. Dutch plastic market [58].

	Netherlands
Production	5390 kt
Conversion	2362 kt
Consumption	2070 kt
Waste	1058 kt
Landfill	3 kt
Energy	537 kt
Sent for recycling	478 kt
Export surplus	20 kt
Input into recycling plants	500 kt
Process losses	190 kt
Post-consumer recycled plastics	300 kt
Pre-consumer recycled plastics	280 kt

Table 44. Belgian plastic market [44].

	Belgium
Production	6820 kt
Conversion	2518 kt
Consumption	1270 kt
Waste	578 kt
Landfill	10 kt
Energy	341 kt
Sent for recycling	227 kt
Export surplus	20 kt
Input into recycling plants	210 kt
Process losses	70 kt
Post-consumer recycled plastics	140 kt
Pre-consumer recycled plastics	160 kt

Table 45. German plastic market [55].

	Germany
Production	9910 kt
Conversion	12522 kt
Consumption	10670 kt
Waste	5419 kt
Landfill	35 kt
Energy	3120 kt
Sent for recycling	2264 kt
Export surplus	650 kt
Input into recycling plants	1610 kt
Process losses	540 kt
Post-consumer recycled plastics	1050 kt
Pre-consumer recycled plastics	900 kt

Table 46. French plastic market [57].

	France
Production	4780 kt
Conversion	4977 kt
Consumption	6450 kt
Waste	3760 kt
Landfill	1159 kt
Energy	1672 kt
Sent for recycling	929 kt
Export surplus	240 kt
Input into recycling plants	690 kt
Process losses	250 kt
Post-consumer recycled plastics	440 kt
Pre-consumer recycled plastics	330 kt

Appendix C Additional figures

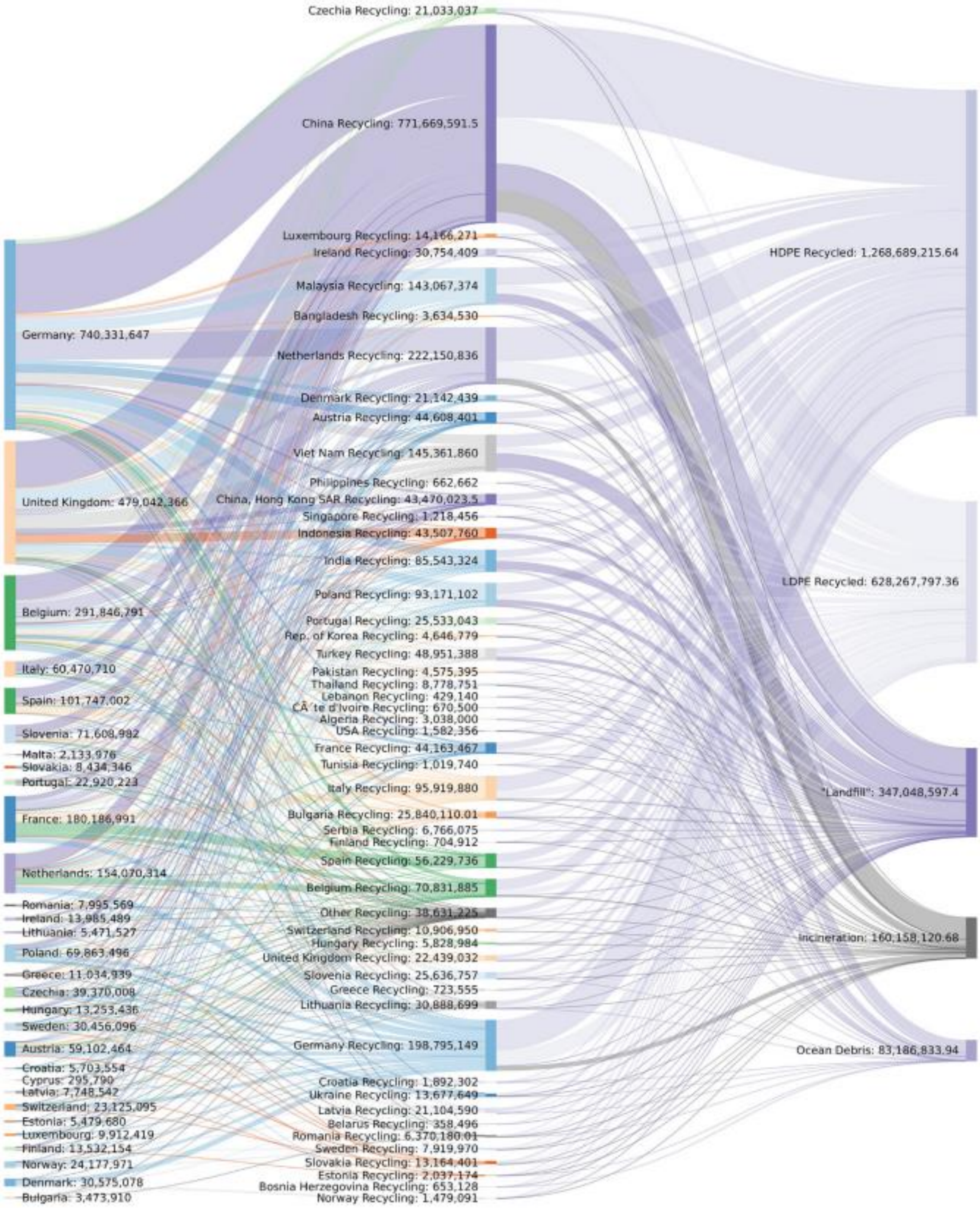

Figure 67. Plastic pathways for polyethylene based on an average recovery scenario [17].

Formula for calculating recycled packaging according to Afvalfonds:

Recycled (glass, paper, plastic, wood) =

weight reported by waste management facility as delivered for recycling

+ findings from data verifications that have not (yet) been included in declaration

- share of not-packaging and impurities

- share of contamination on top of the alleged quality norm

Figure 68. Formula for calculating recycled packaging [32].

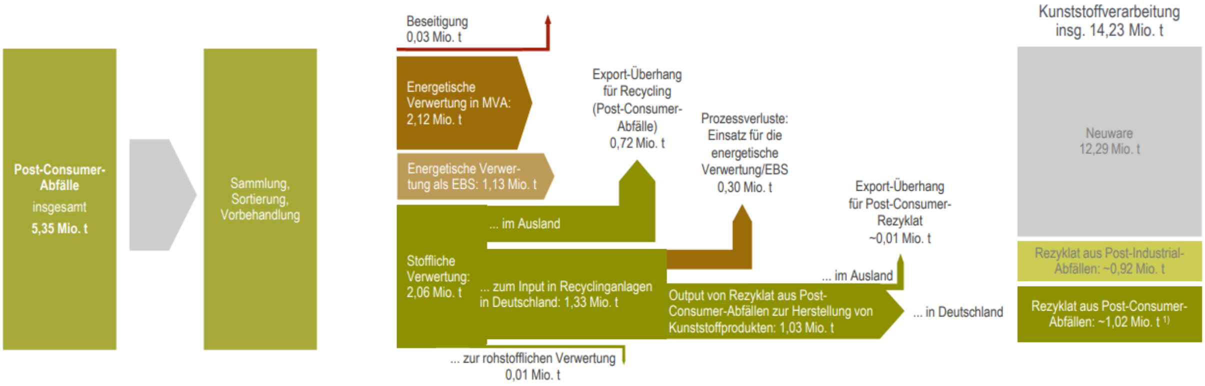

Figure 69. Post-consumer plastic mass flow [85].

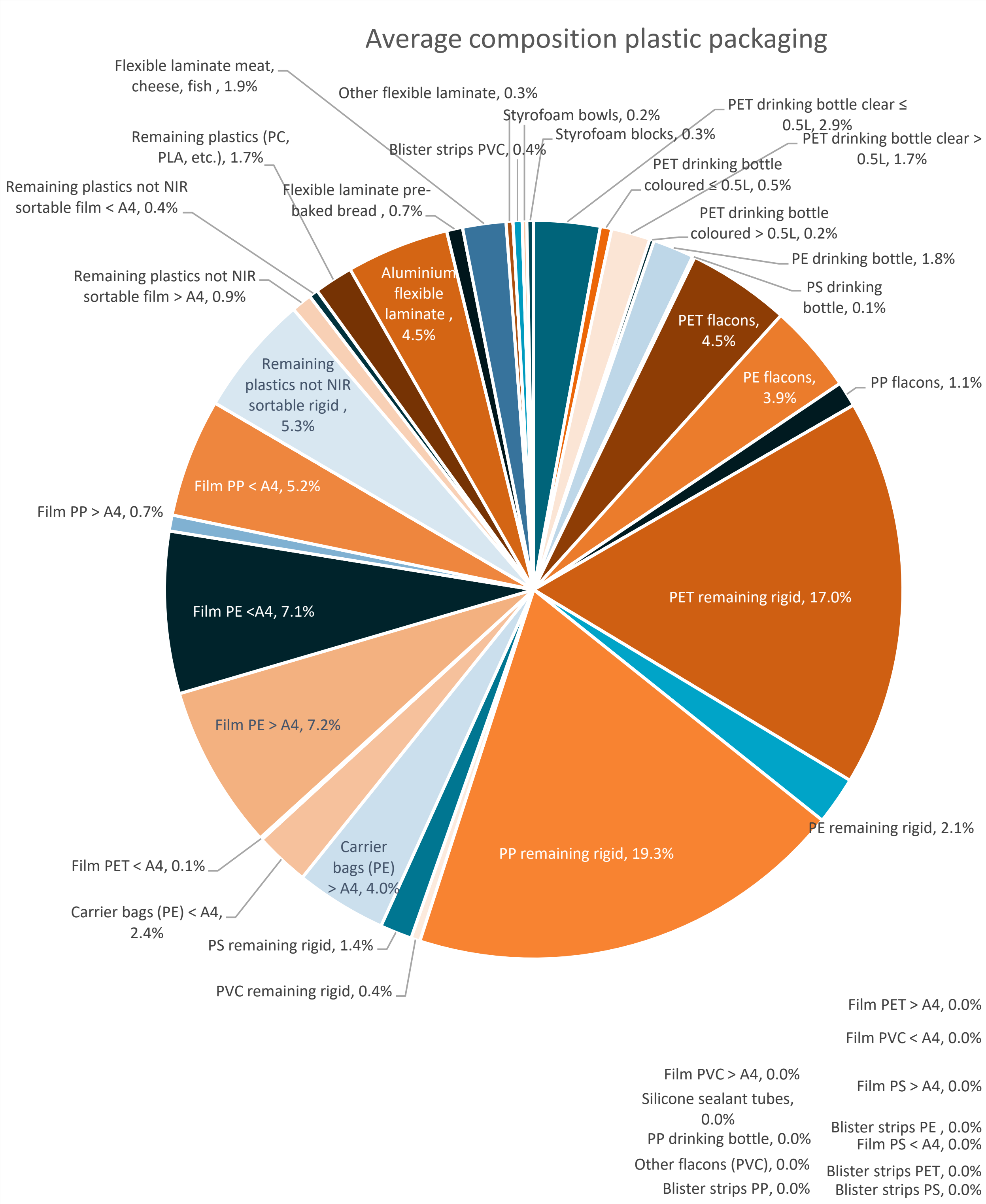

Figure 70. Average composition of plastic packaging [59].