REDUCING PLASTIC WASTE IN CANADA

Funded by the European Union

State of Recycling Technologies for Flexible Plastic Packaging

In Europe

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Glossary of Terms

CIMPA	Circular Multilayer Plastic Approach
CLP	Classification, labelling and packaging of substances and mixtures
CoC	Chain of Custody
CPA	Circular Plastics Alliance
D4ACE Guidelines	Design for a Circular Economy Guidelines
DSD 310–1 DSD 323–2	‘Duales System Deutschland (DSD) GmbH’, which is the German dual system and has developed the standards for the degree of allowed contamination in sorted bales of recyclable plastic. DSD 310–1 is composed of at least 92 wt% plastic films, with dimensions larger than an A4 paper, which are mostly made of PE. DSD 323–2 consists of at least 90 wt% plastic films, which are mostly made of either PE or Polypropylene (PP), i.e. it has a polyolefin (PO) composition
EB	Electron-beam inks and coatings
EPR	Extended Producer Responsibility
EU	European Union
EFSA	European Food Safety Authority
EVOH	Ethylene-vinyl alcohol copolymer
HDPE	High density polyethylene
ISCC	International Sustainability and Carbon Certification
LDPE	Low Density polyethylene
MRF	Material Recovery Facilities
NIR	Near Infrared
NIR-VIS	Near Infrared – visible
rPE	Recycled Polyethylene
rPO	Recycled Polyolefins
rPP	Recycled Polypropylene
PA	Nylon plastic
PCR	Post-consumer recycled (materials)
PPWD	Packaging and Packaging Waste Directive
PPWR	Packaging and Packaging Waste Regulation (proposed)
PET	Polyethylene Terephthalate
PE	Polyethylene
PMD	Plastics, Metals and Drinks packaging
PO	Polyolefin
PP	Polypropylene
PS	Polystyrene
PRO	Producer Responsibility Organization
PVC	Polyvinyl chloride
PVDC	Polyvinylidene dichloride
QRP	Quality Recycling Process
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
$scCO_2$	super-critical carbon dioxide
SCFs	supercritical fluids
UV	Ultra violet
WFD	Waste Framework Directive
VOCs	volatile organic compounds

Executive Summary

This report is an overview of the **state-of-the-art technologies for recycling flexible plastics**, as well as recent activities that are contributing to moving towards a circular economy for flexible plastic packaging in Europe. It features a summary of the European context and key legislative and policy drivers that that are mobilizing stakeholders in Europe to increase the collection and recycling rates for flexible plastic packaging.

The report reviews activities at the country level for member states that are particularly active in plastic recycling innovation. For example, the requirement to collect all or most flexible plastic packaging in Germany, the Netherlands and Belgium as well as ramping up of recycling targets for plastic packaging has been a key driver to expand collection to all flexible plastic formats in those countries.

While the current **recycling target** for plastics in the European Commission's Packaging and Packaging Waste Directive (PPWD) is set at 22.5% for the entire European Union (EU) member states to achieve individually, Germany, the Netherlands and Belgium have all implemented plastic packaging recycling targets that are higher than this EU Directive at 58.5%, 42% and 50%, respectively. While it may be possible to achieve the 22.5% recycling rate by collecting only rigid plastic containers, higher targets require the collection, sorting and recycling of flexibles as well as rigids. With increasing recycling targets for plastic packaging in the EU to 50% and 55% in 2025 and 2030 respectively, the expansion of collection systems to include all flexible plastic packaging formats will be a likely requirement in all European Member States, to achieve these ambitious targets.

The **collection of flexible plastic packaging** comingled with other plastic packaging, metal containers and drink/liquid cartons in the light-weight packaging category is the preferred approach to maximise the sorting and recovery efficiencies. At state-of-the art sorting facilities for light-weight packaging, flexible plastic packaging can be effectively captured using wind-sifters and ballistic sorters to aggregate flexible plastic packaging so that it can be subsequently sorted by optical sorting units that are specifically adapted to manage flexible plastic packaging and films.

Recognizing that the **quality of recyclates** from conventional mechanical recycling of household flexible plastic packaging is not high enough to incorporate into new packaging, several proposed improvements to existing mechanical recycling technologies have emerged on the European market to meet increased demand for recycled content in packaging. For example, the Quality Recycling Process (QRP), developed by CEFLEX combines already existing technologies to improve the quality of polyethylene (PE) and polypropylene (PP) recyclates produced from processing commodity bales, enabling them to be used in new non-food contact packaging applications such as mono-PE and mono PP stand-up pouches, PE collation shrink, and PP labels. Additionally, deinking technologies such as Keycycle Deinking are now commercially available and their use to treat post-consumer flexible plastic packaging, beyond in-house production scrap is being further explored. Other deinking processes that will likely lead to improvements in the mechanical recycling process such as supercritical CO_2 are also being researched in Europe.

Chemical recycling processes have gained interest as complementary technologies to mechanical recycling, especially for the more difficult to recycle plastic packaging formats that are currently being either landfilled or incinerated with energy recovery. Thermal decomposition technologies such as pyrolysis are particularly suited for polyolefin plastics such as PE and PP of which flexible plastic packaging primarily consist of. With so much of flexible plastic packaging waste currently generated in Europe being sent to landfill or energy recovery, it is not surprising that chemical recyclers and chemical manufacturers are targeting this feedstock material as it is not in direct competition as feedstock for the majority of mechanical recyclers at this time. Pyrolysis oil, the main output from the pyrolysis process, can be used as an alternative feedstock material to offset the use virgin naphtha in ethylene steam cracker plants operating in Europe. By using a mass-balance approach, the allocation of recycled feedstock to non-fuel products can offset the use of virgin fossil resources, reduce the CO_2 emissions from incineration with energy recovery, and provide virgin equivalent plastics suitable for use in food grade applications.

At first glance, it may appear that both **mechanical and chemical recycling technologies** are targeting different waste streams with chemical recyclers focussing on mixed plastics bales that are currently being sent to incineration with energy recovery, and mechanical recyclers focussing on DSD 310-1 and DSD 323-2 commodity bales. DSD is the abbreviation for 'Duales System Deutschland (DSD) GmbH', which is the German dual system and has developed the standards for the degree of allowed contamination in the sorted bales. DSD 310–1 is composed of at least 92 wt% plastic films, with dimensions larger than an A4 paper, which are mostly made of PE. DSD 323–2 consists of at least 90 wt% plastic films, which are mostly made of either PE or Polypropylene (PP), i.e. it has a polyolefin (PO) composition (Bashirgonbadi et al. 2022).

Despite this, the recently proposed model bale specification for pyrolysis very much resembles the DSD 310-1 and DSD 323-2 specifications with respect to the required levels of PE and/or PP and maximum levels of contaminants such as PVC/PVDC, PET/EVOH/Nylon, and PS. This implies that in fact, it is likely that both mechanical recyclers and chemical recyclers (pyrolysis) will be competing for the same material, especially if the advancements in mechanical recycling and product design lead to increased opportunities to include recycled content in new flexible plastic packaging applications.

An important consideration for EPR programs that are responsible to meet the recycling targets on behalf of their producer members, is the yield of the recycling process and what can count towards meeting **recycling targets and recycled content levels in new packaging**. While the precise allocation rules have yet to be established in European implementing acts, the recycling efficiencies associated with the use of pyrolysis oil in steam crackers could expect ranges between 55% and 73%. Considering a range of factors, the overall efficiency of recycling 1 tonne of polyolefin-based flexible plastic packaging may yield a 40% - 55% recycling efficiency rate. Processing yields for both conventional mechanical recycling and CEFLEX's QRP of DSD 310-1 and DSD 323-2 commodity bales have been estimated to be between 64%-66%, which is considerably higher than that of pyrolysis processes that produce pyrolysis oil that is fed into steam crackers.

Ultimately, its likely that improved mechanical recycling, emerging dissolution/purification and chemical recycling (thermal depolymerization) will all have a role in the management of flexible plastic packaging waste generated from households in the European Union.

1. Introduction and Background

1.1 Report Objective

This report is an overview of the state-of-the-art and recent activities in the flexible plastic packaging value chain that are contributing to moving towards a circular economy for flexible plastic packaging in Europe. It features a summary of the European context and key legislative and policy drivers that that are mobilizing stakeholders in Europe to increase the collection and recycling rates for flexible plastic packaging.

The primary focus of the report is to examine 4 (four) main areas of activity in the management of flexible plastic packaging and highlight progress and innovations in leading European Union (EU) countries: (1) Collection; (2) Sorting; (3) Mechanical Recycling, and; (4) Physical and Advanced/Chemical Recycling. Each areas features examples of business innovations and case studies.

1.2 Background - Generation of Household Flexible Plastic Packaging Waste in Europe

In the EU 27 +3, 53.56 million tonnes of plastics were placed on the market in 2020. Plastic packaging from household, commercial and industrial sources accounted for 33.5% of this total, representing just under 19 million tonnes. In 2020, 46% of all plastic packaging managed in the EU was sent to recycling, with just over 37% and 21% sent to energy recovery and landfill respectively (Plastics Europe, 2022).

Total household plastic packaging generated in the EU 27 +3 in 2020 has been estimated to be just under 11.5 million tonnes of which 45%, or approximately 5.1 million tonnes was sent to recycling. Approximately 40% (4.6 million tonnes) is managed through incineration with energy recovery, and the remainder is sent to landfill (15% or 1.7 million tonnes) (Plastics Europe, 2022).

With respect to household flexible plastic packaging, it is estimated that just over 4 million tonnes is placed on the European market annually (CEFLEX, 2022). Approximately 47% of flexible packaging is made of low-density mono polyethylene (LDPE), 7% is mono high density polyethylene (HDPE) and 21% is polypropylene (PP) mono-materials. (CEFLEX 2022). Around 26% are multi-material combinations of PE/PP, PET/PE, PET/PP, PA/PE laminates. The amount of household flexible plastic packaging collected and sent to recycling (most of which as PE flexibles) in Europe in 2018 was estimated to be 406,000 tonnes (PRE, 2020).

Based on this, it is estimated that only **10% of all household flexible plastic packaging** that is generated in Europe is collected and sent for recycling, which is considerably lower than the total for all household packaging. The remainder is sent to energy recovery and landfill facilities.

1.3 Overarching Policy Drivers for Plastics Circularity

European stakeholders acknowledge that several EU Strategies, directives and regulations are driving action and investments to increase the collection and recovery of plastics, including flexible plastic packaging. A suite of complementary directives and a newly proposed regulation on packaging and packaging waste have create significant momentum for change across the plastics value chain and within governments.

In December 2015, the EU Commission adopted an **EU Action Plan for a Circular Economy**[1], which identified plastics as a key priority and committed the Commission to prepare a strategy addressing the challenges posed by plastics throughout the value chain and taking into account their entire life-cycle. In 2017, the Commission confirmed it would focus on plastics production and the goal of ensuring that all plastic packaging is recyclable by 2030.[2]

In 2018, amendments to the **Packaging and Packaging Waste Directive (PPWD)[3]** saw increases to recycling targets for plastic packaging from the current 22.5% to 50% by 2025 and 55% by 2030. Not only was this a significant increase in the absolute recycling rate target for plastics, the rules on the calculation to determine the attainment of the target were also amended to account for downstream losses in recycling process, effectively lowering existing performance levels.

Also in 2018, the European Commission released its **EU Strategy for Plastics in a Circular Economy**.[4] The Circular Plastics Alliance (CPA) is an initiative under the strategy, in particular under Annex III related to voluntary pledges by industry. The European Commission launched the Circular Plastics Alliance in December 2018 to help plastics value chains boost the EU market for recycled plastics to 10 million tonnes by 2025. According to the CPA, achieving the 10 million tonnes target requires producing an additional 3.4 million tonnes of recycled plastics in Europe by 2025 (compared to 2020). To achieve this, sorting capacities should increase by at least 4.2 million tonnes by 2025 and recycling capacities by at least 3.8 million tonnes. This corresponds to estimated investment needs between € 7.6 billion and € 9.1 billion. To reach the target, the CPA estimated that over 80% of the increase in recycled plastics should come from packaging, with the remainder from the other sectors covered by the CPA including agriculture, construction, automotive and electrical and electronic equipment.

More recently on November 30, 2022, the European Commission released its ambitious proposal for a **Packaging and Packaging Waste Regulation (PPWR)**, that will repeal the PPWD, if approved by the European Council and the Parliament. Within the proposal, there are specific measures that aim to ensure that all packaging placed on the European market is either reusable or recyclable by 2030 and to reduce packaging, over-packaging and therefore packaging waste. Because the proposal is for a Regulation, rather than a Directive, Member States must apply the provisions in their entirety and no longer transpose the requirements in their national laws. This ensures a harmonized regulatory framework across all Member States, that supports investment, reduces waste and promotes high-quality recycling, which will apply equally in all EU Member States.

While the proposed regulation maintains the recycling targets for 2025 (50%) and 2030 (55%) for plastic packaging established in the current PPWD, it introduces new requirements and targets for reduction, reuse and recycled content. Article 38 requires Member States to reduce the amount of packaging waste generated per capita, compared to a baseline year of 2018. In 2030, Member States are required to reduce total packaging waste generated per capita by 5% compared to 2018. This increases to 10% by 2035 and 15% by 2040 compared to the baseline generation per capita in 2018.

The reuse targets in the Directive are for specific product categories, and with respect to household flexible plastic packaging, other that the requirement for transport packaging for the transportation and delivery of non-food items via ecommerce, these targets don't generally apply. Specifically, in the proposal, 10% of transportation packaging to facilitate the delivery of non-food items must be reusable packaging within a system for re-use by 2030. This increases to 50% by 2040.

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[1] COM(2015) 614 – EU Circular Economy Action Plan https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en
[2] Commission Work Programme 2018 - COM(2017) 650.
[3] The Packaging and Packaging Waste Directive (PPWD) DIRECTIVE 94/62/EC environment.ec.europa.eu/topics/waste-and-recycling/packaging-waste_en#law
[4] EU Strategy for Plastics in a Circular Economy, 2018 environment.ec.europa.eu/strategy/plastics-strategy_en#:~:text=The%20EU's%20plastics%20strategy%20aims,the%20environment%20and%20human%20health.

With respect to increasing the demand for recyclable materials, the PPWR introducers recycled content requirements in new plastic packaging placed on the market by 2030 and 2040. The recycled content should include materials recovered from post-consumer plastic waste and are presented in Table 1.

Table 1: Proposed Targets in the Packaging and Packaging Waste Regulation

Recycled Content	By Jan 1, 2030	By Jan 1, 2040
Contact sensitive packaging made of PET	30%	50%
Contact sensitive packaging made of all other plastics than PET	10%	50%
Singe-use plastic beverage bottles	30%	65%
Other plastic packaging	35%	65%

To support this requirement, a methodology for calculating and verifying the percentage of recycled content recovered from post-consumer plastic waste, per unit of plastic packaging will be established through the adoption of an implementing act by December 31, 2026 becoming mandatory by 1 January 2029. With respect to recycled content, there is a requirement that by January 1, 2030, Extended Producer Responsibility (EPR) schemes for packaging modulate fees based on the quantity of recycled content in new packaging. By 2030, all packaging placed on the European market must be designed for recycling. In the proposal, packaging can be considered recyclable where it complies with the following criteria:

- It is designed for recycling;
- It is effectively and efficiently separately collected in accordance with the Article 43(1) and (2);
- It is sorted into defined waste streams without affecting the recyclability of other waste streams;
- It can be recycled so that the resulting secondary raw materials are of sufficient quality to substitute the primary raw materials;
- It can be recycled at scale.

The commission expects to adopt delegated acts that will lay down the criteria for determining the recyclability of specific packaging types and creating a recycling performance grade from A to F, with packaging that scores a grade F with a recyclability score of less than 70% would not be considered recyclable. The regulation also requires EPR schemes to modulate fees that producers pay to account for the recyclability score.

2. Industry Initiatives Driving Technology Development

There are a number of industry-led initiatives that are driving innovation and technology development to address flexible packaging within Europe. This section presents key highlights of some of the most prominent industry initiatives that have evolved under the policy framework discussed in the previous section.

2.1 Industry Value-chain Initiative for Flexible Plastics Packaging

The Circular Economy for Flexible Packaging (CEFLEX)[5], is a collaborative European initiative with over 190 stakeholders representing all parts of the European flexible plastic packaging value chain, including material producers, film producers & packaging converters, brand owners & retailers, waste collectors, sorters and recyclers, and others in the broader flexible plastics ecosystem. CEFLEX's Vision, which is called Mission Circular, commits to the collection of all flexible packaging and over 80% of the recycled materials channelled into valuable new markets and applications to substitute virgin materials. A 5-step roadmap to build a circular economy for flexible packaging has been endorsed by CEFLEX stakeholders, together with a set of actions needed by each part of the value chain to make it happen. By 2025, CEFLEX targets an established collection, sorting and reprocessing infrastructure and economy for post-consumer flexible packaging across Europe. It will be based on end-of-life technologies and processes which deliver the best economic, technical and environmental outcome for a circular economy.

2.2 The Role of Extended Producer Responsibility Organizations (PROs) in the Value Chain

Extended Producer Responsibility (EPR) schemes for packaging play an essential role in ensuring the collection, sorting and recycling of post-consumer flexible plastic packaging. As well, they play a substantial role in coordination within the packaging waste supply chain, as well as financing collection and recovery. The EU requires EPR schemes for packaging to be implemented by December 2024 and most countries rely on 'Producer Responsibility Organisation' (PROs) for their management. PROs are established to deliver on this mandate and implement the obligations of responsible producers.

PROs work with all parts of the plastics value chain and end-of-life management businesses to help provide the conditions for each actor to make improvements that will benefit the entire system. PROs in Europe work with local authorities, brand owners (fillers) packaging manufacturers, sorters, recyclers, among others by collecting information and providing insights on what is happening to the packaging as it moves through the system so that brand owners can understand the impact of their product design choices on the sorting and recycling infrastructure.

The European Extended Producer Responsibility Alliance (EXPRA)[6] is a participating stakeholder in CEFLEX. In CEFLEX's five focus arears of Design for Recycling, Collection, Sorting, Recycling, and End Markets, a number of "EPR complimentary activities" have been identified in collaboration with EXPRA.

- <u>Design for Recycling</u>: EPR programs, through the PROs, can include modulation of fees that producers pay to finance the system to incent mono-PE and mono-PE flexible formats over more difficult to recycle multi-laminate flexible formats in line with the D4ACE Guidelines.
- <u>Collection</u>: EPR organizations can often influence which types flexible packaging formats are to be collected in the national system, or at minimum the decision of local authorities who may have the responsibility for collection. Under CEFLEX's "EPR Criteria for Circularity" all flexible plastic packaging is to be targeted for separate collection, including on the go flexible packaging.

[5] More information of CEFLEX can be found at ceflex.eu
[6] More information can be found at expra.eu

- Sorting: EPR programs can set recovery targets and bale specifications for flexible plastic packaging that drive improved sorting outcomes. PROs may even invest in research and development or direct investment in sorting infrastructure.
- End Markets: PROs can incentivize recycled content use, through fee modulation, with reduced fees for packaging placed on the market containing recycled content. PROs may even pay recyclers to process the sorted flexible plastic packaging where markets are still not fully developed. An important role for PROs is planning and developing recycling end markets together with the various actors.

2.3 Design for Recycling Guidelines – Flexible Plastic Packaging

While it is estimated that a high proportion of the total household flexible plastic packaging that is placed on the European market is either mono PE, mono PP, or a combination of PE/PP, a significant quantity of flexible packaging remains made of multi-layered and multi-material resin combinations with or without additional barrier layers that are problematic for the recycling process. These non-recyclable complex combinations of materials are problematic for both mechanical and chemical recycling processes and efforts to improve design are an important strategy to increase the recycling rates of flexible plastic packaging in Europe.

Design for recycling guidelines generally accept that for flexible plastic packaging to be considered recyclable the following conditions must be met:

- ✓ Packaging must be made of materials that are accepted in the approved collection system for packaging waste.
- ✓ Packaging must be able to be effectively sorted at material recovery facilities (MRFs) or sorting facilities into pre-defined streams or commodities for downstream recycling.
- ✓ During the recycling process, the material is processed at a commercial scale and is reclaimed as a raw material for use in new products or packaging.

Within the new EU proposed regulation, similar criteria are listed as requirements when determining whether packaging is to be considered recyclable or not.

2.4 CEFLEX – Design for a Circular Economy (D4ACE)

CEFLEX published its Design for a Circular Economy (D4ACE) guidelines in June 2020. The CEFLEX D4ACE guidelines have been developed by, and for, the whole flexible packaging value chain. The content is based on value chain consensus, using the best available data from testing and commercial practices. The guidelines are intended to act as a catalyst, facilitating and enabling the value chain to design flexible packaging to be recyclable, while providing waste management and recycling companies with increased confidence to invest and develop the sorting and recycling infrastructure required to make all flexible packaging circular.

The guidelines cover key elements of the structures of polyolefin-based flexible packaging, including thresholds for mono-PE and mono-PP used, functional barriers, size and shape, density, adhesives, pigments, additives and fillers, printing inks, and labels. For each element, guidance is given in terms of compatibility with a PE or PP mechanical recycling process. Reasons are provided for the guidance, along with general design advice. The D4ACE guidelines provide a method to rank a package's design as either 'compatible with', 'limited compatibility', or 'not compatible' with current PE or PP mechanical recycling on each of the design criterion.

2.5 Recyclass Certification

RecyClass is a comprehensive cross-industry initiative that works to advance plastic packaging recyclability and to establish a harmonized approach towards recycled content calculation and its traceability in Europe. Activities within RecyClass include the development of Recyclability Evaluation Protocols and scientific testing methods for innovative materials which serve as the base for the Design for Recycling Guidelines and the Recycling Online Tool. RecyClass offers Recyclability Certifications for plastic packaging and Recycled Content Traceability Certification for plastic products.

With respect to flexible plastic packaging, Recyclass has produced Design for Recycling Guidelines for:

1. Natural PE Flexible Films for Household and Commercial Packaging
2. Coloured PE Flexible Films for Household and Commercial Packaging
3. Natural PP Flexible Films for Household and Commercial Packaging
4. Coloured PP Flexible Films for Household and Commercial Packaging

Summary of Section 2

Section 2 presented key highlights of the main industry initiatives that have been identified as key drivers of new technology and innovative standards to circularity for plastics in Europe.

The following section presents an overview of the various approaches for collecting flexible plastic packaging in selected European countries that are considered leaders in flexible plastic recycling.

3. Collection Approaches and Sorting Technologies for Flexible Plastics

This section outlines the collection approaches used in selected European countries that collect all or most flexible plastic packaging with other light-weight packaging in the plastics, metals and drinks packaging (PMD)[7] stream as it is commonly referred to in Europe. **Collecting household flexible plastic packaging loose[8] and comingled with other rigid plastic packaging, metals and drink/liquid cartons is the predominant approach used in Europe today**, however there are other variations. The collection of flexibles within the PMD/lightweight packaging stream and separate from glass and paper/board is the preferred approach endorsed by CEFLEX (CEFLEX, 2021).

3.1 Overview of Approach in Germany, Belgium and The Netherlands

In Germany, the collection of all flexible plastic packaging has been included in the EPR program for packaging waste since the origins of the program in 1991. Flexible plastic packaging is collected loose in the Yellow Bag/Cart with other rigid plastic packaging, metal containers and drink cartons (aseptic and gable-top polycoated containers). Glass packaging is collected separately in three separate fractions (clear, brown and green) in centrally located recycling stations where householders bring their recyclables, rather than through curbside collection. Paper packaging is collected curbside via a cart or centrally located bins accessible to householders to bring materials for recycling.

Although there are 11 competing PROs in operation in Germany, collective coordination of the collection contracts that service individual municipalities ensures that standard messaging to consumers regarding what materials are included in the yellow bag/cart can be achieved. Collectively, the PRO's created an educational website[9] that provides information to consumers and other interested parties regarding what materials are accepted and excluded from the yellow bag/cart in Germany.

In Belgium, the inclusion of flexible plastic packaging in the collection system has only recently been established and was phased in between 2019 and 2021. Like Germany, flexible plastic packaging is collected loose with other lightweight plastic packaging, metal packaging and beverage cartons in the so-called PMD[10] bag or Blue Bag. Glass packaging is collected in two fractions (clear and coloured) in centrally located bring stations. Paper packaging is collected with other printed paper either at centrally located bins where householders bring material to, or this is collected at the curb in a separate fraction from PMD.

Fost Plus is the single PRO in operation in Belgium and is responsible for funding both the collection and post-collection management of packaging materials across the country. This also facilitates the nation-wide coordination and promotion of a common collection system in terms of the types and formats of flexible plastic packaging accepted[11] in the PMD fraction. While most flexible plastic packaging formats are accepted in the PMD system, multi-material laminated (plastic and aluminum foil) pouches are not.

In the Netherlands, the inclusion of most formats of flexible plastic packaging into the PMD fraction has been in place since 2009 (KIDV, 2020). In April 2020, metallised plastic packaging (i.e. chip bags) was added to the list of accepted flexibles and therefore all flexible plastic packaging is now accepted in the PMD fraction, with the exception of multi-material laminated (plastic and aluminum foil) pouches. Both glass and paper packaging are collected in separate streams similar to both Germany and Belgium. It is important to note that there are several urban areas

[7] PMD means Plastic, Metals and Drink/Liquid Cartons (polycoated paperboard) packaging.

[8] Residents are asked to place flexible plastic packaging loose within the bag/cart and not to assemble flexibles together (i.e. bag-in-bag). This is important for subsequent sorting steps at the sorting plant.

[9] https://www.mulltrennung-wirkt.de/en/

[10] PMD means Plastic, Metals and Drink Cartons (polycoated paperboard) packaging.

[11] The standard list of accepted materials in the PMD blue bag can be found here

that do not have separate collection for the PMD fraction, and instead collect PMD materials in the residual garbage stream which are subsequently sorted downstream at mixed waste processing facilities.

While the current recycling target for plastic packaging in the PPWD is set at 22.5%, Germany, the Netherlands and Belgium have all implemented plastic packaging recycling targets for household packaging that are higher than the EU Directive at 58.5%, 42% and 50%, respectively. While it may be possible to achieve the 22.5% recycling rate by collecting only rigid plastic containers, this is not the case with the higher targets, requiring the collection, sorting and recycling of flexibles as well as rigids to achieve the higher rates.

3.2 Sorting Technologies and Process for Household Flexible Plastic Packaging

This section provides an overview of the typical sorting processes for the light-weight packaging stream found in Germany, Belgium and the Netherlands with a specific focus on the sorting and capture of flexible plastic packaging into marketable commodities. Figure 1 below provides a general schematic overview of the typical sorting process, which is further elaborated in the sections below.

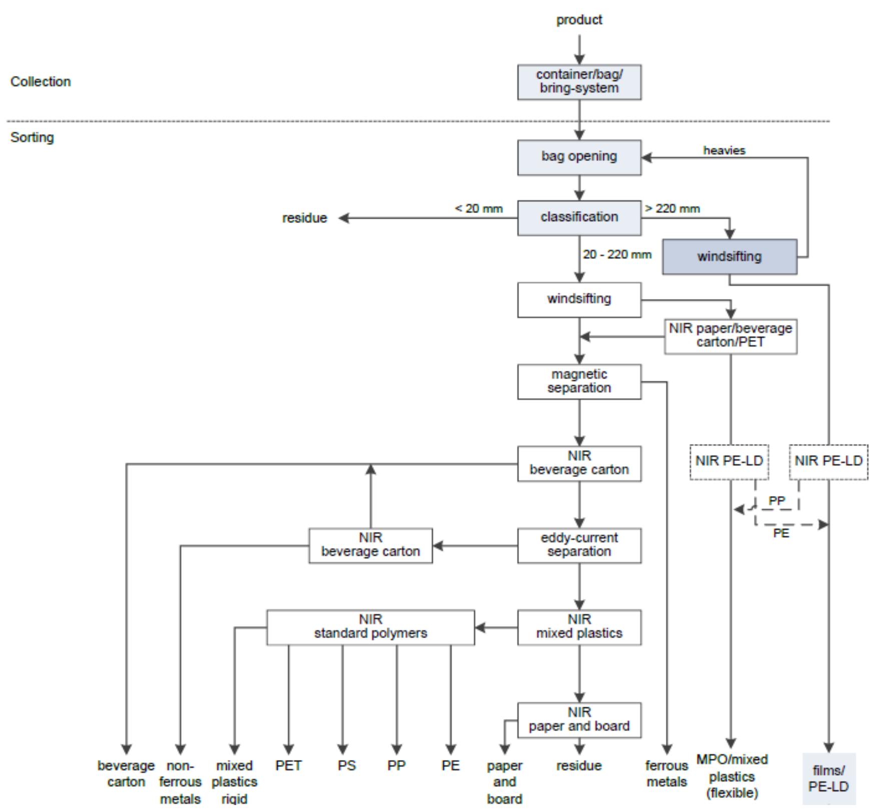


Figure 1: A schematic of a typical Sorting Plant for Light Weight Packaging (LWP) in Germany
Source: Institute cyclos-HTP, (2021)

Inbound Material

Material collected in the yellow bag/cart or the PMD fraction is received at MRFs directly from collection vehicles that service residential routes, but also more commonly in transfer-vehicles that have consolidated material from various receiving facilities. This material is delivered in truck trailers with walking floors that facilitate the emptying of the loads on the tipping floor.

Bag Opening and Drum Feeder

While packaging waste is sometimes collected loose in curbside bins, a considerable amount of packaging waste collected in yellow or blue LDPE plastic collection bags. To effectively sort household packaging and specifically flexible plastic packaging at sorting facilities, these bags must be opened using automatic bag breakers. The bag breaking process also helps to liberate any materials that have joined together during compaction in collection vehicles as well as other recyclables that may have been placed in shopping carrier bags by inhabitants. The typical configuration is to have two bag openers set up in a series with a dosing unit/drum feeder to ensure a uniform flow of light-weight packaging to be subsequently sorted in the sorting facility (Institute cyclos-HTP, 2021).

Table 2: List of Equipment Suppliers – Bag Openers and Dosing Equipment

Manufacturer/supplier	Model Name	Information	Video
Matthiessen Lager und Recyclingtechnik	Bag Opener	Website	Demo
Protechnika	Bag Opener	Website Brochure	Demo
Sutco	Dosing Feeder/Bag opener	Website Brochure	n/a
Veccoplan	VSA Bag opener	Website	Demo

Size Classification -Trommel Screens

After bag opening, material is directed through a series of screens to classify material into at least 3 size classes (fines, medium fraction, and coarse fraction). The most prominent screen types for initial upfront sorting used in European sorting facilities that process lightweight packaging are trommel or rotary screens. A trommel or rotary screen is an inclined rotating drum with shelfs on its surface that lift input material until it nears the top of the drum. The material then falls, tumbling onto other materials at the bottom of the drum. This action helps to loosen recyclables that have been compacted together in collection vehicles. As the tumbling continues smaller fractions filter through holes in the screen plating, while larger size materials are discharged at the end.

Figure 2: Example of a trommel screen

The first trommel screen in sorting facilities serves several key purposes in the preparation of input material for further sorting downstream. These screens may also be fitted with spikes to assist with opening any bags that were not liberated in the de-bagging stage and are equipped with anti-wrapping protection that prevents plastic film and other tanglers from clogging the screen holes. The initial trommel screen may also be used to divide the material flow into parallel sorting lines for more efficient material flow (Institute cyclos-HTP, 2021). Screen holes with a diameter of 220 mm are most commonly found in the initial trommel screen in European sorting plants. Approximately 85%-90% of the total input material falls through the holes in the first trommel while approximately 10-15% exits the trommel overflow as oversized material. The outflow material (or course fraction) is then transported on a conveyor and subjected to wind sifters that effectively remove lightweight plastic film packaging fractions from the heavier oversized material using air suction created by rotary fans. A sample of European-based trommel screen manufacturers is found in the table below.

Table 3: List of Equipment Suppliers – Trommel Screens

Manufacturer/supplier	Model Name	Information	Video
Benzer	Trommel Screen	Website	n/a
MF Emmen B.V	Trommel Screen	Website Brochure	n/a
Stadler	Trommel Screen	Website	Video
Sutco Recyclingtechnik	Trommel Screen	Website	n/a

The heavier fraction that remains on the sorting belt undergoes a manual sort to remove any contamination that cannot be subsequently shredded and is fed back into the beginning of the sorting process. Packaging materials that fell through the holes of the first trommel screen (around 85% - 90% of the input material) are directed to a second series of trommel screens. These trommels sieve out materials that are below 45 mm which are then directed to "fines" screens that remove materials < 20 mm. This fraction is one of several residue streams and makes up approximately 5% of the total input material entering sorting plants (Institute cyclos-HTP, 2021).

While it is commonplace in Germany to subject the materials < 45 mm to subsequent fines screens, sorting facilities in Belgium and the Netherlands do not tend to further sort this fraction and instead direct materials < 45 mm to the residue stream which is subsequently sent for incineration with energy recovery (KIDV, 2020).

The material which exited the second series of trommel screens (the medium fraction) having dimensions between 45 mm and 220 mm is combined with the fraction > 20 mm from the fines screen and is also subjected to wind sifters for removal of lightweight flexible plastic packaging and film. The heavy fraction (mostly rigid containers made of plastics, steel, aluminum and beverage cartons) moves on to subsequent sorting stages.

Wind sifting

Packaging materials that exit the first and second trommel screens pass through wind sifters that remove the flexible plastic materials from heavier three-dimensional plastic, metal and paperboard containers. **Wind sifters are designed to effectively remove flexible 2D film packaging** fractions from the heavier rigid 3D containers material using air suction created by rotary fans (Institute cyclos-HTP, 2021). The lighter plastic flexible packaging and film fraction that is removed via the first wind sifter is mostly large format > 220 mm Polyethylene (PE) film packaging and overwrap and includes the bags that were used by residents to collect packaging materials. Because this stream is a fairly PE-rich homogenous mix, NIR-based sorting may or may or may not take place in sorting facilities and this material may therefore be sent directly to material bunkers for subsequent baling, prior to a final quality control (QC) by manual sorters. **The material commodity from this material is known as the, DSD 310-1.**

In state-of-the-art facilities subsequent sorting of clear PE from coloured PE films may also take place. In such facilities it is likely that the light fraction that is removed from the **second wind sifter** as well as the 2D film materials that are separated by the ballistic sorter are combined with the larger PE-rich flexibles removed from the first wind sifter on the flexible material NIR-VIS sorting line. In sorting facilities that produce only DSD 310-1 bales from materials removed from the first wind sifter (i.e. larger format PE Films) other flexible plastic packaging removed from the second wind sifter is likely sorted to the mixed plastic DSD 350 bale (KIDV, 2020).

Table 4: List of Equipment Suppliers – Wind Sifters/Air Classifiers

Manufacturer/supplier	Model Name	Information	Video
MF Emmen B.V	Wind sifter	Website Brochure	n/a
Nihot	WSS & WSF windshifter	Website Brochure	Video Video
Schultz & Berger	Blow-Suction classifier Drum classifier Three-fraction classifier Kidney classifier Swivel Plate classifier Stage classifier	Website Brochure	n/a
Westeria	Air Star® Air Lift®	Website	Video

NIR Sorters with Air Flow Control

Sorting of 2D flexible plastic packaging using Near Infrared (NIR-VIS) optical sorters on fast moving conveyor belts has proven difficult with conventional optical sorter units, and adaptations to improve this have emerged in recent years as more sorting facilities have targeted flexibles to be separately sorted into commodity bales. To effectively sort flexible plastic packaging with NIR-VIS optical sorters, modifications to standard optical sorting units that limit the movement of lighter 2D materials such as paper and flexible packaging on the sorting belt is required. This modification is needed because if a target material's placement on the belt changes between the point at which it is has been detected by the sorting unit and the point at which it is ejected by air nozzles, the sorting unit will either miss the targeted material or incorrectly sort a material to the wrong fraction.

Many European suppliers of NIR sorting equipment have introduced adaptations to their systems that utilize laminar air flow to stabilize lightweight materials moving along high-speed conveyor belts so that belt speeds can support the required throughput of the facilities. Below is a list of the major European-based manufacturers offering such equipment with videos demonstrating these innovations.

Table 5: List of Equipment Suppliers – NIR Optical Sorters for 2D Materials

Manufacturer/supplier	Model Name	Information	Video
Bollegraaf Recycling Solutions	Opti-Sort	Website	n/a
Pellenc	ST Mistral Film +	Website Technical Sheet	Demo
Stadler	STADLER PX acceleration conveyor	Website	n/a
Steinert	Unisort Film	Website Technical Sheet	Demo
Tomra	Autosort™ SpeedAir	Website Technical Sheet	Demo

Ballistic Sorting

After the main flow of packaging materials has passed through the overhead magnets and eddy current separators to remove ferrous metal and aluminum packaging respectively, materials are sent to a ballistic sorter that separates flat 2D packaging, including any remaining 2D flexible plastic packaging not removed by the second wind sifter, from the three-dimensional mostly rigid plastic packaging containers. The 2D materials that ride up the paddles of the ballistic sorter are directed to the flexible plastic sorting line where these materials are subjected to the NIR optical sorters that are targeting LDPE/HDPE, PP or a combination of PE/PP (MPO) to create separate commodity bales such as the DSD 310-1, DSD 323-2 or in some cases DSD 350 mixed plastics.

Case Study: Digital Watermarks – Holygrail 2.0.

Driven by AIM - European Brands Association and powered by the Alliance to End Plastic Waste, over 160 companies and organisations from the packaging value chain have joined forces under Digital Watermarks Initiative HolyGrail 2.0 with the ambitious goal to advance the application of a pioneering digital technology to enable better sorting and improved recycling rates for packaging in the EU.
The objective of the initiative is to assess the applicability and feasibility of digital watermarking technologies for accurate sorting and develop the business case for their use at large scale. Digital watermarks can be embedded on packaging in two ways: the first is by manipulating the artwork on the packaging to include imperceptible codes, each the size of a postage stamp that are replicated to cover the entire artwork of the packaging; the second is to embed digital watermarks on plastic packaging through the blow molding process, whereby the codes are embossed on the container surface. In both cases the digital watermark codes are barely detectable by the human eye. The digital watermark codes are able to carry a range of attributes (e.g. manufacturer, SKU, resin type, food vs. non food, etc.) and the codes are linked to a standardized database which the waste industry will have access to.

To utilize the digital watermarks in automatic sorting lines, a specific high-speed camera module is required as an 'add-on module' to existing Near Infrared (NIR) optical sorting units. Pellenc ST and Tomra Sorting Solutions have been selected as the vendors for the ad-on detection module development. Both companies have successfully produced detection units that are integrated within their respective NIR sorting units. The high-speed camera will detect the digital watermark on the packaging and relate the code to the attributes in the standardized database. Depending on which attributes are selected, the sorting unit can be programmed to eject the targeted package directing it to the selected stream. It can also be used to reject items by identifying undesirable packaging formats and ejecting these items to a specific residue stream. In the context of flexible plastic packaging, this might entail rejecting multi-laminated plastic packaging formats that would negatively impact the quality of sorted PE or PP film materials, especially if these barrier layers or incompatible polymers cannot be detected by standard NIR technologies.

In Phase 3 of the Holy Grail 2.0 project (starting in 2023), both the Pellenc ST and Tomra units will be installed in five commercial sorting and recycling facilities in France and Germany that are operating under normal conditions. The units will be installed in two Material Recycling Facilities (MRFs), one Plastic Recovery Facility (PRF), and two plastic recycling plants. In this phase, there is an expectation that HolyGrail 2.0 members operating in these countries will digitally watermark at least 10 SKUs from their product portfolios. P&G has committed to having over 100 of their products in Europe carry digital watermarks. Consumers will be able to purchase on-shelf products with digitally watermarked packaging, which will enter the waste stream after consumption. A successful completion of the industrial tests would bring the technology to TRL 9 – actual system proven in operational environment.

More information on the Holy Grail 2.0 project can be found here

Case Study: PreZero Eitting– State of the Art Sorting Facility in Germany

PreZero was founded in 2018 and is now in operation in 11 countries in Europe. It is part of the Schwarz Group, which includes the Lidl and Kaufland retail chains. Lidl and Kaufland together make the Schwarz Group the largest retailer in Europe. PreZero is both a Producer Responsibility Organization (PRO) in Germany and a waste management company that operates collection, sorting and recycling activities across Europe. PreZero operates seven sorting plants in Germany and the Eitting Plant is the newest and most modern facility in its fleet (Kampmann, 2022). The Schwarz Group is quite unique in the marketplace with its approach to meeting its producer responsibility obligations in Germany through the operation of its own PRO. In Germany, PreZero provides the sorting of packaging for approximately 20-25 million inhabitants or roughly 30% of the German population. PreZero is involved in all parts of the end-of-life value chain for packaging, including collection, sorting, recycling and has the ability to incorporate recycled material into new products and packaging that Lidl and Kaufland brands place on the market (Kampmann, 2022).

The Eitting sorting facility was commissioned on January 12, 2022 and is designed to process up to 120,000 tonnes/year of lightweight packaging collected from German households, including plastic packaging (both rigid and flexible), aluminum and steel containers, and aseptic and gable-top cartons. Glass and paper packaging are collected in separate streams. At Eitting, inbound packaging materials are sorted into 18 separate fractions (Kampmann, 2022).

With respect to flexible plastic packaging, 4 separate fractions/commodities are produced at the Eitting facility. This includes LDPE Film (transparent, and coloured separately), PP Flex (polypropylene) and MPO Flex (mixed polyolefins). Additional sorting at the Eitting facility has been attributed to the need to meet increasing recycling targets for plastic recycling in Germany and in addition, since PreZero owns some downstream markets it is in their interest to produce additional streams (Kampmann, 2022). The facility has a total of 38 NIR (near infrared) optical sorters, almost twice the amount installed compared to other facilities. Current end markets for the PP Flex sorted at the Eitting plant are polypropylene (PP) rigid recyclers. Unlike PE film, PP film is compatible with rigid formats and can be incorporated into PP recyclates that can be used to produce rigid non-food grade plastic packaging or other products using injection moulding (Kampmann, 2022). What is also quite unique is the screen size used in the upfront sorting in the trommel screens. In Eitting, the "fines" screens remove all materials less < 20 mm at the start of the sorting line (typical screen size in sorting plants remove materials that are less than 40-50 mm). The driver to actively capture the smaller packaging pieces is the higher recycling targets in Germany for plastics (Kampmann, 2022).

More information about PreZero can be found here.

3.3 Mechanical Recycling Technologies for Flexible Plastic Packaging

Most flexible plastic packaging that has been effectively sorted into commodity bales have mainly been marketed as DSD 310-1 which predominately consists of LDPE film and LDPE flexible packaging. Pioneering sorting plants, in Germany[12] and Belgium[13], are also producing a mixed polyolefin (PO) bale called DSD 323-2. More recently, and only in the most advanced large-scale sorting facilities in Germany such as the PreZero facility in Eitting, a more in-depth sorting of flexible plastic packaging has been seen with separate commodities being produced for LDPE Natural, LDPE Coloured, Polypropylene, and Mixed PO Flex.

According to CEFLEX, most if not all, of the DSD 310-1 commodity bales that are produced at sorting facilities across Europe are sent for mechanical recycling within the EU (CEFLEX, 2021). Of this, approximately 50% of the plastics in the DSD 310-1 bales are recycled into film applications such as garbage bags or construction film. The recyclates from household generated film are often blended in with other commercial and industrial post-consumer PE films to

[12] An estimated 30% of German sorting plants are creating DSD 323-2 bales from their sorting processes (CEFLEX, 2021b).
[13] All 5 of the newly commissioned sorting plants under contract to Fost Plus are creating the DSD 323-2 commodity.

improve the performance of the end products. Up to 50% of the contents of these 310 bales end up as residue from the recycling process and is sent to energy-from-waste (EfW) facilities (CEFLEX, 2021b).

For the 323-2 bales, currently up to two-thirds of this commodity produced at European sorting facilities is being exported to countries outside the EU. Of the one-third that remain in Europe and processed in mechanical recycling facilities, approximately 50% gets recycled into "robust" or "durable" products such as plastic park benches, composite plastic lumber, while the remaining 50% ends up as residue in the recycling process and is sent to energy-from-waste (EfW) facilities (CEFLEX, 2021b).

Conventional Mechanical Recycling

In conventional mechanical recycling facilities that process household flexible packaging (see Figure 3 below), the recycling process starts by opening the bales and shredding the material into roughly 10 cm x 10 cm sized pieces. For the DSD 310-1 commodity bales, metals and non-PE materials are typically removed prior to the cold washing step using an overbelt magnet and NIR sorters. For DSD 323-2 material bales, metals and non-PO materials are only removed during the washing, density separation, and extrusion steps (Lase et al, 2022).

Cold washing consists of a number of process steps including washing the flexible plastic packaging in 25–40 ◦C water, wet granulation, and friction washing. Prior to entering the cold wash, the materials are further size-reduced into flakes roughly 1 cm x 1 cm in diameter. Contaminants such as organic residues, paper and labels, are further removed by a friction washer, whereby a high-speed screw is used to remove contaminants by centrifugal forces.

Following this, the remaining higher density non-PE/PP polymers and metals and the target PE and/or PP polyolefin materials are separated in a sink-float tank, which also functions as a washing step. The target polyolefin material with a density of < 1 g/cm^3 floats and is removed for further processing, while the higher density polymers and metals sink and are removed as residue. Before extrusion, the materials are dried using mechanical and thermal drying units to remove moisture. In the final stage, a single melt filter extruder is used to remove some of the remaining contaminants in the polymer melt (Lase et al, 2022).

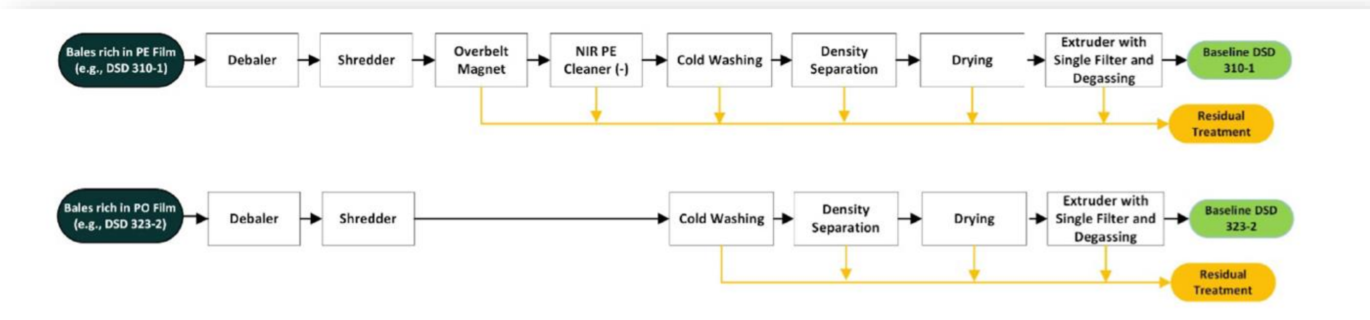


Figure 3: Schematic of a typical conventional recycling plant for household flexible plastic packaging
Source: Lase et al, 2022

Coloured and natural PE films are comingled together and often include heavily ink printed flexible plastic packaging within this mix, so the resulting characteristics of the recyclates produced from conventional mechanical recycling process of flexible plastic packaging limits their use to non-packaging applications. The recyclates from the conventional recycling of DSD 323–2 bales (mixed PE and PP) also have limited applications, none of which are in film (Bashirgonbadi et al, 2022). The material typically goes to durable or robust profile extrusion for the production of park benches or flooring slabs (Faraca and Astrup, 2019).

Innovative Mechanical Recycling

To address the limitations of recyclates from flexible plastic packaging produced through conventional mechanical recycling processes as described above, the following section highlights some of the innovations that have been developed in Europe to date, some of which have only been demonstrated in industrial trials while some are commercially available on the market today. To help boost recycling rates and expand sustainable end markets, a team of CEFLEX stakeholders have developed a Quality Recycling Process (QRP). The QRP is based on existing and readily available technology, however it includes more advanced sorting and recycling steps than found with conventional mechanical recycling of flexible plastic packaging described above (CEFLEX, 2021b).

Figure 4 outlines the steps to be employed when processing flexible plastic commodity bales of DSD 310-1 and DSD 323-2 that are produced at European sorting facilities that manage household flexible plastic packaging.

Figure 4: CEFLEX QRP Extra Process Steps for Increased Quality
Source: CEFLEX 2021b

The four additional steps include:

1. An additional NIR-VIS sorting step;
2. A hot washing step in addition to standard wet washing;
3. An additional filtration step during extrusion (double-filtration) and;
4. Deodorisation of the finished pellets.

Figure 5 illustrates the Tier 1 QRP process for the DSD 310 LDPE bales that are commonly produced at sorting facilities in Germany, the Netherlands and Belgium and other European countries. Because of the relatively high percentage of transparent LDPE flexible plastics found in these bales, additional NIR-VIS[14] sorting to separate this material to process as a separate fraction through the QRP process is conducted. The remaining material, or the so-called 'drop fraction' is also consolidated for separate treatment. Both the natural PE fraction and the coloured PE rich drop fraction are subjected to pre-washing, hot washing, sink-float separation, mechanical and thermal drying, extrusion with double melt filtration and a pellet deodorizing step.

[14] Optical sorters based only near-infrared (NIR) technology can only distinguish the polymer type when sorting flexible plastic packaging. Additional visual spectroscopy VIS is required to sort Natural LDPE from Coloured LDPE.

As part of the semi-industrial trials conducted by the CEFLEX team, examples of packaging applications using the recyclates from Recycled Polyethylene (natural and colour) are shown in Figure 5. Examples of collation shrink used to group multi-pack products containing up to 30% Recycled Polyethylene natural recyclates from the QRP process were produced by Plastotechnica and RKW (CEFLEX, 2021b). A mono-material sealable pouch also containing 30% rPE natural was successfully converted by Constantia Flexibles during the semi-industrial trials. For the Recycled Polyethylene (colour), also known as rPE Flex, garbage bags were made using the recyclate which is the most common application in conventional recycling processes today. Even though PE natural has been removed from this fraction, the quality is still sufficient to produce the garbage bags with blown film (CEFLEX, 2021b).

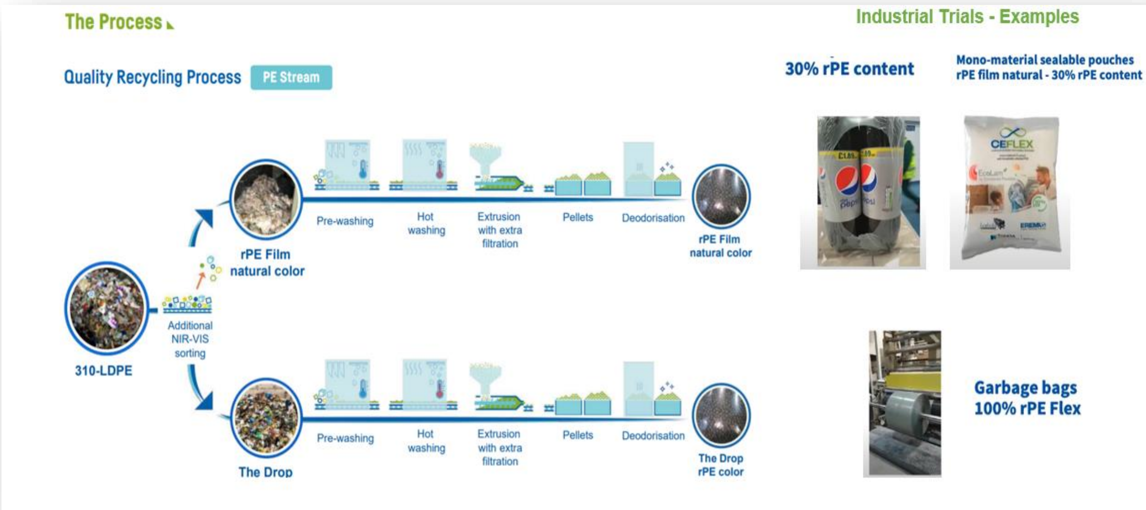


Figure 5: CEFLEX's QRP Process – 310 LDPE Bale.
Source: CEFLEX 2021b

Figure 6 provides an illustration of the Tier 1 QRP process for the DKR 323-2 PO Flex bales that are commonly produced at sorting facilities in Germany and Belgium and to a lesser extent in the Netherlands.

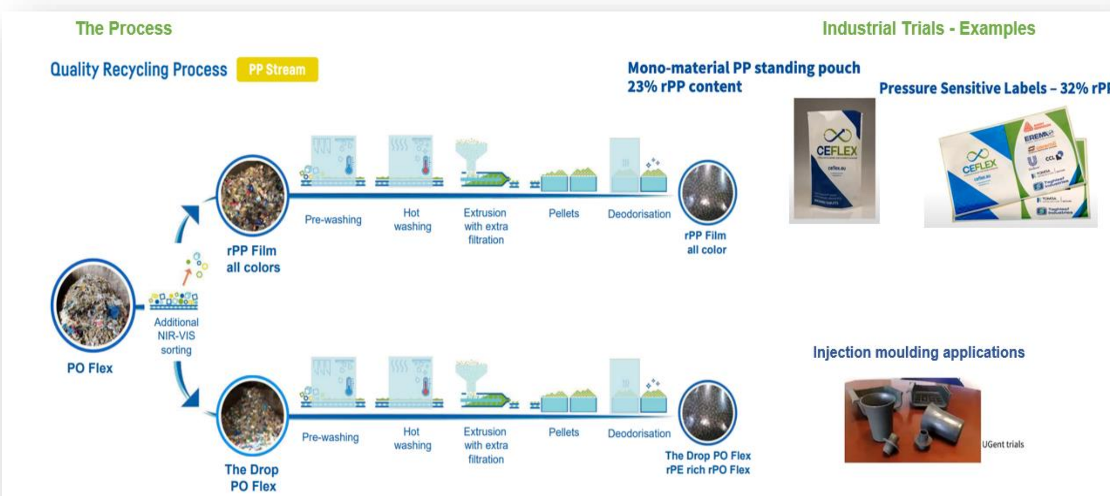


Figure 6: CEFLEX's QRP Process – 323-2 Bale (MPO Flex).
Source: CEFLEX 2021b

Because of the relatively high percentage of PP flexible film found in these bales, additional NIR sorting to separate the PP material (both coloured and transparent) as a separate fraction to be processed is specific in the QRP process is conducted. The remaining material, or the so-called 'drop fraction' is also consolidated for separate treatment. Both the PP fraction and the PO new fractions are subject to a pre-washing, hot washing, sink-float separation, mechanical and thermal drying, extrusion with double melt filtration, pellet production and a pellet deodorizing step in the Tier 1 scenario (CEFLEX. 2021b). Examples of packaging applications using the recyclates from recycled polypropylene and the recycled polyolefins produced during the trials are shown in Figure 6. As can be seen, an example of a stand-up pouch using up to 23% recycled polypropylene was produced. In the other example, film labels containing over 30% recycled polypropylene were also successfully converted during the industrial trials.

CEFLEX has demonstrated that by applying the QRP process it is possible to mechanically recycle flexible plastic packaging back into a wider range of non-food flexible packaging, including more demanding packaging applications. The Quality Recycling Process produces film grade quality Recycled Polyethylene and Recycled Polypropylene polymers appropriate for non-food flexible packaging by applying near infrared (NIR-VIS) sorting by polymer and colour, followed by hot washing and extrusion with extra filtration and deodorization.

The real innovation of the QRP process is the newly established film grade recyclates for natural Recycled Polyethylene and all colour Recycled Polypropylene, which have proven to meet performance characteristics making these materials suitable for replacement of virgin polymer film grades. Prior to the development of the QRP process, there were no known recycling facilities that were producing a PP film grade recyclate for use in packaging applications. While the processing yields associated with the QRP process are similar to conventional recycling of household film (i.e. 64%-66% and 66% respectively), the quality improvement of the recyclates and suitable end-use applications can potentially lead to higher market value for these materials (CEFLEX, 2021b).

Commercialization of the QRP Process – ValueFlex

In November 2022 CEFLEX announced a new collaboration with the Alliance to End Plastic Waste to demonstrate a commercial scale solution to household recycle flexible plastic packaging in Europe. The Alliance and CEFLEX invited expressions of interest (EOI) to partner in developing a first-generation ValueFlex facility with a 50,000 tonne annual processing capacity. The plant will be based in Europe and aims to be operational by 2025. The partners intend that this first-generation commercial implementation will provide a "blueprint for replication", acting as a key enabler to meet market demand for high quality post-consumer recyclates from mechanical recycling, and to provide fit-for-purpose feedstocks for chemical recycling (Alliance to End Waste, 2022).

Hot Washing Lines

In CEFLEX's QRP an additional hot washing step has been added to the conventional cold washing step to increase the removal of contaminants. While common for PET recycling lines, only more recently has the use of hot washing begun to be introduced to the recycling process of PE and PP flexible plastic film recycling. Under elevated temperatures of greater than 80 ◦C with additional washing agents such as caustic soda and detergents, a hot washing step can effectively remove adhesive and organic waste residues as well as partially remove some inks (Lase et al, 2022). Below is a selection of European companies offering hot washing solutions.

Table 6: List of Equipment Suppliers – Hot Wash Lines

Manufacturer/supplier	Model Name	Information	Video
Herbold Meckesheim GmbH	Post-consumer film line Herbold Hot washing	Website Brochure – Wash line Brochure – Hot Wash	Demo
Lindner Washtech GmbH	Post-consumer film line Herbold Hot washing	Website Website – Hot-wash system	Demo
Sorema Plastic Recycling Systems	Post-consumer film line	Website	Demo Demo

Deodorizing Finished Pellets

One of the main challenges with conventional mechanical recycling of flexible plastic packaging is the odour of the finished recyclates. This limits the use to certain applications such as plant trays, park benches, pipes, or in the case of flexible PE, garbage bags or bin liners.

The INTAREMA® ReFresher[15] cleaning process developed by EREMA reduces odours caused by low volatility, high molecular substances that remain on pellets after the extrusion and pellet production process. The technology keeps the pellets at the required temperature at which volatile materials can be discharged relatively quickly. The ReFresher uses the system's own heat energy from the pellets which are preheated during the extrusion process (at least 60 °C). Used in conjunction with the INTAREMA® TVEplus® extruder an ideal process-stable preparation can be achieved, requiring only relatively short residence times inside the ReFresher™. The INTAREMA® TVEplus® removes the highly volatile odorous substances during extrusion while the downstream thermal-physical ReFresher cleaning process manages the low-volatile, high-molecular odour matter.

Applying a hot air stream for a few hours can significantly reduce the overall odour intensity of recycled pellets with an efficiency varying between 51% and 99% (Kol et al, 2021). A disadvantage of this technique is the relatively long contact time that is needed to achieve the maximum feasible removal efficiencies, typically between 4 and 7 hours. Depending on its size, the ReFresher has a capacity between 350 kg/h and 4000 kg/h.

De-inking Technologies

Although inks are one of the necessary components of flexible plastic packaging, they are a significant source of contamination in plastic recycling. As all printed plastic films are generally collected and processed together, a brownish, grayish or black recyclate is often obtained (CEFLEX 2020).

The presence of ink also causes recycled films to be less stiff, weaker, and denser compared to the original material, and therefore its price is considerably lower than the price of films free of ink. Furthermore, during the processing or reprocessing, residual ink can also decompose and produce gases causing rancid odor formation and also decrease the physical properties of the finished pellet (Kol et al, 2021).

Water-based Deinking - Cadel Deinking/Keycycle Deinking

Cadel Deinking, now Keycycle Deinking[16] is a patented and commercially available process to remove inks from flexible plastic packaging using both physical and water-based chemical treatment methods. It was developed by researchers at Alicante University in Spain and received funding under the European Union's Horizon 2020 research and innovation programme. Figure 7 presents a visual of this facility.

Figure 7: Cadel/Keycycle Deinking Demonstration Plant

[15] More information on the INTAREMA® ReFresher can be found here.

[16] In 2019 a subsidiary of EREMA Group, Keycycle, became the exclusive worldwide distributor of the patented Cadel De-inking technology, and as of December 2022, Keycycle acquired the trademark rights and rebranded the product as Keycycle Deinking.

The objective of the project was to develop and demonstrate water-based technology capable of removing inks without damaging the printed plastic film inputs. A fully operational demonstration plant with a capacity of 100 kg/hour was developed and is still in operation today. In this closed-loop recycling plant, printed plastic films pass through several treatments such as grinding, deinking, two-step washing, drying, and pelletizing in order to obtain ink free plastics with high optical quality. According to Keycycle the process is suitable for PE, PP, PET and PA printed flexible film plastics and is effective at removing all ink types including water-based inks, solvent-based inks, UV and EB inks. The new industrial scale plants now available on the European market have throughputs of up to 1,200 kg/hour. With plants on this scale, the Keycycle deinking process will open the door to the post consumer recycling segment, where the removal of printing inks enables another significant quality upgrade for the recycled pellets.

Eight plants have been ordered since the market launch with five of those now in operation at Keycycle customers' sites. These sites are processing either in-house scrap generated at converters own sites as well as post-industrial scrap, however Keycycle has been demonstrating its deinking process with both inhouse waste film and post consumer film. At the K 2022 trade fair in October of this year, post-consumer flexible plastic packaging was recycled on site. Comparisons were made with material that was pre-treated in a Keycycle deinking plant prior to extrusion to material without deinking. The difference in quality of the two streams of recycled pellets was clearly visible.

The process steps are as follows[17]:

- Input materials are first shredded into pieces ranging from 6 mm to 11 mm to allow for the penetration of the cleaning solution.
- The ground material is fed into the cleaning tank containing a de-inking solution made up of a mixture of surfactants in water at proportions between 0.1 and 5% by weight and with a basic pH between 11 and 13[18]. During this stage the printing ink is removed from the plastic film and is dispersed, but not dissolved within the de-inking solution. According to the patent description, the surfactants used in the cleaning solution include hexadecyltrimethylammonium bromide, dodecyl trimethylammonium bromide, or dodecyl sulfate.
- The de-inked plastic film is then transferred to the first rinsing tank to remove residual ink and cleaning fluids. The de-inking solution with the dispersed inks is sent to a centrifuge to separate the dispersed ink from the solution. The de-inking solution is continuously fed back into the cleaning tank reducing the consumption of de-inking solution needed.
- The rinsed film from the first rinsing tank is transferred to the second rinsing tank where any remaining de-inking solution and inks on the film plastic are removed. The patented system uses counter current washing such that clean water enters the system in the second rinsing tank first and is subsequently transferred to the first rinsing tank which drastically reduces the quantity of water required in the process. Both the deinking solution and the rinsing water are continually reused in the system, with the consequent savings in reagents and waste handling.
- After the film has been rinsed in the second rinsing tank it moves to the mechanical drying stage where the material is pressed in a mechanical screw to remove water. This is followed by a thermal drying stage and then a final extrusion process and pellet production.

[17] For a video of the Cadel Deinking Open House click here. A second video explaining the process can be found here.
[18] Patent 2868244 Summary – located at https://www.ic.gc.ca/opic-cipo/cpd/eng/patent/2868244/summary.html?query=alicante&type=basic_search

Solvent-based Deinking: Blue Plastics BV

A finalist in the Alliance to End Plastic Waste's – Alliance Prize -Circular Solutions for Flexibles, CleanBlueTech is a solvent-based closed-loop washing technology that claims to remove smell, glue, print-ink, and organic residues from plastic flexible film waste including post-consumer residentially collected streams.

According to Blue Plastics BV, the process uses 70% less energy and 100% less water than conventional washing processes in operation today. The process does not rely on high processing temperatures and does not use harmful chemicals, with the washing solvent captured and reused in a closed-loop system. Because the system uses no water, solvent-based washing is suitable for water-stressed regions.

CleanBlueTech units can be integrated into existing recycling lines and the output capacity of one CleanBlueTech facility can be between 1,500 kg/hour and 3,000 kg/hour. Technical feasibility was validated with the construction of a pilot plant in the Netherlands, and the quality of the resulting reyclates were validated by partners, including flexible plastic packaging converters.

Blue Plastics B.V. has established a plan for the scaling up and commercialization of its technology. It has the support of a strong network of stakeholders that span from plastic converters to waste management and regulatory entities. Blue Plastics is planning to set up joint venture partnerships for commercial deployment of CleanBlueTech worldwide.[19]

Deinking using Supercritical Fluids - CO_2

An emerging alternative to water-based cleaning and organic solvents involves extraction of inks and other contaminants with supercritical fluids. A supercritical fluid is a substance whose pressure and temperature are above its critical point. This means it shows the properties of a fluid with high diffusivity (gas) and high dissolving power (liquid). This form of extraction is more efficient for substances with a low vapour pressure and compounds with a low molecular weight.

COtooClean Process

Winner of the Alliance to End Plastic Waste's – Alliance $3 M Prize - Circular Solutions for Flexibles, COTooCLEAN is a multi-participant project that aims to develop a unique commercial process that can be integrated into mechanical recycling operations. This innovative process targets high-quality film applications to ensure that recycling targets can be met. With the commercial and technical capabilities of its partners Unilever, Amcor, Viridor, Allied Bakeries, Suprex, University of Nottingham, School of Chemistry and BioComposites Centre, Bangor University, the project aims to deliver a commercial process that can efficiently and effectively clean and decontaminate post-consumer polyolefin films to a food-grade status (Packaging Europe, 2022).

Based on low-pressure super-critical CO_2 ($scCO_2$) combined with green co-solvents the process can, in a single step, remove oils, fats and printing inks and effectively decontaminate polyolefin films under European Food Safety Authority (EFSA) Challenge Test conditions back to food contact levels (Packaging Europe, 2022). ScCO2 is a non-toxic, non-flammable and non-corrosive solvent that can efficiently remove potential contaminants that are commonly found in post-consumer films. Its potential to recycle film back to food-grade quality will not only facilitate film recycling, offering a new post-consumer recycled materials source, but will also facilitate significant reductions in waste to landfill, displacement of virgin resin and significant savings in resources and reductions in carbon emissions and water usage. $ScCO_2$ is widely used in the extraction of food flavours and components, such as helping to remove caffeine from coffee. According to Nextek, a simple phase change can isolate dissolved contaminants and free the CO_2 for re-use as a solvent once again. In this way it does not produce aqueous waste containing impurities and contaminants, or decontamination solvents. The process has the potential to provide a unique technology that will fill the gap in recycling food-grade films (Packaging Europe, 2022). According to the

[19] More details on the company can be found on its website and on the Alliance's list of finalists.

Alliance for Plastic Waste, the relatively simple modification to the existing mechanical recycling process makes the potential impact of COTooCLEAN even greater because of its scalability to global adoption over time. No information could be found on the level of technological readiness of the COTooClean process at this time.

CIMPA – A Circular Multilayer Plastic Approach

A Circular Multilayer Plastic Approach[20] for value retention of end-of-life multilayer films- is an EU funded, Horizon 2020 project that aims to develop a recycling value chain for post-industrial and post-consumer multilayer films (from food and agricultural applications). The CIMPA project has received funding from the European Union's Horizon 2020 research and innovation programme. One specific workstream of the project is focussed on developing de-contamination strategies to improve the quality of post-consumer recycled plastics. In standard extrusion and pelletizing systems, the removal of volatile organic compounds (VOCs) through degassing is somewhat limited and combined with the high temperatures used by recyclers to ensure all polymers are fully melted, VOC levels and associated odours in the pellets are usually very high and distinctive.

To address this issue, two technologies are being tested and optimized in CIMPA:

1. Conventional devolatilization: that involves a twin-screw extruder and multiple stripping agents.
2. Special devolatilization: that consists in tandem single-screw extruders, and supercritical $CO2$ ($ScCO2$).

Devolatilization is a complex process, which depends on multiple parameters such as temperature profile, shear profile, screw configuration, placement of venting, residence time, among others. Several stripping agents can be added to improve the devolatilization process. Inside the extruder, the stripping agents are gasified forming bubbles which are dispersed in the melt to form a micro-foam. The micro-foam has a specific surface area and therefore a high capacity for transfer and diffusion of contaminants. Supercritical fluids such as carbon dioxide are special stripping agents. The fluid exhibits particular properties and has an intermediate behavior between that of a liquid and a gas. In particular, supercritical fluids (SCFs) possess liquid-like densities, gas-like viscosities and diffusivities intermediate to that of a liquid and a gas. If gases are used in supercritical conditions, these conditions must be achieved and maintained inside the extruder.

In CIMPA project the following strategies are being implemented:

- Adjustment of process conditions to improve decontamination efficiency
- VOC removal of multilayer agricultural films, and household waste film
- Residual solvent removal from polyolefins, after physical recycling process
- One-step additivation (stabilization) during decontamination to avoid further degradation of recyclates and reduce thermal history.

Summary of Section 3

Section 3 presented a detailed review of the collection approaches used in selected European countries that collect flexible plastic packaging, including innovative sorting, processing, and mechanical recycling technologies.

Section 4 presents a detailed overview of the innovative advanced chemical recycling technologies being used in Europe already for flexible packaging.

[20] More information on the CIMPA project can be found here.

4. Advanced Physical and Chemical Recycling of Flexible Packaging

More recently, numerous stakeholders including brand owners, chemical companies and resin producers, have been advocating for the development of chemical or advanced recycling as a complimentary approach to mechanical recycling, especially for difficult to recycle plastic packaging that is currently being landfilled or incinerated.

Proponents of chemical recycling point out that achieving high recycling yields through mechanical recycling has proven challenging, with recyclates generally having few applications, drawing lower market prices and are unsuitable for use in food grade packaging. Chemical recycling however, has the potential to generate outputs or products that can be used to produce recycled chemicals and polymers with virgin-like properties and are suitable for food contact applications. Because the recycling takes place far upstream in the process of manufacturing polymers (i.e. pyrolysis oil feedstock into ethylene steam crackers) chemically recycled polymers are identical to virgin polymers. This allows for easier integration of recycled polymers into the plastic value chain including no disruptions of the converting processes and packaging design specifications. It could also provide a solution for meeting recycled content commitments for food grade or other applications if necessary infrastructure investments are brought online.

Not all stakeholders view chemical recycling as a panacea for addressing plastic waste and meeting circularity objectives. For example, Zero Waste Europe purports that chemical recycling should not divert the real solution to plastic pollution, which is replacing single-use plastics, detoxifying and simplifying new plastics, and designing business models to make efficient use of plastics. The Prevent Waste coalition of European civil society organisations, in its recent position paper on 10 priorities to Transform EU Waste Policy notes that: "Clear definitions and requirements are needed to ensure that chemical recycling does not undermine more circular approaches higher in the waste hierarchy or lead to adverse environmental impacts. The input should be limited to degraded and contaminated plastics, never plastics coming from separate collection, and output limited to new plastics, not fuel".

With respect to chemical recycling's position on the EU waste hierarchy, a coalition of 42 European NGOs wrote a letter to the European Directorate-General for the Environment to request a clarification on the role of different technologies marketed as 'chemical recycling' in the EU waste hierarchy. In the letter the group recommend that only chemical recycling technologies which produce polymer materials are legislated as 'recycling' while processes that produce feedstock for petrochemicals are defined as 'chemical recovery', as polymer materials should be kept in use as long as possible and processing of plastic to oil or gas should be approached only as a last resort. The group notes that "clarifying the distinction between 'chemical recycling' and 'chemical recovery' minimizes the risk of diverting waste supply chains away from reuse and recycling towards petrochemicals feedstock recovery".

Plastics Europe has noted that it has seen an increase in planned chemical recycling investment, from EUR 2.6 billion in 2025 to EUR 7.2 billion in 2030. The production of recycled plastics from chemical recycling is estimated to increase to 1.2 million tonnes by 2025 and 3.4 million tonnes by 2030. With this planned contribution of 1.2 Mt of recycled plastics produced through chemical recycling by 2025, Plastics Europe members are providing a leading role in delivering on the European Commission's Circular Plastics Alliance target of 10 Mt recycled plastics used in European products by 2025 (Plastics Europe, 2022).

Conversion to feedstock technologies (pyrolysis, gasification) represents 80% of these planned capacities with 44 planned projects in 13 EU countries (Plastics Europe, 2022).

4.1 The Main Types of Advanced Recycling Technologies

Chemical/advanced recycling can be broadly grouped into three main types of technological processes, including **chemical depolymerization**, **purification and thermal depolymerization**. (Eunomia, 2020), (Closed Loop Fund, 2022). These are described here.

Chemical depolymerization is the process by which a polymer chain is broken down through the use of chemicals and has numerous names including depolymerization, chemolysis, hydrolysis, glycolysis and solvolysis (Eunomia, 2020). Because the chemical depolymerization process is only possible for certain types of plastic, the most relevant examples being polyethylene terephthalate (PET) and other polyesters, polyurethane (PU), polyamides (PA) and polylactic acid (PLA), it has limited applications to manage flexible plastic packaging waste which is predominately polyethylene (PE) or polypropylene (PP).

Purification is an emerging technology which process does not alter the molecular structure of the polymer during the recycling process. It is noted as an advanced technology distinct different from mechanical recycling in that the plastics are dissolved in a solvent that allows the removal of additives and impurities, yielding a purified plastic that is more like virgin plastics than mechanically recycled plastics. Because the plastic molecules themselves are not altered during the process, purification, even though it uses chemicals, it is technically not considered chemical recycling.

Thermal depolymerization, also known as thermal cracking and thermolysis, is the process by which a polymer is broken down into smaller hydrocarbon molecules using heat treatment. There are two main approaches to thermal depolymerisation, delignated by the use of oxygen as a reagent within the process. *Pyrolysis*, also known as thermal cracking, utilises high temperatures in the absence of oxygen, while *gasification* employs low volumes of oxygen to aid the degradation process.

Pyrolysis typically takes place at moderate to high temperatures (300 – 900 °C) and at an atmospheric pressure that facilitates the creation of a liquid fraction, known as pyrolysis/pyrolytic oil, as well as char and non-condensable gaseous by-products. The conventional process can be adapted in a number of ways to alter the reaction conditions and resulting outputs, and include such adaptations as plasma pyrolysis, microwave assisted pyrolysis, catalytic cracking and hydrocracking (additional of hydrogen).

Gasification typically occurs at higher temperatures (700 – 1500 °C), converting plastic inputs into a gaseous mixture of carbon dioxide, carbon monoxide, hydrogen, methane, water and other light hydrocarbons, collectively known as synthesis gas (syngas). It can also be utilised to produce chemical feedstocks such as ethanol, methanol and ammonia.

Thermal Depolymerization – Pyrolysis

Most of the developments in chemical recycling of flexible plastic packaging in Europe to date have focused on pyrolysis technologies that produce pyrolysis oil as a drop-in replacement for virgin naphtha in stream crackers that produce ethylene and propylene, the monomers used to make polyethylene and polypropylene.

Given that approximately 70%[21] of the feedstock used in ethylene steam crackers operating in Europe is naphtha, it is not surprising that pyrolysis has been the focus of chemical recycling technologies for polyethylene and polypropylene resin producers (Petrochemicals Europe, 2022), as it provides an alternative feedstock to fossil-based naphtha, and fits into their existing chemical processes and infrastructure.

[21] 70% of the feedstock used in steam crackers operating in Europe is Naphtha, followed by Propane/Butane 18%, Ethane 4.3% CC4 + others 3.6% and Gas Oil 4.5% (Petrochemicals Europe, 2022).

Proposed Model Bale Specification for Pyrolysis Operations

A recent report commissioned by the Alliance to End Plastic Waste, has proposed a Model Feedstock Specification for pyrolysis operators. The model specification is meant to form a baseline characterization and has been produced based on discussions with pyrolysis operators in Europe and the US (Eunomia, 2022). It forms a useful first step towards a better understanding of the input requirements of pyrolysis operators, especially in the context of the ability of these processes to recycle multi-material flexible plastic packaging.

Interestingly, the study found that to create quality outputs that are suitable for direct integration into the plastics production value chain (i.e. steam crackers), pyrolysis operators require well sorted, clean, and largely homogenous feedstocks. Polyethylene (PE) or polypropylene (PP) levels of at least 85% by weight of a bale are required by pyrolysis operators with a maximum total contamination level of 15%. Individual contaminant thresholds are stated for PVC/PVDC (1%), PET/EVOH/Nylon (5%), polystyrene (7%), metal/glass/dirt/fines (7%), paper/organics (10%), with the combined presence of all contaminants not to exceed 15% (Eunomia, 2022).

From this work it is clear that both mechanical and advanced recyclers require consistent streams of feedstock with minimal contamination. and while pyrolysis should be viewed as a recycling outlet for a different range of materials, it should not be viewed as a recycling outlet for contaminated materials or unsorted materials.

Pyrolysis Feedstock Preparation

With the anticipation of new pyrolysis capacity coming on-line in Europe, EREMA has introduced a new product line called the Chemarema® series to assist their chemical recycling customers in preparing their post-consumer feedstocks for introduction to their pyrolysis reactors.[22]

Using their experience from the development of technology and services for mechanical recycling, the main features of their feedstock preparation unit include:

- The ability to handle materials such as flexible plastic packaging with low bulk densities as low as 50 kg/m^3
- Inertisation by the removal of oxygen
- Removal of moisture of up to 10%
- Ensuring scalability of chemical recycling process by fast and efficient introduction of heat within the material in the shortest time.

The Preconditioning Unit (PCU) is the core of the Chemarema® process for feedstock preparation. Running with Erema's patented Counter Current® technology it provides a wide process window required when dealing with non-homogenous materials and mixed input streams associated with chemical recycling process utilizing pyrolysis. The PCU cuts the input materials to the correct size needed, compacts the fluffed up flexible materials, heats the material up to just below the melt temperature, dries moisture content of up to 10% and buffers and doses the material into the extruder.

Receiving material from the PCU at melt temperature, the single screw extruder can be kept short, robust and efficient. The melted output of the extruder is the hand-off point between the Chemarema® system and the down-stream chemical recycling process, developed and owned by Erema customers.

Please refer to Annex A for a list of pyrolysis operators and planned facilities in Europe.

[22] More information on this technology can be found here.

Case Study: Plastic Energy

Plastic Energy uses a patented, thermal anaerobic conversion (TAC™) technology to convert end-of-life mixed plastics into pyrolysis oil, branded as TACOIL™. TACOIL™ can be used as an alternative feedstock to virgin naphtha to create new plastics. Plastic Energy targets mixed and contaminated post-consumer multi-layered plastics and films that would otherwise be sent to energy from waste or landfill. TACOIL™ produced must comply with two EU Regulations, (EC) 1907/2006 on the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and EC 1272/2008 on the classification, labelling and packaging of substances and mixtures (CLP). TACOIL™ has received “end of waste” status in The Netherlands to be used as a raw material for producing new plastics and is in the process of gaining this status in multiple other European countries.

<u>The Process</u>
Plastic Energy’s feedstock for its process focuses on post-consumer waste including films, multi-layer or multi-material packaging primarily made of LDPE, HDPE, PP and PS. It can handle very low amounts of PET and PVC and other #7 plastic resins. Washing of the waste material is not a pre-treatment requirement. Waste plastics are converted into the liquid hydrocarbon products by extruding and pumping the plastic feed in molten form into reactor vessels. The reactor vessels are externally heated by furnace systems to a temperature in excess of 350 degrees Celsius and without the presence of oxygen. This produces rich saturated hydrocarbon vapour from the molten plastic. This flows out of the reactor vessels through contactor vessels and will condense the heavier vapour fractions to maintain a target outlet temperature set point which is determined by the end-product specification. This is then distilled at near-atmospheric pressures in a downstream atmospheric distillation column. The TAC™ process yield is approximately 73%-75% pyrolysis oil, 18% syngas, and 8-10% char. The syngas produced in the reactor is used to power the facility and the char is sold to the construction industry[23].

<u>Operational Plants and Future Plants in Europe</u>
Plastic Energy’s has two commercial plants in Spain each with capacities of 5,000 tonnes/year. Since April 2020, 100% of the recycled TACOIL™ produced at these plants are solely used to make new plastics (Plastic Energy, 2020). Plastic Energy has offtake agreements with TotalEnergies, SABIC, and ExxonMobil for the use of the TACOIL™ in their European steam crackers that produce ethylene and propylene. In September 2020, TotalEnergies and Plastic Energy announced a joint venture to build a plastic waste conversion facility with a capacity of 15,000 tonnes per year at the TotalEnergies Grandpuits zero-crude platform in France. The project is expected to be operational in 2023.

In 2021 Plastic Energy announced the start of construction for its advanced recycling plant in northern France. This plant has an initial capacity of 25,000 tonnes of plastic waste per annum, with plans to scale-up to 33,000 tonnes. The plant will be located adjacent to ExxonMobil’s Notre Dame de Gravenchon petrochemical complex. Plastic Energy signed an offtake collaboration agreement with ExxonMobil. As per the agreement, TACOIL™ from this Plastic Energy plant will be used by ExxonMobil to create virgin-quality certified circular polymers and other high-value products. Start-up of the advanced recycling plant is anticipated in 2023.

Plastic Energy is currently in the process of building a new facility in Geleen, The Netherlands through its joint venture with SABIC -called SABIC Plastic Energy Advanced Recycling B.V. or SPEAR B.V. The plant will have an annual processing capacity of 20,000 tonnes and will process difficult to recycle mixed, multi-layered and low-density materials. It is expected to be operational by 2023. In June 2022, Avfalfonds Verpakkingen and Nedvang entered into an agreement with SPEAR to supply flexible plastic packaging from post-separated residual waste and is in talks with various market actors who can pre-treat the material prior to delivery to SPEAR.[24]

Plastic Energy plans to build a second advanced recycling plant in Sevilla, Spain, in addition to their existing operational plant. The plant will process and convert 33,000 tonnes of post-consumer end-of-life plastic waste yearly, that would otherwise be destined for landfill or incineration. TotalEnergies will convert this raw material into virgin-quality polymers, which can be used for food-grade packaging. The TACOIL™ produced at this facility will be used for the manufacturing of high-quality polymers in TotalEnergies’ European-based production units, following a successful processing experimentation in TotalEnergies’ petrochemical platform in Antwerp.

<u>Licensing</u>
Plastic Energy’s advanced recycling technology is being licensed by Axens. Axens will provide its customers with associated services that includes basic engineering, supply of proprietary equipment, and technical assistance for start-up and operation of the plant, leveraging the expertise of Plastic Energy at each step.

4.2 Future Integration of Mechanical and Chemical Recycling Technologies

In August 2022, Circular Resources, the parent company of Plastic Energy purchased Duales System Deutschland Group (DSD), including the affiliated companies Der Grüne Punkt – Duales System Deutschland GmbH and Systec Plastics GmbH. The acquisition of DSD has been characterized as enabling the creation of the industry's first integrated mechanical and chemical recycling solution for plastic packaging waste. The agreement is expected to unlock further synergies between the mechanical and chemical recycling of plastic waste in Europe, enabling plastics currently lost from the value chain to be returned to the recycling loop. The merger ultimately will create a large-scale provider of recycling solutions in Europe with an assured, stable and high-quality inflow of raw materials for recycling.

4.3 The Importance of Mass Balance Accounting in Chemical Recycling

Proponents of chemical recycling argue that "mass balance method" provides a workable set of rules to ensure the traceability of recycled feedstock into new products. Mass balance is a Chain of Custody (CoC) system that is being increasingly used to verify plastic recycled content, especially for processes that rely on chemical recycling. Because thermal depolymerization chemical recycling processes need to tap into the existing chemical production process infrastructure (i.e. steam crackers or gasification plants), recycled feedstock will not exist in physically separate flows from other raw materials, with all materials needing to be blended in the chemical manufacturing complex. This means it is not possible to physically track where a recycled feedstock ends up (Ellen MacArthur Foundation 2020).

Co-feeding both recycled and virgin feedstock into the same network of chemical production plants offers a pragmatic way to enable the chemical industry to transition towards a circular economy. By feeding into existing and continuously running steam crackers or synthesis gas plants, the full scope of the plastic value chain can be accessed, and the same end products can be manufactured with the same quality level with minimal upfront investment (Ellen MacArthur Foundation, 2020).[25]

Chemical Recycling Europe has identified various interpretations of the mass-balance approach reflecting different accounting methodologies to value recycled content from chemical recycling processes, especially in the context of determining what might count towards recycling targets, both in terms of recycled content in packaging targets or recycling targets in the Waste Framework Directive or Packaging and Packaging Waste Regulation.

These include "free-attribution", "fuel-exempt", and "polymer-only" allocation methods (Chemical Recycling Europe, 2022). Similarly, Eunomia presented common allocation approaches when considering how to measure recycled content from chemical recycling processes that produce multiple co-products. These included the "proportional", "polymers only", "fuel-use excluded", "auto-consumption excluded" and "free" allocation approaches (European Commission DG ENV and Eunomia, 2022).

- With "proportional allocation", recycled content allocation can only be based on what is theoretically present in the output fraction.
- With "polymers only", only outputs directly linked to the production of polymers can be freely allocated.
- With "fuel use excluded", materials used as fuel in the recycling process and co-products that are used as fuels are excluded, with the remaining material being freely allocated.

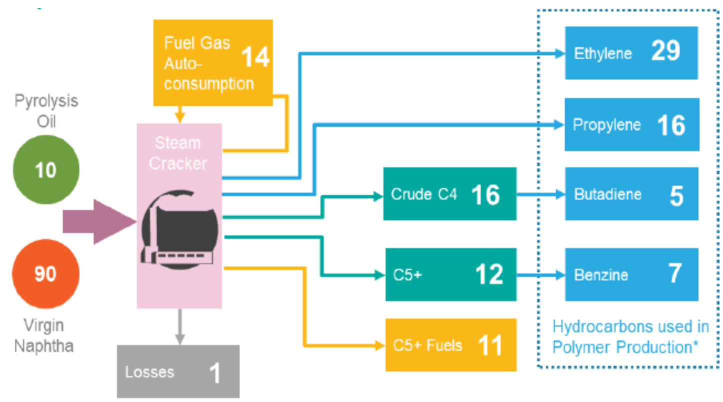
[23] Plastic Energy – Chemical Recycling in Practice - https://www.basf.com/global/documents/en/sustainability/we-drive-sustainable-solutions/circular-economy/chemcycling/Plastic%20Energy_BASF%20Dialog%20Forum.pdf

[24] https://www.afvalfondsverpakkingen.nl/nl/actueel/persbericht-reactie-stichting-afvalfonds-verpakkingen-en-nedvang-werken-samen-om

[25] This does not include the costs of producing the pyrolysis oil or recycled feedstock, but refers to the existing infrastructure to produce ethylene using alternative feedstocks to fossil naphtha.

- With “auto-consumption excluded”, only materials that are used as fuel in the recycling process are excluded, with free allocation for the remaining material including any fuels.
- And finally, with “free allocation”, all outputs (including process fuel), with the exception of system losses, can be freely allocated.

By way of example, the figure below provides an illustration of the impact of applying the different allocation methods when accounting for recycled content in products and co-products produced at a steam cracker that is utilizing both pyrolysis oil from a chemical recycling plant and virgin naphtha as input material. The products and co-products produced at European steam crackers include ethylene, propylene, butadiene, benzine and fuels. In this particular example, 25% of the output is used in fuel applications (including 14% to run the cracking process i.e. process fuel). The example mass balance calculation shows the process from most strict (A) – “proportional allocation” where allocation takes place equally across all products and process loses are taken into account, to least strict (E) “free allocation” where free allocation is applied minus losses (European Commission DG ENV and Eunomia, 2022). As can be seen from the Mass Balance Conversion Factors for each allocation method, the calculated efficiencies of the process change considerably with the choice of allocation method used with efficiency rates that range from 29% to 99%, (i.e. conversion factors of .29 to .99).



	A	B	C	D	E
Allocated Recycled Ethylene (losses)	2.9 (71%)	5.7 (45%)	7.4 (27%)	8.6 (15%)	9.9 (1%)
Virgin Ethylene	26.3	23.5	21.9	20.7	19.3
Mass Balance Conversion Factor	0.29	0.55	0.73	0.85	0.99
Recycled Input Required to Meet 25% RC Output	85%	44%	34%	29%	25%

A Proportional
B Polymers Only
C Fuel Use Excluded
D Auto-consumption Excluded
E Free

*Examples of typical output hydrocarbons that are commonly (but not always exclusively) used in polymer production. Benzene can be used as a precursor to styrene used in polystyrene and butadiene is commonly used in various types of rubber.

Figure 8: Impact of various Allocation Methods on Conversion Factors of Chemical Recycling
Source: European Commission DG ENV and Eunomia, 2022

Under the ISCC Plus standard for recycled and bio-based materials, the ‘free allocation’ minus system losses is the predominant method used to allocate recyclable material inputs to product outputs. The ISCC Plus standard has been widely adopted by pyrolysis chemical recyclers and resin producers to certify the recycled content being generated from the processing of pyrolysis oils in steam ethylene steam crackers. As the free allocation method provides for the highest allocation of input materials to output recycled content, it is not surprising that the chemical industry prefers the free allocation method to quantify recycled content in packaging and the attainment of recycling targets.

The allocation method used is also particularly important in the context of any potential EU recycled content targets for specific products and packaging, as well as for measuring adherence to recycling targets in EPR schemes for packaging. Eunomia notes that would be problematic to adopt the 'free allocation' and 'auto-consumption excluded' methods due to the required compliance with the recycling definition in the Waste Framework Directive (WFD) Art 3(17) that does not include energy recovery and the reprocessing of waste into materials that are to be used as fuels. This restriction means that plastic waste that will be used as a fuel is not considered recycling and cannot contribute to recycling targets under the WFD. This has also been confirmed in the proposal for a Regulation on Packaging and Packaging Waste (PPWR)[26], specifically in Art 47 (9) which states that:

"*The amount of packaging waste materials that have ceased to be waste as a result of a preparatory operation before being reprocessed may be counted as recycled provided that such materials are destined for subsequent reprocessing into products, materials or substances to be used for the original or other purposes. However, end-of-waste materials to be used as fuels or other means to generate energy, or to be incinerated, backfilled or landfilled, shall not be counted as recycled*".

This will likely mean that any future measurement of recycled content and evidence of recycling would be limited to the use of the 'fuel use excluded', 'polymers only', or the 'proportional' allocation method', and this will impact the overall contribution to recycling targets that thermal depolymerization technologies such as pyrolysis can achieve.

While industry had initially advocated for the 'free allocation' method to be used when calculating recycled content and achievement of recycling targets, both Plastics Europe and Cefic[28] have confirmed that the use of the 'fuel use exempt' method is an acceptable approach as a way forward for how the recycled content can be assigned to the outcome products. Ultimately, the choice of allocation method and which aspects will contribute towards either recycled content requirements or calculating recycling performance will be decided through implementing or delegated acts of the European Union.

Case Study: Flexible Plastic Packaging using ISCC Plus Certified Polymers

There are a number of examples of new packaging applications that have been developed using resins from chemically recycled plastics waste certified under the [ISCC Plus system.](#) For example, in 2019 Unilever's Magnum® brand introduced over 600,000 ice cream tubs made from certified circular PP from [SABIC's TRUCIRCLE™](#) brand using TACOIL™ from Plastic Energy. In 2020, this was rolled out to over 7 million tubs across Europe which launched the world's first ice cream tub made from recycled content (using the mass balance approach). SABIC's certified circular materials are made to the same high specifications and properties as virgin products and are an easy drop-in solution to current production and converting processes.

Another example of use of TACOIL™ to produce certified recycled content using the mass balance approach is the collaborative project of Sealed Air, in partnership with Tesco, Plastic Energy, SABIC[27], and Bradburys Cheese. In this partnership, Tesco collected flexible plastic packaging from households at its stores across the UK and sent it to Plastic Energy, which converted it into TACOIL™ at its pyrolysis plant. The recycled pyrolysis oil was used by SABIC as an alternative to traditional fossil fuel to make new plastic pellets that are safe for food packaging (through a mass balance approach). Sealed Air uses the new resin pellets to create new packaging film with the same performance and food-grade characteristics as virgin plastic. An illustrative video of the project can be found [here.](#)

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[26] COM (2022) 677 final. Proposal for a Regulation of the European Parliament and the Council on packaging and packaging waste (amending Regulation (EU) 2019/1020 and Directive (EU) 2019/904 and repealing Directive 94/62/EC.

[27] Source: SABIC

[28] European Chemical Industry Council cefic.org

Publicly Available Life Cycle Assessments (LCAs)

Table 7 presents a list of publicly available Life Cycle Assessments that can demonstrate the evaluation process for pyrolysis using a case study approach.

Table 7: List of Publicly Available Life Cycle Assessments

Commissioning Company	Practitioner	Title	Year	Link
BASF	Sphera Solutions GmbH	Evaluation of pyrolysis with LCA –3 case studies	2020	Download
Consumer Goods Forum	Sphera Solutions GmbH	Life Cycle Assessment of Chemical Recycling for Food Grade Film	2022	Download

Solvent-Based Purification/Dissolution Technologies

Purification/dissolution is a physical process that involves dissolving plastic in a solvent, then separating and purifying the mixture to extract additives and dyes to ultimately obtain a “purified” plastic. The purification process does not change the polymer on a molecular level. In many cases the solvent is recovered through evaporation and subsequent distillation. The following case study presents an overview of how this technology has been implemented by APK n Germany.

Case Study: Purification technology implemented through APK - NewCycling®

Founded in 2008, APK is a German-based mechanical and physical recycler that recovers virgin-quality like polymers from mixed plastic waste using its patented NewCycling® solvent-based recycling technology. Original investors in APK include venture capital firms MIG Fonds, Athos KG and more recently Salvia. In 2018, APK and Mol-Group, a Hungarian petrochemicals company, formed a strategic partnership to further develop the Newcycling® technology and bring it to eastern Europe. APK’s advanced physical, solvent-based recycling technology is able to separate individual polymer types with results that outperform processes based on mechanical recycling alone. At its first pre-commercial scale plant in Merseburg, Germany, the initial focus has been on been on post-industrial LDPE/PA multilayer packaging, but the process can also handle PE/PP, PE/PET and other multi-laminate plastic packaging formats.

Since 2019, APK has operated a fully scaled-up NewCycling® plant with a capacity of 8,000 metric tons of post-industrial waste per year. The NewCycling® processing line operates in the same facility as APK’s mechanical recycling line that has capacity to process 12,000 tonnes/year of post-consumer LDPE films collected from households in Germany. APK currently produces commercially available LDPE and PA polymer grades marketed as Mersalen ® LDPE NCY and Mersamid ® PA-6 NCY. Mersalen ® LDPE NCY is suitable for use in various flexible plastic applications including films, labels/stickers and stand-up pouches. Mersamid ® PA-6 NCY, can be used in applications such as injection molding (with or without fiberglass reinforcement) or extrusion.

At the end of 2021, APK announced that it successfully implemented an industrial scale pilot to recycle post-consumer film collected from households using its NewCycling® process. During the first phase of the campaign APK reported problem-free processing, yield and mechanical values of the recyclate. In June 2022, APK AG reached an agreement to purchase the Clariant’s research and development unit in Frankfurt, Germany. The highly experienced research team at the Frankfurt site forms an essential pillar of the company’s success. Although APK is currently capable of producing transparent films from household plastic waste, further refinement steps will be implemented in the newly acquired pilot plant, with the aim of producing market-ready recycled products from other types of plastics, e.g. polypropylene or PVC. This will also ease the burden on the production facility at APK headquarters in Merseburg, Germany, so that series production there can run at full capacity to meet the high demand. In collaboration with MOL Group, planning is underway for the construction of additional plants employing the NewCycling™ patented process for recycling post-consumer flexible plastic packaging waste.

More information: APK AG website

Annex A List of Pyrolysis Facilities in Europe

Company	Type	Technology	Country	Outputs
BlueAlp	Technology Provider - Patent	Pyrolysis	Netherlands	Pyrolysis oil
Renasci	Operator	Pyrolysis	Belgium	Pyrolysis oil
LyondellBasell - MoReTec	Chemical/Polymer Company	Pyrolysis -	Italy	Pyrolysis oil
LyondellBasell - MoReTec	Chemical/Polymer Company	Pyrolysis -	Germany	Pyrolysis oil
TotalEnergies/Plastic Energy	JV	Pyrolysis	France	Tacoil
Plastic Energy	Technology Provider - Patent	Pyrolysis	France	Tacoil
Plastic Energy	Technology Provider - Patent	Pyrolysis	Spain	Tacoil
Plastic Energy	Technology Provider - Patent	Pyrolysis	Spain	Tacoil
Plastic Energy	Technology Provider - Patent	Pyrolysis	Spain	Tacoil
Sabic/Plastic Energy	Chemical/Polymer Company	Pyrolysis	Netherlands	Tacoil
Mura	Technology Provider	HydroPRS - pyrolysis	UK	Naptha, Distillate Gas Oil, Heavy Gas Oil, Heavy Wax Residue
DOW/Mura	JV	HydroPRS - pyrolysis	Germany	Naptha, Distillate Gas Oil, Heavy Gas Oil, Heavy Wax Residue
ReNew ELP	Operator	Pyrolysis	UK	Naptha, Distillate Gas Oil, Heavy Gas Oil, Heavy Wax Residue
Ravago/Neste	Technology Provider	Pyrolysis	Netherlands	Pyrolysis oil
Clariter	Technology Provider	Pyrolysis	Netherlands	Solvents, Waxes, Oils
Recycling Technologies	Technology Provider	Pyrolysis	Scotland	Plaxx
Recycling Technologies	Technology Provider	Pyrolysis	England	Plaxx
Quanta Fuel	Technology Provider	Pyrolysis - catalytic	Denmark	Pyrolysis oil
Quanta Fuel	Technology Provider	Pyrolysis - catalytic	Denmark	Pyrolysis oil
Quanta Fuel	Technology Provider	Pyrolysis - catalytic	Norway	Pyrolysis oil
Quanta Fuel	Technology Provider	Pyrolysis - catalytic	UK	Pyrolysis oil
OMV	Chemical and Energy	Pyrolysis	Austria	ReOil®
OMV	Chemical and Energy	Pyrolysis	Austria	ReOil®
Pryme	Technology Provider	Pyrolysis - catalytic	Netherlands	Pyrolysis oil
Indaver	Waste Management	Pyrolysis	Belgium	Pyrolysis oil
ARCUS Greencycling Technologies GmbH	Technology Provider	Pyrolysis	Gernamy	Pyrolysis oil
Honeywell - Upcycle Process	Technology Provider	Pyrolysis	Spain	Pyrolysis oil
Enval	Technology Provider	Pyrolysis -microwave	UK	Pyrolysis oil
Fuenix Ecology Group	Technology Provider	Pyrolysis	Netherlands	Pyrolysis oil

References Cited

Bashirgonbadi, A.; Saputra Lase, I.; Delva, L.; Van Geem, K. M.; De Meester, S.; Ragaert, K. (2022). Quality Evaluation and Economic Assessment of an Improved Mechanical Recycling Process for Post-Consumer Flexible Plastics. Waste management (Elmsford) 2022, 153, 41–51. https://doi.org/10.1016/j.wasman.2022.08.018 .

CEFLEX. (2021 a). Position Statement: Collection Systems for Flexible Packaging in a Circular Economy.

CEFLEX. (2021 b). A Quality Recycling Process for Household Flexible Plastic Waste – A new approach to an emerging market demand. Retrieved December 1, 2022, from https://youtu.be/NPWCDxMtP70 .

CEFLEX. (2020). Designing for a Circular Economy – Recyclability of polyolefin-based flexible packaging. Technical Report. June 2020.

CEFLEX. (2022). CEFLEX scope based on EU market (2019 data) https://ceflex.eu/flexible-packaging-in-europe/

Ellen MacArthur Foundation. (2020). Enabling a circular economy for chemicals with the mass balance approach – White Paper.

Eunomia (2020). Chemical Recycling State of Play. Report for CHEM Trust. December 8, 2020.

Eunomia (2022). Feedstock Quality Guidelines for Pyrolysis of Plastic Waste – Report for the Alliance to End Plastic Waste. August 2022. Available online

European Commission DG ENV and Eunomia (2022). Study to develop options for rules on recycled plastic content for the implementing act related to single-use plastic bottles under Directive (EU) 2019/904. Available online

Faraca G, Astrup T. Plastic waste from recycling centres: Characterisation and evaluation of plastic recyclability. Waste Manag. 2019 Jul 15;95:388-398. doi: 10.1016/j.wasman.2019.06.038. Epub 2019 Jun 25. PMID: 31351625.

Horodytska, O.; Valdés, F. J.; Fullana, A. Plastic Flexible Films Waste Management – A State of Art Review. (2018). Waste management (Elmsford) 2018, 77, 413–425. https://doi.org/10.1016/j.wasman.2018.04.023.

Institute cyclos-HTP., (2021). Verification and examination of recyclability. Requirements and assessment catalogue of the Institute cyclos-HTP for EU-wide certification (CHI-Standard). Available [online].

Kampmann, C,. (2022). Innovative Sorting in Eitting – Europe's most modern sorting plant for lightweight packaging. Presentation at the EPRD webinar on Advances in the collection and sorting of flexible packaging. Retrieved December 10, 2022 from https://drive.google.com/file/d/1r35jJdsZYgVAV1xLIU593DllByTXiPsl/view?usp=sharing

KIDV. (2020). Roadmap – Multi-layer flexible plastic packaging in a circular economy. Netherlands Institute for Sustainable Packaging (KIDV). August. 2020.

Kol, R. et al., 2021, 'Recent Advances in Pre-Treatment of Plastic Packaging Waste', in D. S. Achilias (ed.), Waste Material Recycling in the Circular Economy - Challenges and Developments, IntechOpen, London. 10.5772/intechopen.99385.

Lase, I.S., van Rhijn, F., Dewulf, J., Ragaert, K., Delva, L., Rossen, M., Brandsma, M., Langen, M., De Meester, S. (2022). Material flow analysis and recycling performance of an improved mechanical recycling process for post-consumer flexible plastics. Waste Management, 153 (2022)249-263.

Petrochemicals Europe. (2022). European Market Overview – Cracker Feedstocks in the EU 15 + Norway as of 2020. Retrieved December 1, 2022, from https://www.petrochemistry.eu/about-petrochemistry/petrochemicals-facts-and-figures/european-market-overview/ .

Plastics Europe. (2022). The Circular Economy for Plastics – A European Overview. Available [online] https://plasticseurope.org/wp-content/uploads/2022/06/PlasticsEurope-CircularityReport-2022_2804-Light.pdf

Ragaert, K.; Delva, L.; Van Geem, K. Mechanical and Chemical Recycling of Solid Plastic Waste. Waste management (Elmsford) 2017, 69, 24–58. https://doi.org/10.1016/j.wasman.2017.07.044.