TEXTE
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publisher:
German Environmental Agency

German Environmental Agency

Umwelt Bundesamt

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REFOPLAN of the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection

Project No. (FKZ) 3719 34 309 0
Report No. (UBA-FB) FB001378/ENG

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On behalf of the German Environment Agency

Imprint

Publisher
Umweltbundesamt
Wörlitzer Platz 1
06844 Dessau-Roßlau
Tel: +49 340-2103-0
Fax: +49 340-2103-2285
buergerservice@uba.de
Internet: www.umweltbundesamt.de

Report performed by:
Ramboll Germany GmbH
Werinherstrasse 79
81541 Munich

Report completed in:
November 2023

Edited by:
Subject area III 1.2 Product responsibility - electrical appliances, vehicles and batteries
Christian Kitazume

Publication as pdf:
http://www.umweltbundesamt.de/publikationen

ISSN 1862-4804

Dessau-Roßlau, February 2024

Abstract: Enhancing the recycling of technical plastics in the view of increasing substance legislation requirements using the example of waste electrical and electronic equipment (WEEE) and end-of-life vehicles (ELVs)

The present report addresses the question of how the recycling of technical plastics from WEEE and ELVs can be sustainably strengthened. The importance of the topic is reflected in the objectives of the European policy to strengthen the recycling of plastic waste, the increasingly complex variety of products and the increased generation of corresponding waste and the associated environmental impacts. Although there is a considerable potential for the recycling of corresponding plastics in Germany, the status is deficient and targeted measures are needed to develop appropriate capacities.

The report provides a comprehensive status quo analysis on the legal framework, material requirements, a description of the most relevant types of plastics as well as interfering and polluting substances during recycling, a detailed account of the use of plastics in electrical and electronic equipment as well as in vehicles, and a detailed description of the existing process chains for the treatment of plastics from the two waste streams. In addition, lab-scale experiments were carried out in which promising approaches were tested.

Against this background, separation and recycling strategies were derived and measures and recommendations for action were developed for political as well as economic actors. The strategies and measures follow the overriding objective of promoting environmentally sound mechanical plastics recycling from WEEE and ELVs in Germany.

Kurzbeschreibung: KUREA

Der vorliegende Bericht widmet sich der Fragestellung, wie sich das Recycling technischer Kunststoffe aus Elektroaltgeräten und Altfahrzeugen nachhaltig stärken lässt. Die Bedeutsamkeit der Thematik spiegelt sich in den Zielen der Europäischen Politik zur Stärkung des Recyclings von Kunststoffabfällen, der komplexer werdenden Produktvielfalt und nicht zuletzt dem erhöhten Aufkommen entsprechender Abfälle und damit verbundenen Umweltauswirkungen wider. Obwohl für das Recycling entsprechender Kunststoffe in Deutschland ein erhebliches Potential besteht, ist der Status als mangelhaft anzusehen und es Bedarf gezielter Maßnahmen, um flächendeckende Kapazitäten zu entwickeln.

Der Bericht enthält einen umfassenden Sachstand zu den rechtlichen Rahmenbedingungen, Materialanforderungen, eine Beschreibung der relevantesten Kunststofftypen sowie von Stör- und Schadstoffen beim Recycling, eine detaillierte Darstellung des Kunststoffeinsatzes in Elektro- und Elektronikgeräten sowie Fahrzeugen sowie eine detaillierte Beschreibung der existierenden Prozessketten für die Behandlung von Kunststoffen aus den beiden Abfallströmen. Zudem wurden praktische Versuche durchgeführt, in denen bisher wenig beachtete und zugleich vielversprechende Ansätze getestet wurden.

Auf dieser Grundlage wurden Separations- und Recyclingstrategien abgeleitet sowie Maßnahmen und Handlungsempfehlungen für politische wie auch wirtschaftliche Akteure entwickelt. Die Strategien und Maßnahmen folgen dem übergeordneten Ziel, ökologisch sinnvolles werkstoffliches Kunststoffrecycling aus Elektroaltgeräten und Altfahrzeugen in Deutschland voranzubringen.

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List of abbreviations & terminology

Term	Description
2K, 3K, 4K composites	2-component, 3-component, 4-component composites
ABS	Acrylonitrile butadiene styrene
AltfahrzeugV	German End-of-life Vehicles Ordinance
APPLiA	European Association of Domestic Appliance Manufacturers
ASA	Acrylonitrile-styrene-acrylate copolymers
BDE	Brominated diphenyl ethers
BMU	German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMUV	German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
BPA	Bisphenol A
Br-	Bromine-free and low-bromine
BTBPE	1,2-Bis(2,4,6-tribromophenoxyl)ethane
BTEX	Aromatic hydrocarbons benzene, toluene, ethylbenzene and xylenes
Cd	Cadmium
CFRP	Carbon fiber reinforced plastic (also carbon fiber reinforced plastic)
CG	Collection group according to ElektroG
ChemG	Hazardous Substances Protection Act
CLP	Classification, Labelling and Packaging
CP	Chlorinated paraffins
CRT	Cathode-ray tube
DBDPE	Decabromodiphenylethane
DecaBDE	Decabromodiphenyl ether
DEHP	Di-ethylhexyl phthalate
DP	Dechloran Plus
EAG-BehandV	German Waste Electrical and Electronic Equipment Treatment Ordinance
EBA	Primary treatment facility for waste electrical and electronic equipment (German: Erstbehandlungsanlage)
EC CLP Regulation	Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures; and

Term	Description
EC ELV-Directive	Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles
EC REACH Regulation	Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals
EC Waste Framework Directive	Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives
ECHA	European Chemicals Agency
EEE	Electrical and Electronic Equipment
ElektroG	German Electrical and Electronic Equipment Act
ElektroStoffV	German Electrical and Electronic Equipment Substances Ordinance
ELV	End-of-Life Vehicle
EPDM	Ethylene-propylene-diene, M-group (M-group=saturated main chain)
EPS	Expanded polystyrene
EU POP Regulation	Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants.
EU RoHS Directive	Directive 2011/65/EU of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in EEE
EU WEEE Directive	Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment
EVOH	Ethylene-vinyl alcohol copolymer
Fe	Iron
HBCDD	1,2,5,6,9,10-Hexabromocyclododecane
HF	Heavy fraction
HIPS	High-impact polystyrene
IDIS	International Dismantling Information System
IRK	Infrared Rotary Kiln
IT	Information technology
KrWG	German Circular Economy Act
kt	Kilotonnes (1 kt corresponds to 1000 tonnes)
LAGA	German Federal /Länder Working Group on Waste
LCD	Liquid crystal display
LED	Light-emitting diode
LF	Light fraction

Term	Description
LIBS	Laser-induced breakdown spectroscopy (laser-induced plasma spectroscopy)
MCCP	Medium-chain chlorinated paraffin
MOHs	Mineral oil hydrocarbons
NEF	Non-ferrous
NIR sorting	Near infrared: Sorting according to plastic type-specific reflection spectrum in the near infrared range
PA	Polyamide
PAH	Polycyclic Aromatic Hydrocarbon
Pb	Lead
PBDE	Polybrominated diphenyl ethers
PBT	Polybutylene terephthalate
PC	Polycarbonate
PCB	Printed circuit boards
PCR	Post-consumer recycling
PC-RCR	Post Consumer recycled content ratio
PE	Polyethylene
PE-HD	Polyethylene - High Density
PE-LD	Polyethylene - Low Density
PET	Polyethylene terephthalate
PFAS	Per- and polyfluorinated alkyl substances
PFOA	Perfluorooctanoic acid
PFOS	Perfluorooctane sulfonic acid
PMMA	Polymethyl methacrylate
POM	Polyoxymethylene
POP	Persistent Organic Pollutant
POP Waste Ordinance	Ordinance on the Separate Collection and Monitoring of Non-hazardous Waste Containing Persistent Organic Pollutants
PP	Polypropylene
PP+talc	Polypropylene additivated with talcum powder
PPO	Polyphenylene oxide
PS	Polystyrene

Term	Description
PST	Post-shredder technology
PU, PUR	Polyurethane
PVC	Polyvinyl chloride
SAN	Styrene acrylonitrile
SCCP	Short-chain chlorinated paraffin
SCIP database	Database for information on Substances of Concern In articles as such or in complex objects (Products)
SHF	Shredder heavy fraction
SIN	Substitute it Now
SLF	Shredder light fraction
SME	Small and medium-sized enterprises
SVHC	Substances of very high concern
t	Tons
TA Luft	Technical Instructions on Air Quality Control
TBBPA	Tetrabromobisphenol A
TCEP	Tris(2-chloroethyl)phosphate
UBA	Federal Environmental Agency Germany (German: Umweltbundesamt)
UV	Ultraviolet radiation
VOC	Volatile organic compound
WEEE	Waste electrical and electronic equipment
WEEE	Waste Electrical and Electronic Equipment
XPS	Extruded polystyrene
XRT sorting	X-ray transmission sorting (by material density)

1 Introduction

Background

The global, as well as the European, demand for plastics has increased significantly over the past decades, leading to a significant growth in both the quantities of plastics produced and the resulting plastic waste. In 2018, the global production of plastics is estimated at 359 million tonnes, of which nearly 62 million tonnes were produced in the EU28 (including Norway and Switzerland) (PlasticsEurope, 2019a, pp. 14-15). Alongside Asia and the NAFTA region (Canada, USA, Mexico), the EU is one of the three largest producers of plastics. Taking into account exports and imports, consumption in the EU28 was approximately 51 million tonnes in 2018. Most plastics were used for packaging with 39.9 % of the consumed quantity and in the construction sector with 19.8 %. In third and fourth place were vehicles with 9.9 % and electrical and electronic equipment (EEE) with 6.2 % of the amount consumed, respectively (PlasticsEurope, 2019a, pp. 19, 23). Due to the different applications and lifetimes of plastic components and products, this resulted in a generation of approximately 29 million tonnes of plastic waste for the EU28 in 2018 (PlasticsEurope, 2019a, p. 28). Again, plastic waste from packaging accounts for the largest share (over 50 %), followed by plastic waste from waste electrical equipment (WEEE), and - among other material flows - also from end-of-life vehicles (ELVs).

The EU Commission has recognised the importance of this material stream and in 2018 presented an EU plastics strategy to shape the way plastics are produced, used, and recycled. The long-term goal is to reduce plastic waste and strengthen recycling and reuse (European Commission, 2018). The automotive sector as well as the electrical and electronics industry are explicitly mentioned as important areas of application for plastics, whose waste also represents a significant source for plastics recycling. At present, a large part of the plastic waste from WEEE and ELVs is still recovered as energy with recycling potentials not fully exploited. The recycling of plastics from WEEE is ecologically advantageous, as it causes only a quarter of the greenhouse gas potential compared to energy recovery and the production of new material. Therefore, mechanical recycling of plastics from WEEE and ELVs would be a preferred recovery option. However, positive effects can only be achieved if the recyclates produced are of high quality, are returned to the market in sufficient quantities and their quality is adequate for the different areas of application. Pollutants that can be carried over to the recycled plastics must be taken into account here.

The European WEEE Directive sets recycling and recovery targets for WEEE, but not for the plastics it contains. Only the removal of plastics containing brominated flame retardants is prescribed. A significant change is the German Ordinance on Requirements for the Treatment of Waste Electrical and Electronic Equipment (EAG-BehandV), in force since January 2022. The ordinance expands and specifies the German Transposition of the EU WEEE Directive with regard to the removal of pollutants and the conservation of resources.

Recommendations by the German Environment Agency for specific mechanical recycling rates indicate that there is as yet untapped potential with regard to plastics recycling (Moser et al., 2016). This can also be deduced from the collection rate of WEEE. In recent years, Germany has collected less than half of the WEEE placed on the market, so that a significant proportion has remained unused (Löhle et al., 2020).

The same applies to the automotive sector. The volume of ELVs in Germany results in a large potential of installed and recyclable plastics of which only a fraction has been dismantled for reuse or recycling. Although there are general recycling quotas for the reuse of large plastic parts (e.g. bumpers or hubcaps), there are no specific quotas for plastic recycling. Reasons for the unused recycling potential of mechanically recyclable plastics include technical challenges in automated separability, technical impurities or pollutants contained in plastics, and a lack of sales markets for recyclates.

Objective

The aim of the research project is to develop coherent and consistent recycling strategies, specifically separation and processing strategies. The focus is on plastics from WEEE and ELVs that are mechanically recyclable and on the improvement of material plastics recycling. This includes the following steps:

- Demonstrating appropriate shredding and sorting techniques;
- Identifying optimal separation locations for mechanically recyclable and non-mechanically recyclable plastics;
- Demonstrating suitable technical optimisations of the treatment/recycling processes and the necessary information flows; and
- Identifying adjustments to the legal framework to enable and promote the adaptation of recycling processes in practice to implement the recycling strategy.

In order to define the project objectives, the terms "plastic" and "mechanically recyclable" must be explained in more detail. The differentiation between mechanical and non-mechanical recycling is a purely technical distinction. Mechanical recycling includes mechanical and thermoplastic processing methods that preserve the chemical structure of the plastic. In this sense, plastics are a homogeneous mixture that cannot be separated mechanically. Consequently, they must be fed into recycling in sorted form.

"mechanically non-recyclable plastics" are in contrast:

- Plastics that are not suitable for a common processing method either due to the properties of the polymer or due to the additives and additives they contain;
- Plastics that contain pollutants and thus may not be processed for legal reasons or their recyclates may not be used in products; and
- Mixtures and composites of (partially) mechanically recyclable plastics (and other materials) that cannot be processed by a common sorting or processing method to produce pure plastics for mechanical recycling, which are appropriate to replace primary plastics.

This study was prepared in the period from 2019 to 2022. Various calculations are based on data that were available as current data during that period. In order to present the current situation in 2022, more up-to-date data was added at various points. However, this has not fundamentally changed the basic situation and the derived statements.

2 Current status regarding the use of plastics from WEEE and ELVs in Germany

2.1 Overview of the legal framework

The legal framework for the separation and recycling of plastics from WEEE and ELVs comprises a large number of relevant legal texts and can be structured into three areas: Overarching legal framework, regulations for specific product waste, chemicals law.

Overarching legal framework:

- **EC Waste Framework Directive -** Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives
- **German Circular Economy Act (KrWG)** - Act to Promote Closed Substance Cycle Waste Management and to Ensure Environmentally Sound Waste Management

The central body of European waste legislation is the EC Waste Framework Directive. It establishes definitions such as waste, recovery and disposal and sets out essential requirements for waste management. In addition, it establishes key principles such as the obligation of proper waste treatment to protect the environment and human health. The use of high-quality waste recovery methods is promoted; and the waste hierarchy is introduced. The KrWG transposes the EC Waste Framework Directive into German law. There, the obligations of producers and holders of waste as well as other actors such as public waste management authorities and producers are defined in principle.

Regulation for specific product waste:

- **EC End-of-Life Vehicles Directive (EC ELV-Directive)** - Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles;
- **End-of-Life Vehicles Ordinance (AltfahrzeugV)** - Ordinance on the transfer, return and environmentally sound disposal of end-of-life vehicles;
- **EU WEEE Directive** - Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment;
- **Electrical and Electronic Equipment Act (ElektroG)** - Act on the placing on the market, the taking back and the environmentally sound disposal of EEE;
  - Ordinance on requirements for the treatment of WEEE Waste Electrical and Electronic Equipment Treatment Ordinance (**EAG-BehandV**); valid from 1 January 2022;
- **EU RoHS Directive -** Directive 2011/65/EU of the European Parliament and of the Council on the restriction of the use of certain hazardous substances in EEE; and
- **Electrical and Electronic Equipment Substances Ordinance (ElektroStoffV)** - Ordinance on the restriction of the use of hazardous substances in EEE.

The listed regulations represent EU regulations and their national implementations that are decisive for the proper management of the waste streams of ELVs and WEEE and in particular their recycling or other recovery. The EU WEEE Directive, for example, specifies requirements for the separate collection of WEEE and at the same time sets collection quotas to be achieved.

In addition to the regulations mentioned above, substance legislation plays a special role in the separation and recycling of plastics. The EU lays down harmonised requirements for the manufacture, marketing and use of substances on their own, in mixtures and in articles. In substance legislation, greater emphasis is placed on regulations that have direct validity for the member states.

- **EC REACH Regulation** - Regulation (EC) No 1907/2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals;
- **SVHC list - (Substances of very high concern)** - List of substances of very high concern that are eligible for regulation under the authorisation procedure; according to Art. 59 (10) REACH;
- **EC CLP Regulation** - Regulation (EC) No 1272/2008 on classification, labelling and packaging of substances and mixtures; and
- **EU POP Regulation** - Regulation (EU) 2019/1021 of the European Parliament and of the Council of 20 June 2019 on persistent organic pollutants.

At the national level, the Hazardous Substances Protection Act (ChemG) lays down supplementary general regulations. The Ordinance on the Separate Collection and Monitoring of Non-hazardous Waste Containing Persistent Organic Pollutants (POP Waste Ordinance) applies specifically to POP waste at national level.

2.2 Different plastic types, additives, interfering substances and pollutants

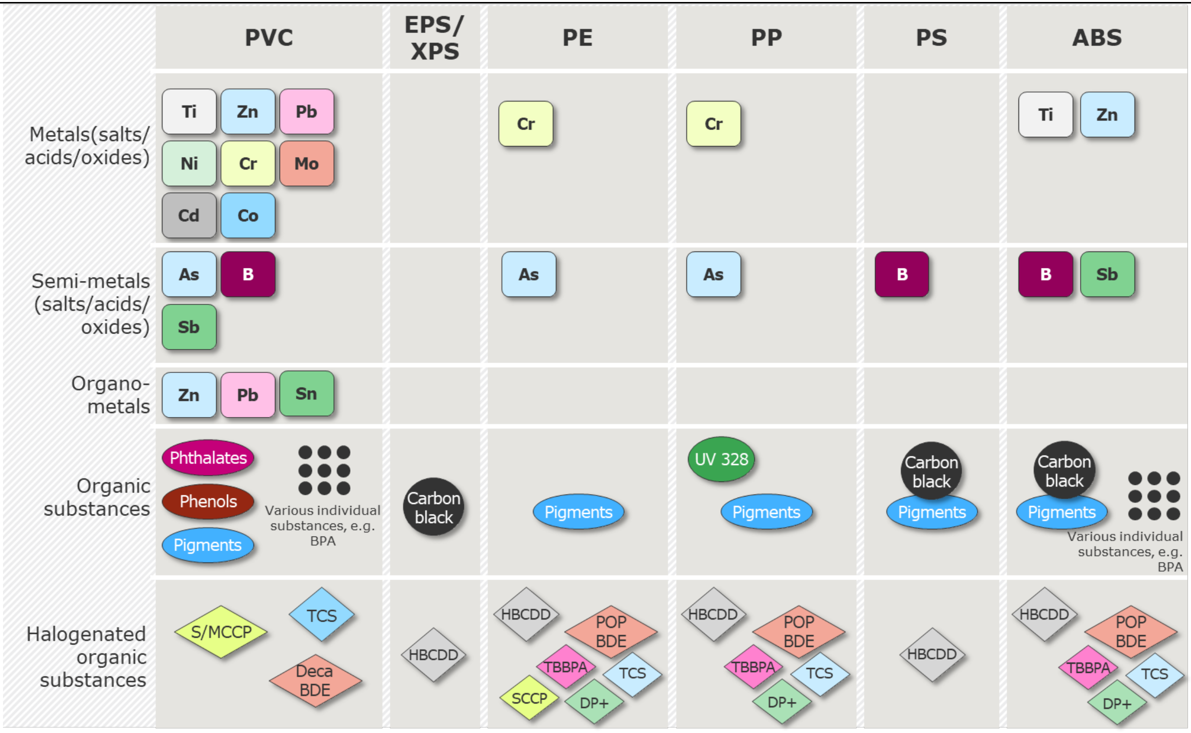
In EEE and vehicles, a wide range of polymers are used for manufacturing processes.

The main polymers used are polypropylene (PP), polystyrene (PS), expanded polystyrene (EPS) and extruded polystyrene (XPS), acrylonitrile butadiene styrene (ABS), acrylic ester styrene acrylonitrile (ASA), styrene acrylonitrile (SAN), polyamide (PA), polyethylene (PE), PE-LD (low-density polyethylene), PE-HD (high-density polyethylene), polyurethanes (PUR), polyvinyl chloride (PVC), polymethyl methacrylate (PMMA), polyethylene terephthalate (PET). Detailed information on the use of plastics in EEE and vehicles can be found in Chapter 3.1.1 or 4.1.1 respectively.

Due to their content of additives (especially pollutants), fillers or reinforcing materials, or due to their use in composites, some plastics are not suitable for a common processing method for legal or technical reasons. Such plastics are therefore considered in the project context as non-recyclable plastics and should be separated and discharged. This is why such information is important when considering the development of recycling strategies in terms of separation and processing strategies for plastics from WEEE and ELVs. On the one hand, knowledge about the content of additives, pollutants, fillers or reinforcing materials as well as the use of composites is a basis for identifying and designing suitable shredding and sorting techniques and optimal separation locations for plastics that cannot be recycled mechanically. On the other hand, this knowledge is also indispensable for answering the question of whether a recycled plastic can be kept in a safe cycle in compliance with the law and taking into account the material requirements.

An overview of important additives and substances is given in Figure 1 in which the most important polymers and typically used additives or substances are listed.

Figure 1: Visualisation of the summary view of different types of plastics and the respective additive types or substances



Source: Illustration adapted based on (Polcher et al., 2020)

Martens and Goldmann (2016) list additives, fillers and reinforcing agents for the general plastics sector. The substances and agents listed below can all play a role in the recycling of ELVs or WEEE:

- Lubricants, anti-blocking agents, release agents - additives (e.g. fatty acid esters: butyl stearate, metal soaps: calcium stearate, fatty acid amides, anti-blocking agent: talc);
- Stabilisers - additives (function for polymer) (antioxidants such as aromatic amines, organic phosphites and lactones; UV absorbers: benzophenones, triazines; heat stabilisers: organic compounds of lead, cadmium, barium, tin and zinc);
- Antistatics (organic antistatics: Fatty acid esters, amines, sulphonates; conductive additives: special carbon black, carbon fibers, metal fibers);
- Flame retardants (halogen-free and inorganic compounds: Hydroxides, borates, phosphates; antimony oxide, aluminium hydroxide, magnesium hydroxide and zinc borate);
- Colourants (inorganic or organic powder pigments: Azo dyes, white pigment: titanium dioxide);
- Plasticisers (phthalates: e.g. dioctyl phthalate, phosphoric acid esters for PVC);
- Bonding agent (e.g. modified PE);
- blowing agent (sodium hydrogen carbonate or azo-dicarboxylic acid diamide); and
- Fillers (chalk, kaolin, talc) and reinforcing agents (glass fiber, carbon fibers, reinforced natural fibers, such as hemp, coir, sisal).

- Composite materials are a composition of different polymers to obtain the desired material properties (e.g. stiffness, weather resistance).

In principle, both additives and fillers as well as reinforcing materials and composite materials can contain pollutants. In this project (based on Polcher et al., 2020) the collective term "pollutant" is used for substances that can have a harmful effect on human health and/or the environment in the short or long term, usually as a result of input into the environment and/or uptake by organisms.

2.3 Specific substances

This section lists important pollutants that are currently or may in the future be subject to legal regulations/restrictions and have been or will be used in EEE and vehicles.

- Short-chain chlorinated paraffins (SCCP)
- Medium Chain Chlorinated Paraffins (MCCP)
- Polybrominated diphenyl ethers (PBDE, i.e. Tetra-, Penta-, Hexa-, Hepta- and DecaBDE)
- Hexabromocyclododecane (HBCDD)
- Bromine-containing plastic additives such as 2,4,6- tribromophenyl allyl ether and 3,4,5,6-tetrachloro-N-[2-(4,5,6,7-tetrachloro-2,3-dihydro-1,3-dioxo-1H-inden-2-yl)-8-quinolyl]phthalimide)), as well as ,1'-(isopropylidene)bis[3,5-dibromo-4-(2,3-dibromopropoxy)benzene] and 1,1'-(isopropylidene)bis[3,5-dibromo-4-(2,3-dibromo-2-methylpropoxy)benzene].
- Di-ethylhexyl phthalate (DEHP)
- Dechlorane Plus (DP)
- Cadmium (Cd)
- Lead (Pb)
- Per- and polyfluorinated alkyl substances (PFAS) comprise more than 4,700 different substances.
- Phenol benzotriazoles such as UV-328

The use of PBDE and HBCDD, formerly commonly used additives, is already restricted today. PBDEs were used as flame retardants in PA, PE, PP, ABS and PUR and other polymers. HBCDD was also used in EPS/XPS, PS, PET (Polcher et al., 2020). PBDE and HBCDD have been substituted by chemical alternatives. In the case of HBCDD in EPS and XPS, the main alternative is polymeric flame retardant: brominated styrene-butadiene copolymer (PolyFR). Other typical alternatives include TBBPA in PA, PE, PP, ABS and PUR or melamine polyphosphates in PE and PP or tris(tribromoneopentyl) phosphate (TTBNPP) in PP (Polcher et al., 2020), TBBPA derivatives, DecaBDE ethane (DBDPE) and 1,2- bis(2,4,6-tribromophenoxy)ethane (BTBPE) (EFSA, 2011, 2012; Egebäck et al., 2012) or dechlorane plus (UNEP, 2021).

2.4 Material requirements and specifications for the use of plastics

Relatively high demands are required for plastics that are used in the areas of EEE or the automotive industry. High loads, high temperatures and long service life should not reduce quality or safety. Especially in comparison to short-lived plastic products (e.g. disposable packaging) there are big differences. Therefore, manufacturers take certain material requirements into account when using plastics. Since the products of the EEE and the automotive industry represent a very heterogeneous group, these requirements for the materials differ greatly in detail. Basically, however, the following material requirements and specifications for plastics can be summarised in the above-mentioned areas:

- Compliance with all substance restrictions;
- Odourless;
- Colour accuracy;
- Use of 'high-performance plastics';
  - Minimal corrosion for longer vehicle life;
  - Extensive design freedom, enabling progressive creativity and innovation;
  - Flexibility in the integration of components;
  - Safety, comfort and economy; and
  - Recyclability.
- Low weight (especially in the automotive industry);
- Plastic parts with high fire protection;
- They are low smoke and high fire protection in case a fire breaks out; and
- they have an insulating effect everywhere to protect against electric shock when touched.

In addition, there are material requirements and specifications that must be met for certain certifications, such as the use of as few different types of plastic as possible (e.g. Blue Angel DE-ZU 78 requirement; EU Ecolabel for televisions; Green IT Fujitsu, Nordic Swan Computers), or that 90 % of the mass of the plastics and metals of the housing parts and chassis must be recyclable (e.g. Blue Angel DE-ZU 78 requirement, Nordic Swan Computers).

2.5 Processing and sorting processes for plastic-rich recyclable material streams

WEEE and ELVs are highly complex material flows consisting of a variety of materials and material compounds. For high-quality recycling, WEEE and ELVs must be broken down and the materials separated according to material type and, if necessary, de-polluted. Only a few types of plastics can be processed together into high-quality blends, so that separation by plastic type is necessary for mixed plastic fractions. Additives are added for specific applications. Certain additives added in the original production can be considered pollutants and cause contamination or quality impairments of recycled plastics. Sorting by additive can therefore be as sensible and necessary as sorting by plastic type (Martens & Goldmann 2016).

Waste sorting technologies can be classified as direct or indirect sorting processes. Direct sorting technologies use material properties such as specific magnetic charge, electrical conductivity and density or external fields such as magnetic, eddy current and gravity. Indirect sorting uses sensors to identify the presence and often the location of recyclables so that automated machines or robots can be used to sort the detected recyclable materials (Gundupalli et al., 2017).

The applied process chain of plastic enrichment and sorting has a significant influence on yield and purities of mechanically recyclable thermoplastics (Schlummer et al., 2016). Pure collection logistics and effective disintegration and sorting processes make a significant contribution to producing high-quality plastic recyclates from complex recyclable material streams (Martens & Goldmann 2016).

By means of early dismantling of suitable plastic components, it is possible to keep the components separated according to plastic types and additives. In this way, less complex fractions can be processed and recycled and ultimately higher yields and recyclate qualities can be achieved.

If plastics from WEEE or ELVs end up in so-called post-shredding technology processes (PST processes), they are shredded unsorted together with other materials and very complex mixed waste fractions are produced. These can only be separated with considerable effort and also not completely by means of processing and sorting processes (extended PST) in such a way that high-quality mechanical recycling of the plastic components is possible.

In Table 1, existing sorting and processing methods are summarised with regard to their functional principles, sorting tasks, input and output characteristics, and examples of applications from the processing of plastic-rich material flows are given.

Table 1: Processing methods for plastic-rich recyclable material streams

Processing method	Functional principle and sorting task(s)	Input/output nature	Application examples
Manual dismantling and sorting	Manual dismantling/separation with standard workshop equipment, if necessary, also with special tools or manual picking for the separation of harmful, disruptive and/or recyclable materials.	Input: whole, if necessary, partially dismantled and devices after rough disintegration Output: Material diversity limited to treated unit types	Removal of pollutants and impurities before and after mechanical shredding according to legal requirements or process-specific criteria Removal of recyclable materials or equipment/components containing recyclable materials
Machine-assisted and (partially) automated dismantling	(Partially) automated dismantling/separation, e.g. by using robots or excavators with special grippers for dismantling and sorting.	Input: Technologies adapted to specific input conditions. Output: limited, device- or component-specific material variety	Automated dismantling and pollutant removal for display screen equipment Dismantling and sorting of iPhones Excavator with tweezers attachment for dismantling and sorting end-of-life vehicle components
Machine disintegration/ Shredding	Comminution of bulk material using forces such as pressure, impact, cut or abrasion to set uniform particle sizes for composite disintegration and produce the optimum particle size range for subsequent sorting stages.	Input: large, partially polluted and/or contaminated equipment or pre-shredded and pre-sorted material Output: disintegrated material in a defined particle size range	Cross-flow hogger or shredder for the disintegration of WEEE Mills or shears for secondary crushing Large shredder for breaking down ELVs, large appliances and other scrap metal
Magnetic separation	Permanent magnets attract Fe metals such as iron, steel and nickel.	Input: sufficiently disintegrated material, grain sizes according to previous disintegration Output: Fe-metals and Fe-metal-depleted, plastic-rich sorting fraction	As a rule, after each comminution stage
Non-ferrous (NF) metal sorting	Rotating neodymium magnets generate a current flow in non-ferrous metals to enable the non-ferrous metals to be discharged via the resulting magnetic field.	Input: Non-ferrous metal-containing recyclable material streams in grain sizes > 0.5 mm Output: Non-ferrous metals and plastic-rich sorting fraction	As a rule, after each comminution stage

Processing method	Functional principle and sorting task(s)	Input/output nature	Application examples
	Alternatives: Density separation in heavy beakers or electrostatic sorting processes		
Electrostatics	Material-specific triboelectric charging of plastics for sorting plastic/plastic mixtures Impingement of the input with negatively charged particles by means of a spray electrode for sorting plastic/metal mixtures on the basis of conductivity	Input plastic/plastic sorting: dry (residual moisture < 0.5%), disintegrated, homogeneous material, ideally 2-component mixture -in grain sizes 2 - 12 mm Output plastic/plastics sorting: with ideal mixtures plastic types-pure sorting fractions with purities > 98%	Plastic/plastic sorting: Separation of ABS and PS, if necessary, with enrichment of PP residues in a middle fraction.
Density separation in liquids	Sorting of disintegrated, wettable and floatable or sinkable materials according to specific material density in a sealing solution or suspension with specifically adjusted density for the enrichment of plastics in defined density windows.	Input: Mixture of materials that differ in density, in the particle size range 2 mm - 25 mm, depending on the process. Output: Light fraction or heavy fraction. For pre-treated, plastic-rich WEEE fractions, purities > 95% can be achieved.	Accumulation of polyolefins in a light fraction (< 1.0 g/cm³) Accumulation of low-bromine/free ABS and PS in the density window 1.0 g/cm³ < x < 1.08 g/cm³ Enrichment of non-ferrous metals in the heavy fraction of heavy sludge
Separating tables	Oscillating, air- or water-flow inclined, perforated levels enable the enrichment of materials in horizontal layers for sorting metal/plastic ground material.	Input: Grain sizes: 0.25 mm - 0.8 mm Output: Metal-rich and plastic-rich sorting fractions	Sorting of cable regrind to recover the copper
Wind sifting	By means of air extraction, material is enriched in the light or heavy fraction in a defined air flow according to gravity and the resistance force caused by the air-flow. Use for separation of fines and/or dust removal.	Input: crushed, disintegrated material that can be enriched according to gravity and the resistance force caused by the air-flow Output: Light fraction or heavy fraction	Separation of flyable fines during comminution Separation of a lint fraction or other flyable materials from material streams (e.g. also in the sorting of packaging waste).
Near infrared (NIR) sorting	Irradiation of material with halogen lamps to measure the material-specific reflection spectrum in the NIR range for sorting according	Input: Separated, soot-free and uncoated material in the defined particle size range with as homogeneous a particle size distribution as	Widely used in the sorting of light packaging, e.g. for sorting TetraPak, PS, PE, PET, paper/cardboard/ carton

Processing method	Functional principle and sorting task(s)	Input/output nature	Application examples
	to plastic types and other materials such as PE, PP, PS, PA, PET, PVC, PC/ABS, PPK, wood.	possible (belt sorting: 10 -150 mm, flake sorter: 2-12 mm) Output: For mixed, plastic-rich and identifiable input streams, sorting purities between 80 and 90% are usually achieved in the first sorting pass.	
Sensor-based sorting in the visible spectral range	Measurement of reflectance spectra in the visible spectral range for sorting by shape, colour or size	Input: Parts of different shape, colour or size in grain sizes 10 - 150 mm Output: fractions sorted by shape, colour or size	Sorting out dark particles from light material streams Recognition of bottle shapes in the sorting of lightweight packaging
Laser-based plasma spectroscopy (LIBS)	A part of the sample surface is heated, vaporised and partially ionised by a high-energy laser pulse. Measurement of the characteristic light emission of the plasma decay for sorting according to metals, plastics and or halogenated plastic qualities.	Input: Disintegrated material in continuous sorting, handheld devices enable the measurement of larger components. Output: Sorted by material type or additive	As a handheld unit in scrap yards for the identification of high-value metals
Laser-induced fluorescence spectroscopy	Measurement and evaluation of fluorescence of plastics excited by laser light (UV to NIR) for sorting by plastic types	Input: plastic-rich material streams as free as possible from metals, elastomers, coatings and inert materials in particle sizes of 4 -20 mm or 15 -75 mm, depending on the unit type. Output: For mixed input streams, target material purities of 80 - 90% are achievable in the first sorting pass.	Plastic type sorting of plastic-rich WEEE and end-of-life vehicle sorting fractions
X-ray based sorting (XRT)	Measurement of the intensity of the transmission of X-rays to draw conclusions about the atomic material density taking into account the particle thickness. For sorting according to atomic material density, e.g. of metals or plastics with specific density due to their additive content.	Input: Material mixtures whose materials differ in atomic density in grain sizes 10 - 30 mm or 30 - 80 mm. Technically possible range: 5 mm - 120 mm Output: Target value is a sum parameter of 500 ppm bromine in low-bromine sorting fraction	Sorting of non-ferrous metals from shredder fractions

Processing method	Functional principle and sorting task(s)	Input/output nature	Application examples
Solvent-based recycling	Selective dissolution, purification of the plastic solution by separating soluble and insoluble foreign materials and recovery of the target plastic	Input: Target plastic-enriched material blends Output: Target plastic with high purities, separated from insoluble and possibly soluble impurities.	Dissolving PE from industrial and post-consumer multilayer composites Separation of brominated flame retardants from PS In the past: PVC recycling
Homogenisation	Agitated silos for the production of homogeneous output qualities with regard to residual moisture, particle size, plastic type distribution, foreign materials and, if necessary, pollutants.	Input: Sorted regrind Output: Homogeneous material in constant quality with regard to optical, mechanical and rheological properties	For plastics recyclers who sort and re-compound large quantities
Odour removal	Odour addition or degassing to remove volatile components to improve recyclate odour and safe process control	Input: Unpleasant smelling material due to proportions of less thermostable material Output: Material with fewer odours and VOCs	Vacuum extrusion for the separation of volatile degradation products
Paint stripping	Dissolving and separating the lacquer layer to improve mechanical and optical properties	Input: Lacquered plastics Output: Plastics free from lacquers	Post-industrial recycling of different types of plastics
Re-compounding	Melting of thermoplastic input materials and shaping by conveying through outlet opening under pressure, combinable with melt filtration, metering units and degassing for purification and modification of sorted regrinds	Input: Impurity level for post-consumer plastics from WEEE < 5%. Output: high-quality recyclates producible from an input purity > 97%.	final step in plastics recycling

3 Electrical and electronic equipment

3.1 The use of plastics in EEE and the amount of plastics in the WEEE waste stream

This chapter first presents the use of plastics in the industry in general, with a focus on Germany. This is contrasted with the quantities of EEE placed on the market and the quantities of WEEE collected. This provides an overview of the market and allows an initial assessment of the mass flows of EEE, WEEE and the plastics contained. Furthermore, plastic shares are given as examples for individual product and equipment groups. Based on the available data, a plausible average value for the percentage of plastics is assumed for the equipment categories in focus. In the further evaluation, the usual plastic composition of the relevant equipment categories is also considered and presented. This is compared to the plastic shares and compositions recorded in the WEEE waste stream.

3.1.1 Use of plastics in EEE

A look at the German plastics market shows that the Electrical and Electronics sector is one of the largest consumers of plastics. With 901 kt of processed plastics in 2017 (2019: 881 kt), the sector ranks fourth behind the packaging industry (4,378 kt; 2019: 4,369 kt), the construction industry (3,520 kt; 2019: 3,583 kt) and the automotive industry (1,611 kt; 2019: 1,509 kt). All values are composed of a substantial part of virgin material and a mostly small share of recyclates - for the EEE sector 96.8 % virgin material and 3.2 % recyclate (2019: 96.5 % virgin material and 3.5 % recyclate) (Conversio Market & Strategy GmbH, 2018, p. 54). In addition, it can be seen that a large proportion of the reported plastic volumes are used in the Cables and Installations sector (34 %), followed by the White Goods sector[1] (24 %), the IT/Telecoms sector (10 %) and the Brown Goods sector[2] (6.5 %) (Conversio Market & Strategy GmbH, 2018, p. 67). However, these data do not allow conclusions to be drawn about the proportion of plastics in individual product groups or collection groups.

The market for EEE is extremely diverse and characterised by its enormous product variety. It is therefore difficult to make a uniform statement about the proportion of plastics and their composition, even within certain product groups. For example, plastics account for up to 70 % of the weight[3] of printers, up to 40 % of flat screens and refrigerators, up to 40 % of laptops, around 20 % of smartphones and less than 10 % of tablets (Baxter et al., 2015; EFRA, 2013; Hartman, 2018; Manhart et al., 2016). For photovoltaic modules, a plastic content of 20 % is recommended (Baxter et al., 2015) and for lighting fixtures a plastic content of <5 % is given (Squire et al., 2021).

Figure 2 shows plastic shares for a selection of household appliances and compares different product groups. The values come from a study commissioned in 2018 by the European Association of Domestic Appliance Manufacturers (APPLiA). As an average value, APPLiA (2019) indicates a plastic content of 32.5 % for household appliances. Freezers have the highest plastic content of the major household appliances shown here at 59 %, while heating and ventilation appliances have the lowest value at 10 % (APPLiA, 2019). Regarding the relevance of the values shown for the German market, it should be noted that air conditioners are still comparatively

[1] White goods refers to household appliances such as refrigerators, washing machines, dishwashers and other household appliances.

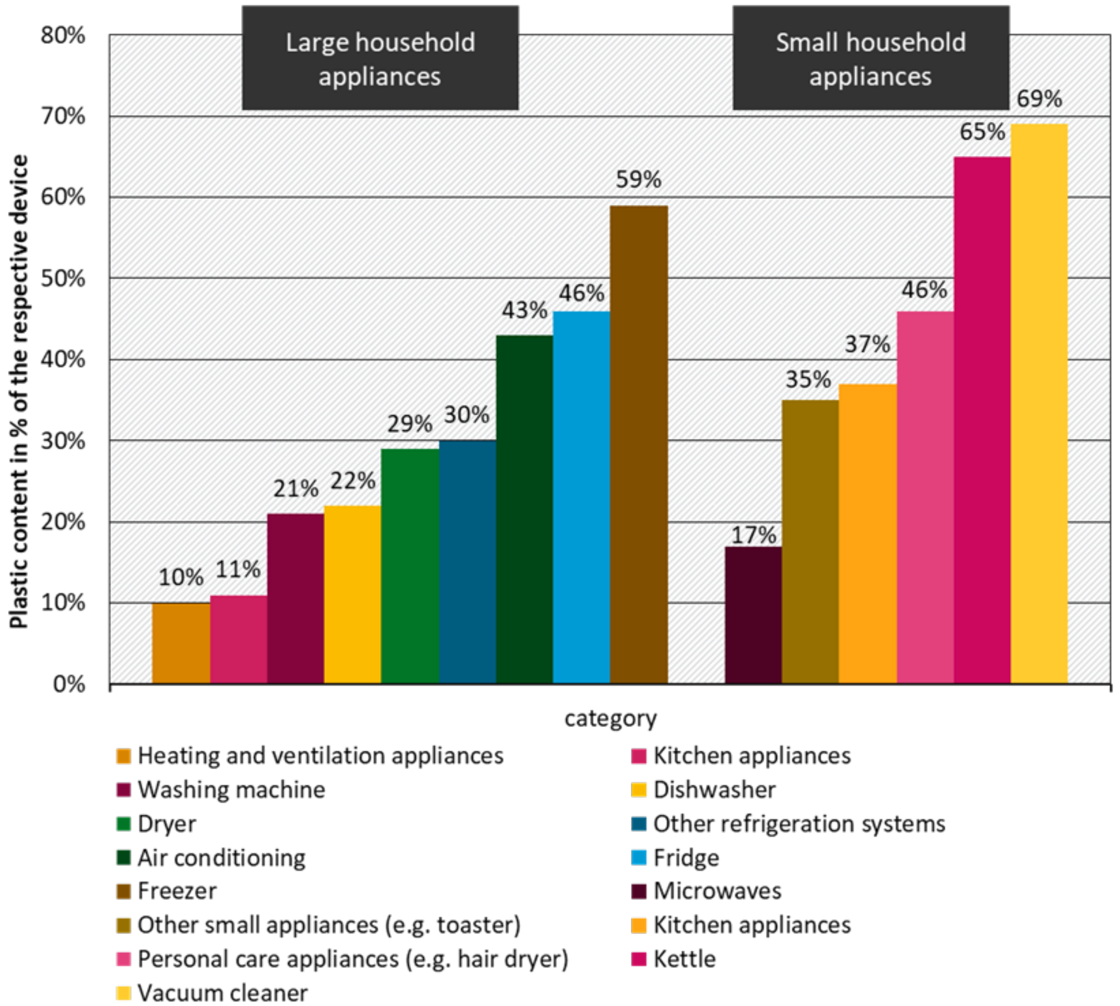
[2] Brown goods refers to radio, television and other consumer electronics equipment.

[3] The value refers to printers excluding the weight for toner cartridges, as these must be removed from separately collected WEEE according to Annex 4 No. 1 ElektroG.

little represented in Germany[4] . At the same time, the level of refrigerator, fridge and freezer equipment is particularly high at 99.9 % of households. For small household appliances, vacuum cleaners have the highest plastic content at 69 %, while microwave ovens have the lowest at 17 %. Looking at the number of appliances in use within the EU, the estimated stock of plastics in the household appliances sector alone is 17.6 million tonnes - of which 12.9 million tonnes in large appliances and 4.6 million tonnes in small appliances (APPLiA, 2019).

Figure 2: Proportion of plastics in selected household appliances

Figures in percent of the plastic content of the respective equipment category



Source: APPLiA (2019)[5]

Like the proportion of plastics, the information on the composition of plastics also varies in the relevant literature. The authors of the Conversio study (2018, p. 59) give the following values, among others, for the quantities processed in the German electrical and electronics sector (see Figure 3): 165 kt PP (18.3 %), 107 kt PE-LD/LDD (11.9 %), 95 kt ABS/ASA/SAN (10.6 %), 89 kt PA (9.9 %), 59 kt PS (6.6 %). Two aspects of the study should be noted here:

- the category "other thermoplastics" (257 kt) includes various plastics whose information was not declared by the manufacturers;

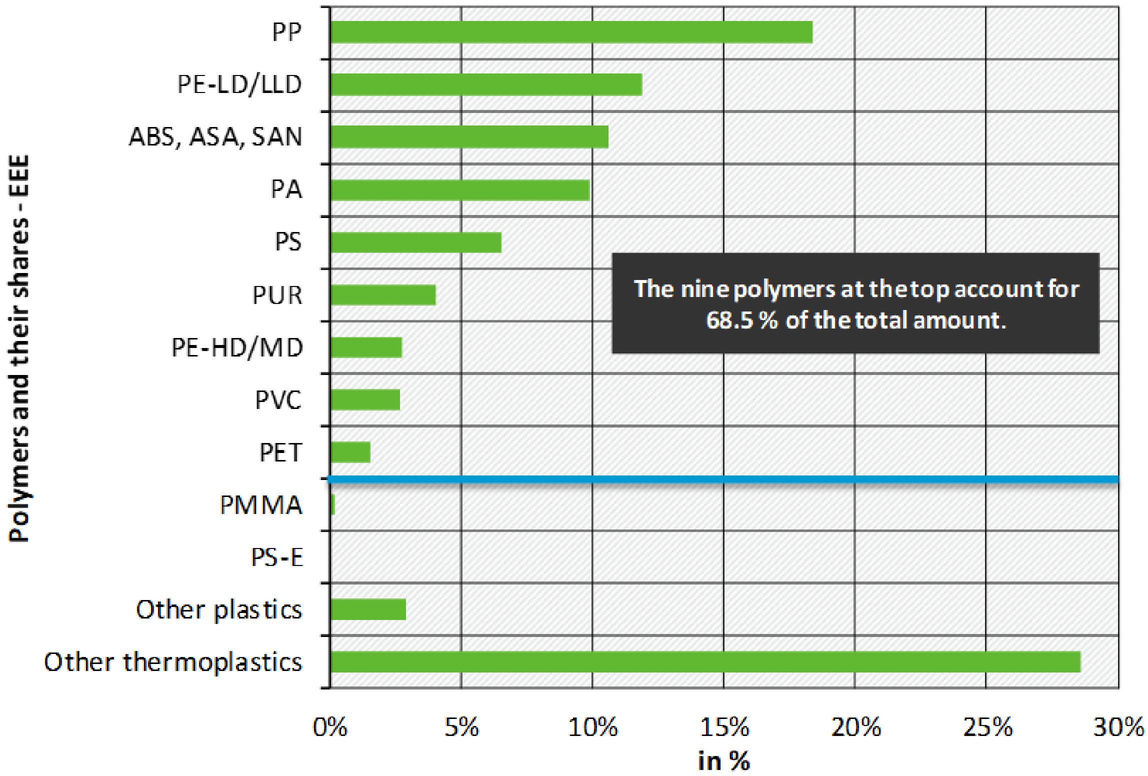
[4] Germany currently only causes comparatively low energy consumption in the area of cooling equipment - around 0.5 % of global energy consumption for cooling in relation to air-conditioning systems (FAZ, 2018).

[5] 0https://applia-europe.eu/statistical-report-2 18-2019/pillar-1/index.html#&panel1-6

- as the data does not represent the quantities of plastics used - but the plastics produced by the German plastics industry for use in EEE (in Germany and abroad) - commodity plastics[6] are partly underrepresented.

Figure 3: Share of polymers used in the electrical and electronics sector

Values for the German market in percent and for 2017



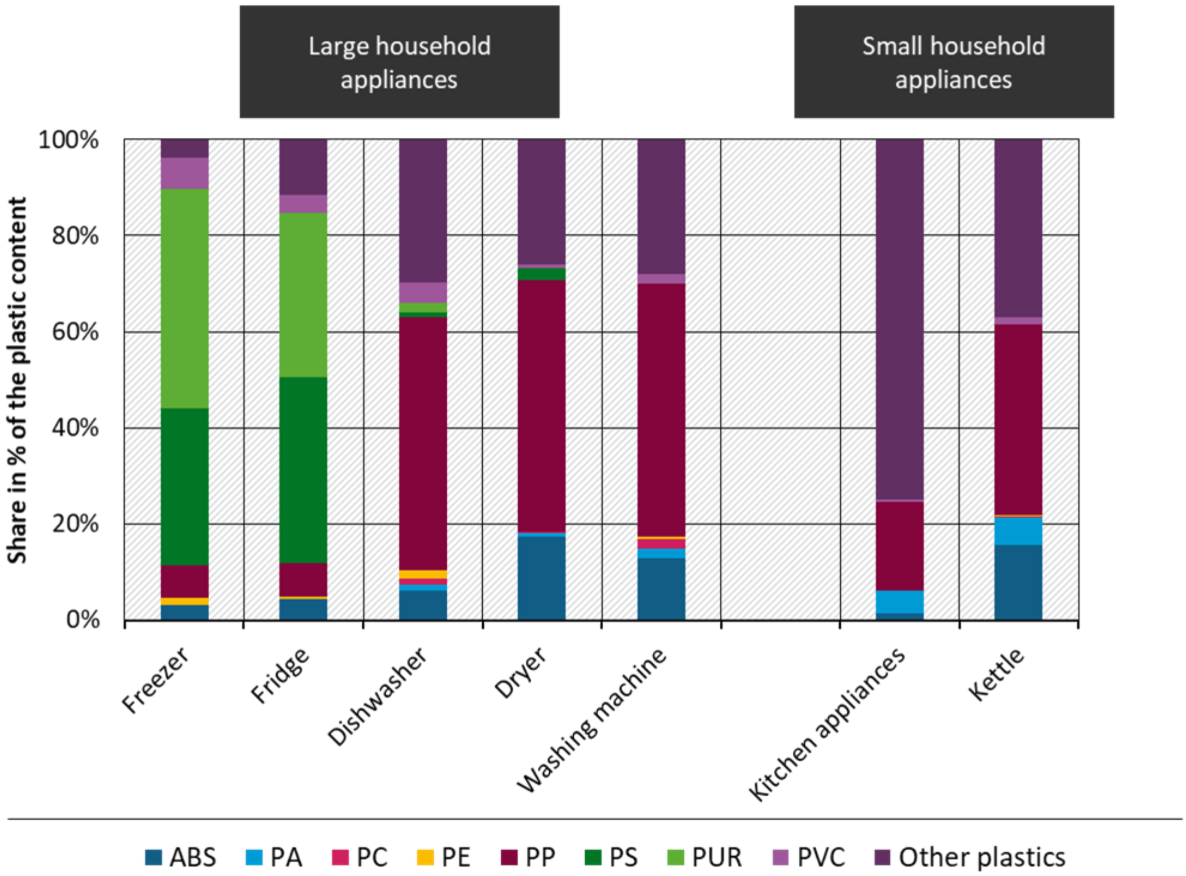
Source: Own illustration based on (Conversio Market & Strategy GmbH, 2018)

The following figure shows a selection of household appliances and their plastic composition. In the area of refrigeration appliances, PUR and PS make up the largest polymer shares in terms of volume (see Figure 4). Foams made of PUR are mostly used as thermal insulation. There is no need for insulation in other large household appliances, so that other polymers such as PP are increasingly used, for example in dishwashers, dryers or washing machines (CECED, 2017).

[6] Commodity plastics are standard plastics that are produced in large quantities and for which no exceptional material properties are required. Examples are PE, PP, PS, PVC (PlasticsEurope, 2019a).

Figure 4: Plastic composition for a selection of household appliances

Values show the plastic composition as shares of the total plastic quantity per product group



Source: (CECED, 2017, pp. 34-37)

3.1.2 Use of plastic recyclates in EEE

This chapter presents the current state of knowledge on the use of recycled plastics in EEE and describes possible developments. Currently, there are no public data collections on the use of recycled plastics (Wilts et al., 2016). Therefore, individual studies, reports, manufacturer information and interviews with experts from the industry are used.

More than 9 million tonnes of post-consumer plastic waste generated in the EU in 2018 was sent for recycling. Of this, almost 80% was treated in Europe to produce around 4.9 million tonnes of plastic recyclates (PlasticsEurope, 2019b, p. 17). It is estimated that at least 4 million tonnes of these recyclates found their way into the production of new products (PlasticsEurope, 2019b, p. 17).

The following values can be summarised for the German market: As already mentioned, a total of 901 kt of plastics were processed in the EEE sector in Germany in 2017 (2019: 881 kt). This value is made up of 872 kt of virgin plastics and 29 kt of recycled plastics (2019; 850 kt and 31 kt, respectively) (Conversio Market & Strategy GmbH, 2018, p. 54). For 2017, this corresponds to a 6.3% share of total plastics consumption in Germany (2019: 7.7%) (Conversio Market & Strategy GmbH, 2018, p. 52). In addition, it can be deduced from this that the use of recyclates was only 3.2 % of the amount of plastics used in the EEE sector (2019: 3.5 %) and is rather low compared to other sectors: agriculture 34.9 %, construction 21.5 %, packaging 9.1 %, vehicles 4.8 % (Conversio Market & Strategy GmbH, 2018, p. 54). This also reflects the assessment of recycling companies surveyed, which assume a current recyclate use of around 3% for the EEE sector, and is roughly in line with PlasticsEurope's assessment, which indicates a value of 2% (PlasticsEurope, 2019b, p. 20). It should be noted that the recyclate volumes reported by Conversio consist of post-consumer (~33%) and production and processing (~67%) waste (2019: 36% to 64%) (Conversio Market & Strategy GmbH, 2018, p. 56).

In addition, it can be noted that the 29 kt of plastic recyclates used in the EEE sector correspond to only 1.6 % of the Germany-wide use of plastic recyclates (2019: 31 kt = ~2 %): Construction 42.9 %, Packaging 22.6 %, Agriculture 11.2 % (Conversio Market & Strategy GmbH, 2018, p. 56).

These values shown for each sector do not allow any statements to be made about the use of recyclates in individual equipment categories. It can be assumed that the differences vary considerably from manufacturer to manufacturer and from equipment category to equipment category. The research and evaluation presented suggests that the use of plastic recyclates for EEE is currently not widespread. This is also supported by other studies such as (Wilts et al., 2016) which found no establishment of the use of recyclates a few years ago. At the same time, however, it can be noted that some manufacturers actively advertise the use of recyclate and state self-imposed targets for its increase. Overall, this suggests that the use of plastic recyclates in the electrical and electronics sector is still very low, but that an increase is on the horizon.

3.1.3 Plastics in the waste stream

In practice, the separate collection of WEEE from private households is usually carried out via municipal collection points of the public waste management authorities or via take-back systems of manufacturers and distributors of WEEE. WEEE that is not collected separately but disposed of with residual waste is usually sent directly to the waste incineration plant for energy recovery. According to the German Federal /Länder Working Group on Waste (Bund/Länder-Arbeitsgemeinschaft Abfall) (LAGA), 2018) the treatment of separately collected WEEE is usually carried out by manual dismantling or by partially or fully automated treatment.

When looking at the WEEE waste stream, there are certain differences to the quantities of WEEE placed on the market with regard to recovery. Significant parts of the waste stream do not run through the designated collection and recovery routes and should not be disregarded for a holistic picture of the waste stream. For the recovery of WEEE in Germany in 2012, it was found that almost half of the quantities generated went through routes outside the official collection and recovery pathway - this includes non-regulatory recycling and a gap in information for more than 30% of the WEEE generated in that year (Huisman et al., 2015, p. 16).

For 2018, the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV, 2020) indicates a quantity of 853,125 t of collected WEEE, of which 841,064 t were treated within the country . About 92 % of the treated quantity is accounted for by the top four equipment groups: Large household appliances (43%), Small household appliances (20%), IT and telecommunication equipment (14%), Consumer electronics equipment (14%)[7] .

Looking at the recycling of the categories shown, a different development can be seen between the years 2017 and 2018. Slightly fewer large household appliances (-2%) and significantly fewer consumer electronics appliances (-11.9%) were recycled in 2018 than in 2017.

Across all equipment categories, 21.6 tonnes (+3.1%) more appliances were recycled. However, it should be kept in mind that the recycling rate was 83.9 % - a minus of 1.9 % compared to the previous year.

[7] The data for the reporting year 2018 follows the 10 equipment categories valid until August 2018 according to Annex I of the EU WEEE Directive. Since 15 August 2018, the classification into six equipment categories (according to Annex III of the EU WEEE Directive) applies.

For the sake of completeness, the following table summarises current values for the 2020 reporting year and presents them according to the 6 equipment categories now in force since 15 August 2018 (according to Annex II of the EU WEEE Directive).

Table 2: Quantities of EEE placed on the market and WEEE collected per product category for the reporting year 2020

Category	Placed on the market (tonnes)	Collected (tonnes)
1. heat transfer	355,534	190,428
2. screens	152,322	113,457
3. lamps	35,774	7,454
4a. Large appliances, except photovoltaic modules	1,238,995	297,749
4b. Photovoltaic module	320,434	15,396
5. small appliances	634,862	290,184
6. small IT and communication devices	110,005	122,351
Total	2,847,926	1,037,019

In addition to the values shown, Destatis (Federal Statistical Office) provides an overview of the total quantities of appliances accepted for primary treatment as well as shares of individual product categories, but makes no statements about the fate of plastic parts contained in WEEE. More recent studies indicate an average plastic content of 10-35% (Maisel et al., 2020). The assumption of Andersson et al. 2019 is similar at 20-35 %. The data collection is not transparent in all studies and the values given should only be compared with each other with reservations. According to Moser et al., (2016), however, it can be assumed that the energetically recycled part of the treated WEEE is predominantly composed of the plastic fraction. Also, LAGA (2018) confirms that mechanical recycling of plastics from WEEE still does not take place on a significant scale. However, there is no information on exact values.

One of the major challenges in the recycling of WEEE is the large number of substances that accumulate in the waste stream. WEEE contains a large number of different polymers (see e.g. Figure 4). In order to change the properties of the individual polymers in a desired way, they are often mixed with other types of polymers (Grigorescu et al., 2019). This further increases the variety of plastics contained in WEEE. As a result, it is difficult to make general statements about the proportion of plastics and polymers in WEEE. In total, WEEE can contain more than 60 different plastics (Köhnlechner, 2019).

Table 3 compares the results on polymers in the WEEE waste stream from different authors and shows that the most important polymer types in the WEEE waste stream are ABS (incl. SAN and ASA), PS (especially HIPS) and PP. Most of the primary data on this comes from practical separation experiments.

Table 3: Plastic polymer shares in the WEEE waste stream per appliance and product category

Analysed device category and products	(Dimitrakakis et al., 2009)	(Chancerel, Rotter, 2009)	(Freegard, Claes, 2009)	(Maris et al., 2015)	(Jandric et al., 2019)
Major household appliances (category)	40 % ABS, 35 % PP, 15 % PC	Not specified	Not specified	Not specified	60 % ABS, 20 % ABS/SAN, 10 % ABS/ASA
Small household appliances (category)	35 % ABS, 35 % PP, 10% PS	Not specified	24 % PP, 15 % SAN, 13 % ABS	Not specified	46 % ABS, 45 % PP
IT & Information Technology (Category)	15% ABS, 40% PS, 19% PC	Not specified	21 % ABS, 14 % ACR, 9 % PS	21% ABS, 45% HIPS, 12% PC/ABS	Not specified
Consumer electronics (category)	42 % ABS, 35 % PS	Not specified	43 % PS, 25 % ABS, 11 % ACR	41% ABS, 37% HIPS	Not specified
Keyboards (product)	Not specified	22 % ABS, 75 % PS	Not specified	Not specified	33 % HIPS, 25 % PS, 11 % ABS/PMMA
Vacuum cleaner (product)	Not specified	95 % ABS, 5 % PP	Not specified	49 % ABS, 31 % PP	69 % ABS, 21 % PP
Smartphones (product)	Not specified	72 % ABS/PC, 25 % ASA/PC	Not specified	Not specified	22 % PP, 22 % PE, 14 % ABS/PC
Enclosures (product)	Not specified	100 % ABS	Not specified	Not specified	71 % ABS, 18 % PS, 6 % HIPS
Printers and power supplies (product)	Not specified	Not specified	Not specified	Not specified	57 % ABS/PC, 17 % PC
Flat screen monitors (product)	Not specified	Not specified	Not specified	Not specified	30 % ABS, 13 % ABS/PC, 13 % ABS/SAN

The three most represented polymers in terms of volume per category and product group are shown.

Wäger et al., (2009) name ABS, HIPS, PP, PS and PC (incl. blends) as plastics that are used most frequently. For this study, actual mass flows of Swiss WEEE recycling systems were analysed (data from 2007) and extrapolations were made to specific EEE categories.

3.1.4 Pollutants in the WEEE waste stream

In general, sorting and reprocessing steps play an important role in the final quality of plastic recyclates. In addition, there is the issue of pollutants that can be found in different quantities and types in plastics and thus in WEEE (Hahladakis et al., 2018). The following pollutants are particularly relevant in the WEEE waste stream: brominated flame retardants (PBDE, HBCDD, TBBPA), chlorinated paraffins (SCCP/MCCP), phthalates (e.g. DEHP), TCEP, DP, PFAS and heavy metals (e.g. cadmium, lead) and MOHs (mineral oil hydrocarbon).

Table 4 shows a summary of pollutants and disposal routes in WEEE and presents different treatment routes as well as examples of further uses of the recyclates per polymer.

Table 4: Summary of pollutants and disposal routes of products identified as relevant in the electrical sector

Plastic type	Product	Pollutants	Collection	Treatment and disposal	In the case of recycling: examples of further use of the recyclates
PE	Smaller parts in large household appliances	POP-BDE, DP, TBBPA	Separate collection via municipal collection points or via take-back systems of manufacturers and distributors; small appliances partly via residual waste	Target plastic of recycling, but no precise data on recycling rate available.	Use again in small household appliances possible, but also other applications
PP	Mainly in housings of large household appliances, but also in small household appliances	POP-BDE, DP, TBBPA	Separate collection via municipal collection points or via take-back systems of manufacturers and distributors; small appliances partly via residual waste	Target plastic of recycling, but no precise data on recycling rate available.	Use again in small household appliances possible, but also other applications
ABS	housings of IT and telecommunication equipment, but also in large household appliances.	POP-BDE TBBPA, DP, UV-328	Separate collection via municipal collection points or via take-back systems of manufacturers and distributors; small appliances partly via residual waste	Target plastic of recycling, but no precise data on recycling rate available.	Use again in small household appliances possible, but also other applications
PS	Housing of various large appliances, but can also be found in small appliances	HBCDD, TBBPA, phthalates, DP	Separate collection via municipal collection points or via take-back systems of manufacturers and distributors; small appliances partly via residual waste	Target plastic of recycling, but no precise data on recycling rate available.	Use again in small household appliances possible, but also other applications
PVC	Especially in cables	Phthalates, SCCP, MCCP, TCEP	Separate collection of cables at material yards	Largely energy recovery	No specific information available
Other polymers	Products in different WEEE categories with different proportions	If flame retardant: POP substances (SCCP, POP-BDE, HBCDD), Dechloran Plus, TBBPA (With ABS. Otherwise: UV-328)	Separate collection via municipal collection points or via take-back systems of manufacturers and distributors; small appliances partly via residual waste	Energy recovery: 78 % Mechanical recycling: 20 Raw material recycling: 1 % Landfill: 1 %	No specific information on selected polymers

Source: Own illustration Ramboll/IVV

3.2 Existing process chains for WEEE

WEEE is collected at collection points for WEEE according to collection groups (§§ 13 f. ElektroG) and handed over to EBA for further processing. These primary treatment facilities carry out manual and mechanical treatment steps to remove harmful substances and recover recyclable materials. This results in plastic fractions that are enriched according to the collection group and in some cases also according to the type of equipment.

The following collection groups will be presented in more detail in this chapter with regard to the treatment processes and process chains used:

- Collection group 1: Heat exchangers
- Collection group 2: Display screen equipment with screen surface > 100 cm^2
- Collection group 4: Large appliances with an edge length > 50 cm
- Collection group 5: Small appliances and small devices of information and telecommunication technology with an edge length < 50 cm

Collection groups 3 (lamps) and 6 (photovoltaic modules) are not considered further in this project, as they only account for a small proportion of the total amount of plastics in the EEEs relative to the other collection groups (compare chapter 3.1.1).

In the subsequent treatment, the plastic fractions, which are usually mixed, can be further sorted in order to produce pure plastic fractions for recyclate production. The extent to which a company is involved in the entire process chain can vary greatly (information based on expert interviews).

3.2.1 Primary treatment WEEE

The primary treatment of WEEE in Germany must be carried out by certified Primary treatment facilities (EBAs) in accordance with § 21 (1) ElektroG. The Ordinance on Requirements for the Treatment of WEEE (EAG-BehandlungsV) sets requirements for the primary treatment of WEEE with regard to the removal of hazardous substances, separation of recyclable materials, dismantling, shredding, recycling, other recovery and preparation for disposal.

Defined components with a high pollutant or resource potential must be removed before coarse mechanical shredding. This applies to printer toners and ink cartridges, photoconductor drums containing cadmium or selenium, components containing beryllium oxide, certain printed circuit boards, PMMA and PC discs from flat screen devices, liquids and gases, and components containing radioactive substances.

After mechanical shredding, remaining mercury-containing components, batteries and accumulators, printed circuit boards, brominated flame-retardant plastics, fluorocarbons, LCDs with a surface > 100 cm^2 as well as backlit displays with gas discharge lamps, external electrical cables, refractory ceramic fibers and capacitors containing polychlorinated biphenyls must be removed.

Some facilities focus exclusively on the primary treatment of one or more collection groups or on certain types of equipment (e.g. data media or desktop PCs). For example, small EBAs such as social workshops may only treat a few tonnes of WEEE per year, while large EBAs first treat several 10,000 t/a (information based on expert interviews).

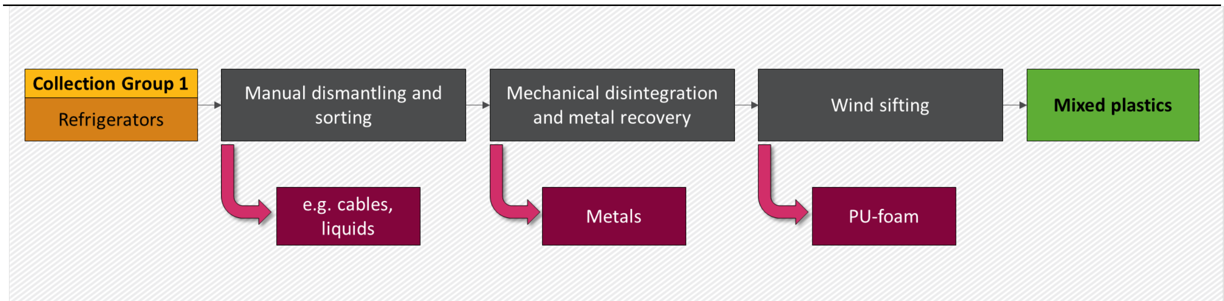
Experts interviewed from the operation of EBAs state that manual and mechanical process steps are used for the proper primary treatment of composite decomposition, removal of pollutants and impurities and sorting of recyclable materials; the degree of automation differs from EBA to EBA and the process chains also differ from collection group to collection group.

In the following, the processes used are explained in more detail for each collection group with regard to the plastic sorting fractions produced, which can be processed for mechanical recycling in the subsequent treatment.

Collection group 1: Heat exchangers

Degassed refrigeration appliances from German collection group 1 (CG 1, groups as listed in § 14 para 1 of the German ElektroG) must be treated in encapsulated facilities in accordance with German Technical Instructions on Air Quality Control (TA Luft) in order to prevent uncontrolled losses of foaming agents. After mechanical shredding of the drained casings, metal parts, plastic parts and the polyurethane foam are separated from each other, resulting in a mixed plastic fraction containing mainly thermoplastics (Figure 5). The polyurethane foam is ground to release and capture the foaming agent bound in the pores. The remaining foaming agent residues can be removed by additional treatment steps (e.g. application of heat). The polyurethane fraction would usually be recycled for energy (information based on expert interviews).

Figure 5: Recycling of appliances of collection group 1 (refrigerators) in EBAs



Source: Own illustration, Fraunhofer IVV

The share of plastics amounts to about 30% of the total input of an EBA surveyed in the course of the interviews. Of these 30%, PS makes up the main plastic type of CG 1 with about 65%. Other existing plastic types are PU, ABS and PMMA (information based on expert interviews) as well as PP and PVC (Wäger et al., 2009). Shelves and drawers can be removed manually before machine shredding for separate marketing as mono-fractions, but this only happens when the market situation is favourable. The mixed thermoplastic fraction contains halogenated and halogen-free plastic qualities and can be further processed in the subsequent treatment. The subsequent treatment usually takes place in Germany or nearby European countries (information based on expert interviews).

Collection group 2: Screens, monitors and equipment containing screens with a surface area of more than 100 cm².

Display screen equipment with a screen area > 100 cm^2 is first subjected to manual dismantling and sorting to remove pollutants. CG 2 comprises various types of equipment that are treated differently by EBAs but have similar material compositions in terms of plastic qualities, including flat screen monitors with liquid crystal display (LCD), CRT monitors, LED monitors and plasma monitors. Manual composite disintegration produces coarse-grained plastic fractions that contain small amounts of non-plastic materials (e.g. screws).

The above-mentioned display units have typical material compositions. Display screen equipment contains in particular flame-retardant and flame-retardant-free ABS, PS and PC/ABS as the main plastic types. PMMA panels from flat panel displays can be sorted by EBAs as a mono-fraction for mechanical PMMA recycling.

Depending on the input composition of the EBAs, the plastic content varies considerably. CRT monitors, for example, are usually much heavier than flat screens, contain higher levels of brominated flame retardants and their quantities fluctuate greatly throughout the year, while flat screens contain a higher proportion of plastic blends. Overall, there is a clear decrease in the amount of CRT screens in EBAs, and regional differences in the amount can also be observed. What all types of equipment have in common is that they are first dismantled, usually manually, in order to remove pollutants and make them available for professional reprocessing or recycling. Through the manual removal of pollutants, the plastics of display screen equipment can be separated from the remaining materials of this equipment and passed on to subsequent treatment facilities.

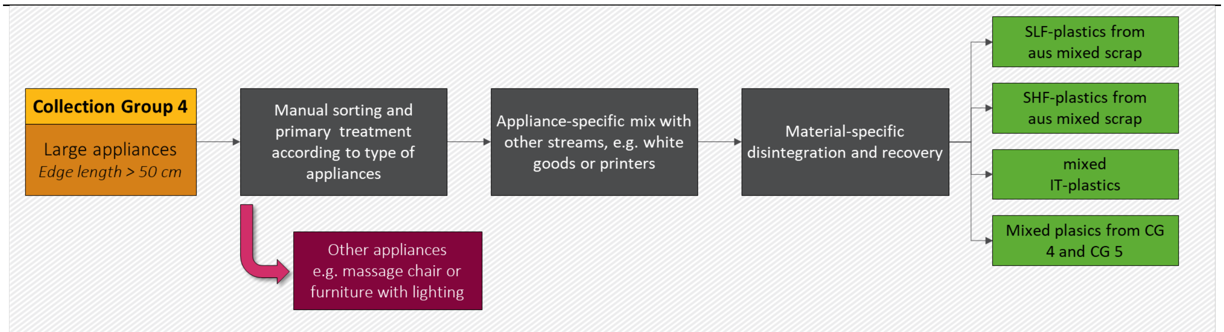
Typical plastic-rich sorting fractions from manual dismantling are cables, circuit boards, enclosure plastics and PMMA discs. The composition of the plastic fractions of the housing varies according to the types and quantities of equipment and also with whether EBAs separate the housing plastics of the different types of display screen equipment or collect them together. A generally valid statement about the composition in terms of plastic yields and qualities can therefore not be made.

Collection group 4: Large appliances

Large electrical appliances containing components to be removed must be identified and dismantled and de-polluted before the first shredding. They may then be fed into a mechanical shredding facility (LAGA, 2018) (information based on expert interviews).

Shredding companies can also act as certified EBAs for CG 4. In addition to de-pollution, EBAs usually sort the classic white goods and appliances that are similar to CG 5 appliances manually, based on their material composition and condition. This enables to treat them in an appliance-specific manner (Figure 6).

Figure 6: Recycling of appliances in collection group 4 (large appliances) in EBAs



Source: Own illustration, Fraunhofer IVV

White goods

Since robust shredding processes are required for the mechanical disintegration of the white goods that have been removed from the pollutant load, they are handed over to shredding companies for further processing after primary treatment in waste incineration plants, where they are shredded together with other scrap in this country. This produces ashredder light fraction (SLF) and ashredder heavy fraction (SHF), with flyable plastic parts accumulating in the SLF and others in the SHF. Interviewed experts from the Netherlands and France state that white goods are treated as a mono-batch. This is desirable from an ecological perspective, but is more expensive.

The dominant type of plastic in white goods is PP, followed by PUR, ABS, PS (Wäger et al., 2009). White PP of CG 4 is usually highly filled.

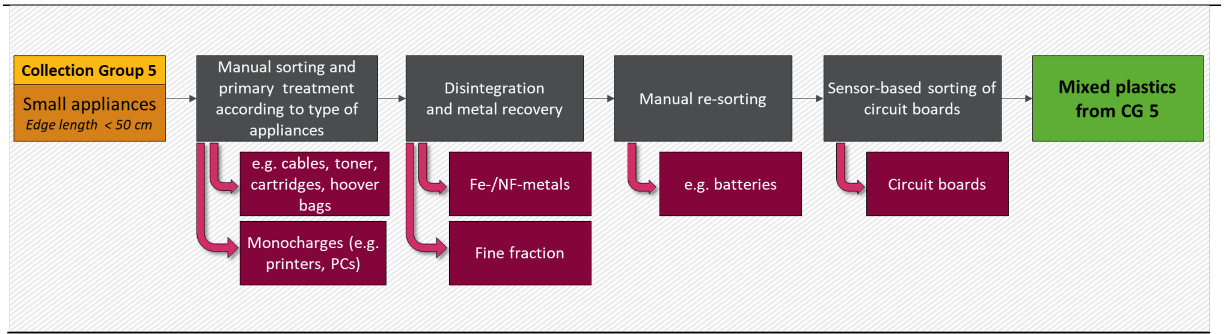
Large appliances with similar material composition as appliances of collection group 5

WEEE collected as large appliances with a material composition similar to CG 5, such as large printers or vacuum cleaners, are transferred by EBAs to other treatment chains. According to the information provided by an EBA, the share of appliances that are transferred from CG 4 to the treatment of appliances in CG 5, for example, is 14 - 15 %.

Collection group 5: Small appliances and small devices of Information and telecommunications technology

The primary treatment of equipment in CG 5 is carried out in complex interconnected plants, which differ in their design from one EBA to the next. Figure 7 schematically shows a possible process chain for primary treatment.

Figure 7: Recycling of appliances of collection group 5 (small appliances and small ICT devices) in EBAs



Source: Own illustration, Fraunhofer IVV

The following practical example is intended to illustrate the complexity and typical process steps of an EBA: In the reprocessing of appliances in CG 5, about 300 intermediate products are produced here in order to sort recyclables and separate out interfering and harmful materials. First, components that are accessible from the outside and need to be removed (e.g. hoover bags, external cables) and recyclables (e.g. desktop PCs) are removed. Then the material stream is roughly broken down and the resulting fine fraction is separated to ensure subsequent sorting in the optimal particle size range. Once again, parts that need to be removed (e.g. batteries or copper-containing recyclables) are removed manually before the material is further shredded, sorted and damaged and contaminated components are removed manually again. After a further shredding stage, fine grain separation and Fe/NE metal removal, an automated sensor-supported sorting of the PCBs and a further metal recovery stage takes place. In smaller EBAs, the proportion of manual process steps can be higher. For example, PCBs are also sorted out manually. According to information from a larger EBA, about 25% of the total input accumulates as plastic-rich output fractions from CG 5. This includes PCBs, fines, cables and a sorting fraction of mixed plastics. The mixed plastics fraction is passed on to downstream processors and accounts for about 2/3 of the plastics.

The plastic types PP, ABS (bromine-containing and bromine-free), PS (bromine-containing and bromine-free) and PC/ABS dominate. Other materials present are usually metals (e.g. 5 -10%), wood, elastomers, paper and, to a lesser extent, other plastics such as POM, PU, PA, PPO/PS and other blends.

After this treatment in EBA, companies market the plastic-rich residual fraction of the sorting for subsequent treatment within Germany, within Europe, but also to non-European countries (information based on expert interviews).

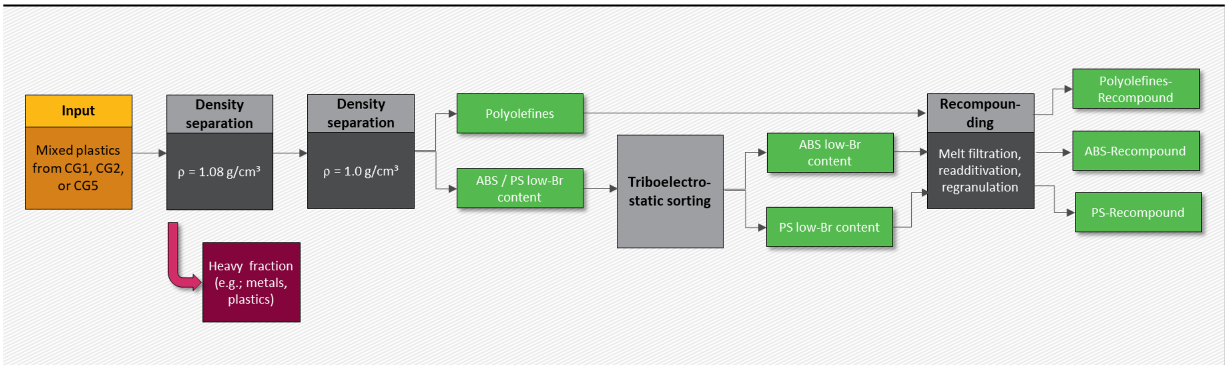
3.2.2 Follow-up treatment WEEE

Downstream handlers state that the sorting fractions they receive from the individual EBAs differ somewhat in composition from EBA to EBA, but that the sorted material is delivered by the respective EBAs in a fairly constant composition and that the material of an EBA is therefore only subject to minor fluctuations.

Preferred grain sizes as input for the subsequent treatment are > 10 mm, for example, inputs in grain sizes > 6 mm are processed by a subsequent treater. Downstream processors treat PP-, PS- and ABS-rich input fractions which, in addition to the foreign plastics PA, PC, PC/ABS, POM and PVC, also contain other foreign materials such as other plastic types and qualities (for example glass- or carbon fiber-reinforced plastics and elastomers) and unusual plastic blends, as well as residual metals (e.g. 3 - 8%), wood, paper and batteries and traces of mercury and cadmium. Not all composites are broken down in EBAs, so that 2-component, 3-component, 4-component composites may be contained in the input. In particular, bonded composites and screw connections can be found in the input.

Core technologies of applied industrial processing of plastic-rich sorting fractions are density-based and electrostatic sorting processes. Figure 8 illustrates the sequence and sorting tasks of these essential process steps.

Figure 8: Processing of the plastic-rich WEEE sorting fractions from EBAs



2-stage density separation with subsequent electrostatic sorting

CG: Collecting group

Source: own illustration Ramboll/IVV

In the first stage, materials with a density > 1.08 g/cm^3 or 1.09 g/cm^3 are separated. In the light fraction, the low-bromine and bromine-free target plastics ABS, PS and PP and, in small proportions, other foreign materials with a density lower than that of the separation medium, such as wood, elastomers and other foreign plastics, are enriched. The light fraction is then sorted by a further density separation step at 1.0 g/cm^3: the low-bromine and bromine-free plastics ABS and PS, and to a lesser extent mineral-filled PP, are enriched in the heavy fraction, and unfilled polyolefins are enriched in the light fraction. The density sorting fraction enriched with ABS and PS 1.0 g/cm^3 < ρ < 1.1 g/cm^3 is further separated into an ABS and a PS fraction by electrostatic sorting. Plastics with a density > 1.1 g/cm^3 are usually separated via the heavy fraction, which contains, for example, a large part of PA, PC, PC/ABS, PVC, POM and PMMA; PP+talc can also have a density > 1.1 g/cm^3 (information based on expert interviews).

The process illustrated in Figure 8 is supplemented by various treatment processes such as mechanical comminution, Fe/NE metal removal, screening, sludge separation, heavy material traps, various classifiers, rubber separation, wood separation and spectroscopic processes or also by further density separation steps or spectroscopic sorting processes in order to separate foreign materials from the target material and to recover further valuable materials. Thus, a metal fraction is usually also produced as a further recyclable material fraction for further material processing. One recycling company has also succeeded in sorting PC/ABS regrind by type (Müller-Guttenbrunn Group, 2019). After the production of single-grade regrind, homogenisation can take place in large agitated silos to prevent quality fluctuations in compounding.

The yields differ from material stream to material stream. For example, yields of 70% can be achieved for plastic-rich input fractions from refrigerators in CG 1. The achievable yields from display screen equipment in CG 2 are largely dependent on the type of equipment. This must also be taken into account for CG 4: the yields depend on appliance groups, e.g. white goods with rather low yields due to the high proportion of highly filled polyolefins or large ICT appliances. From a mixed plastics fraction of CG 5, about 50 % of the plastics are recovered on an industrial scale as single-grade PP, low-bromine ABS and low-bromine PS. PP accounts for about 10 % points of this, ABS and PS for the rest in roughly equal parts. The exact yields vary from recycler to recycler due to differences in process combinations and inputs.

In the following, the determined bromine contents of the plastic-rich sorting fractions of a comprehensive pollutant analysis of various real WEEE streams are presented, which were analysed comprehensively in a study commissioned by the Norwegian Environment Agency.

Table 5: Bromine contents of plastic rich sorting fractions from WEEE

Fraction	Bromine content in mg/kg
PS, ABS and PE/PP regrind sorted from refrigerators	< 300
Heavy fraction from refrigerators	< 1,250
Coarse and fine shredder fractions from large WEEE	< 250
ABS, PS and PE/PP regrinds of plastic-rich sorting fractions from small EEEs	< 1,000
Heavy fraction from small EEEs	maximum value 12,330

Source: Norwegian Environment Agency, 2021The target plastic-enriched regrinds are refined by homogenisation, extrusion, melt filtration, readditivation and regranulation. Melt filtration is usually carried out with melt filters in the size of 180 µm. To modify the recyclate properties, additives are added to improve the impact strength, phase mediators and other additives depending on the desired modification.

The recyclates are produced in different qualities on an industrial scale. Very high purities (>98 %) can be produced, allowing the production of high-quality recyclates through customised re-compounding. EU-RoHS and EC-REACH compliant plastic fractions are further marketed.

The products can be recycled compounds with qualities similar to virgin material, which can be used in new EEE or vehicles, for example. They can also be reused in construction, gardening and 3D printing filament production (information based on expert interviews).

3.2.3 Barriers and obstacles to WEEE plastic recycling

In 2019, approx. 4.6% of plastics were recycled in relation to the total mass of WEEE. In terms of the share of plastics, this corresponds to a rate of 17.6 %. The total amount of recyclate used in the WEEE sector in 2017 was 3.2 % of the amount of plastic used (2019: 3.5 %). Post-consumer recyclates accounted for around 1.1 %.

Various reasons/inhibiting factors are cited in the literature and discussions with stakeholders as reasons for the comparatively low recovery of recyclates from post-consumer waste of WEEE as well as a low recyclate use rate in EEE:

- Poor image of recycled plastics;
- Mismatch of quality, price and volume (primary plastics versus secondary plastics) and thus lack of economic efficiency;
- Insufficient quality (e.g. with regard to material properties, pollutant content, impurity content, etc.);
- Lack of availability of data on recyclates (e.g. to indicate substance contents for the SCIP database);
- Insufficient communication between producers and recyclers;
- Logistical problems in the dismantling of plastic parts;
- Diversity of polymers;
- Mixing of plastic fractions in large shredders;
- Lack of separability of fractions containing pollutants, composites, coated plastics, unusual polymer blends, reinforcing materials;
- Insufficient availability in consistent quantity and quality;
- Lack of demand;
- Lack of recycling capacities (e.g. insufficient sensor-based technologies for identification and separation);
- High investment costs combined with legal uncertainty and consequent lack of willingness to invest; and
- Uneven framework conditions within the EU and the handling of hazardous waste, which complicate or hinder intra-European trade.

Possible measures to promote recycling should take these reasons/inhibiting factors into account and identify suitable promoting factors.

3.3 Practical trials to derive suitable separation and recycling strategies - WEEE trials

From the exchange with experts on technical issues of separation for plastics from WEEE and ELVs, two test series each for WEEE plastics and two test series for end-of-life vehicle plastics were derived. The aim was to specifically gain new knowledge that goes beyond the state of the art for the derivation of separation strategies and recommendations for measures.

- Regarding WEEE, the trials were:
  - Recycling of high-fill polyolefins from separately shredded white goods; and
  - Dry mechanical sorting of WEEE plastics of CG 5 (small appliances).

3.3.1 Recycling of highly filled polyolefins from separately shredded white goods

White goods are collected together with other large appliances in CG 4 of the WEEE collection. They are separated from other appliances, submitted to primary treatment and then usually broken down together with other mixed scrap in large shredders. Non-metallic materials of the mixed scrap feed accumulate in the SLF and in the residues of the SHF, including the polyolefins and, to a lesser extent, other plastic types of the white goods. Polyolefins are the main type of plastic in the white goods and are often mineral-filled or glass-fiber reinforced.

Concept

The test series is intended to provide information on possible polyolefin recyclate qualities that can be achieved via a separate recycling chain for white goods without cross-contamination from other input streams.

After primary treatment, 108 t of white goods were collected and recycled by a large shredder company for a separate shredding trial. The shredder residue fractions $SLF_{<12mm}$ and $SHF_{<20mm}$ were sampled, as the respective larger screen fractions were not accessible for the planned sorting and cleaning processes. Initial laboratory results of the input characterisation served as a basis for the decision to recover highly filled polyolefins from the $SHF_{<20mm}$.

The polyolefins of the $SHF_{<20mm}$ were sorted via sieving (5 mm, use of the coarse grain), density separation ($\rho = 1.3\ g/cm^3$, use of the light fraction) and laser-induced fluorescence spectroscopy. The ground material was regranulated and evaluated by an industrial partner. The analytical product evaluation was carried out at the Fraunhofer IVV.

From the sorted polyolefin regrind, the polyolefins were also selectively dissolved to allow insoluble components to sediment.

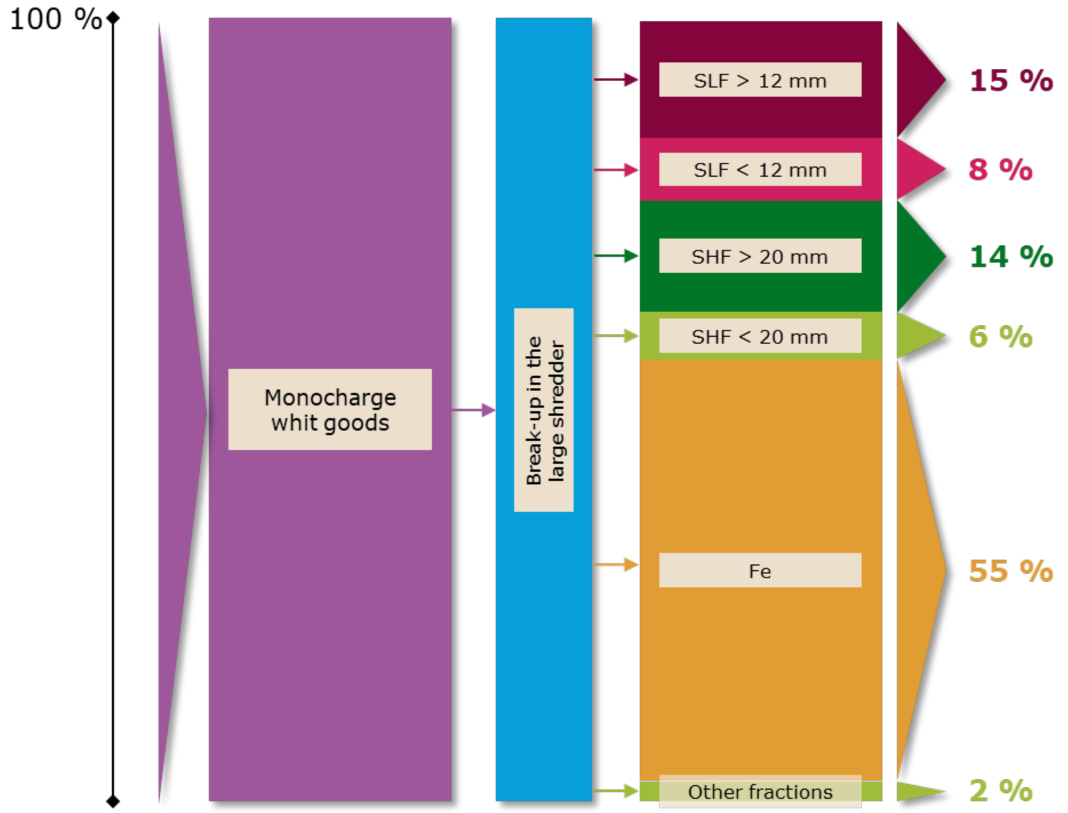
Sorting fractions were characterised and analysed for harmful substances. The analysis of pollutants and interfering substances accompanying the tests includes the quantification of element contents, contents of specific brominated and chlorinated flame retardants, phthalates and BPA.

The three elements silicon, magnesium and calcium were identified in the element content analysis as indicators for typical polymer fillers such as talc (magnesium silicate hydrate) and calcium carbonate.

Results and Discussion

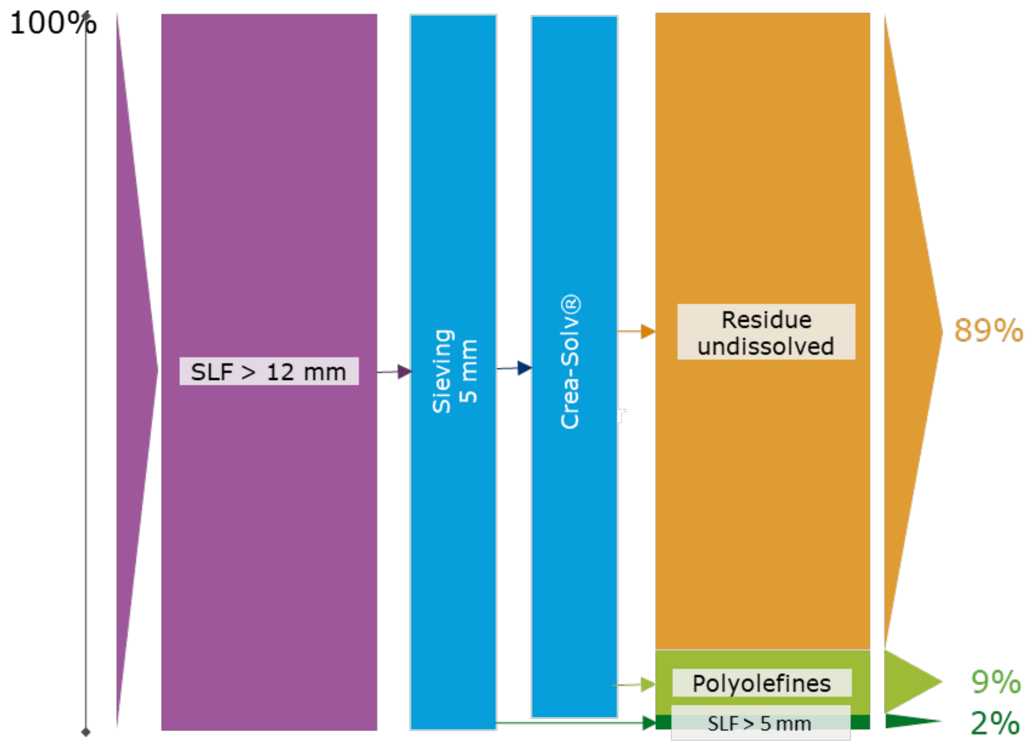
108 tonnes of white goods were fed into the large shredder as input. The mass balances for Polyolefins from white goods, the SLF < 12 mm and the SSF < 20 mm are shown in Figure 9, Figure 10 and Figure 11 respectively.

Figure 9: Polyolefins from (German) collection group 4 – Mass balance large shredder



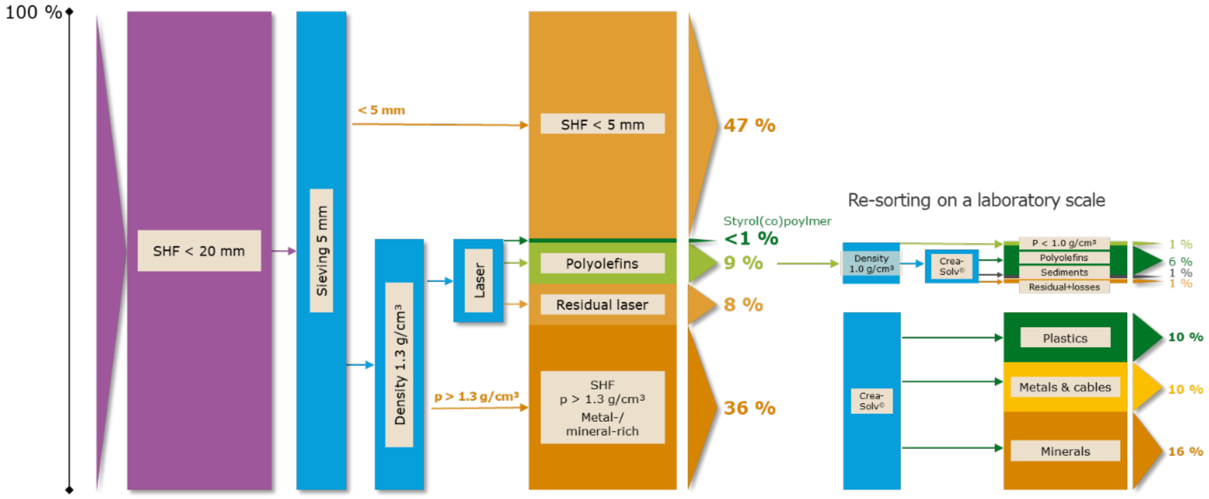
Source: own illustration Fraunhofer IVV

Figure 10: Polyolefins from (German) collection group 4 – Mass balance large shredder SLF < 12 mm



Source: own illustration Fraunhofer IVV

Figure 11: Polyolefins from (German) collection group 4 – Mass balance large shredder SSF < 20 mm



Source: own illustration Fraunhofer IVV

The use of mineral-filled and glass-fiber reinforced plastics has increased in recent years. Thus, the importance of recycling filled plastics is also increasing. For recycling-friendly product design, either processing methods must be established that produce marketable recyclates, or the material selection must already be adapted to available recycling technologies during product development.

The plastics of separately shredded white goods are distributed among all screening fractions of the shredder. The SLF$_{<12mm}$ contains a very high proportion of fines <5 mm and a low polyolefin content (~10%). The SHF $_{<20mm}$ accounted for 6% of the shredder input. The fraction contains a grain size fraction > 5 mm of 53% and is rich in metals and minerals. Metals and minerals were depleted in the test series via a density cut at ρ = 1.3 g/cm^3. 9% polyolefins could be recovered from the SHF $_{<20mm.}$

As expected, the polyolefin yield can be further optimised in the tested process chain; for example, screening of the SHF at 3 mm could be evaluated.

The characterisation of the sorted polyolefins shows a high filler content. Regrind qualities were produced that are within the expected range of mineral-filled polyolefins and are suitable for high-quality recycling. Due to the high proportion of light-coloured plastics, NIR sorting could also perform efficient sorting, although the yield would probably be lower by the proportion of dark polyolefin grades.

Product qualities can be further improved by evaluating colour sorting to separately enrich the high proportion of light-coloured polyolefins. Sedimentation in the solvent-based CreaSolv® process has proven to be a suitable method to remove mineral fillers from the PP to further increase product qualities.

The coarse fractions SLF$_{>12\ mm}$ and the SHF $_{>20mm}$ require further PST processing steps to prepare them for plastics characterisation and sorting. These two coarse fractions of the shredder residues account for 29% of the shredder input, so enrichment of thermoplastic hard plastics for further processing can increase the yields achieved. The results described in chapter 4.2.3 appear to be suitable for this preparation from a technical point of view.

The element contents of Mg, Si and Ca prove the expected high filler content in white goods plastics.

A consideration of the element loads shows that about half of the fillers are separated via the screen cut at 5 mm and approx. 47 mass% are removed from the input stream. On the other hand, the displacement of the fillers into the sorting residues of the spectroscopic sorting is marginal. Both findings were to be expected, the small grain fraction contains more or less the same materials, so that no concentration is to be expected in the fine grain and thus the filler depletion is accompanied by the plastic stream. The lack of purification via the sorting residues is because in the case of white goods, fillers are mainly used in the polyolefin range.

Heavy metal contents were reduced more significantly. An examination of the cadmium and lead loads shows that a large proportion of the elements were shifted to the fine fraction smaller than 5 mm. The sorting residues and the fine fraction also offer a sink for phosphorus and chlorine.

Analytical results for the content of selected element are shown in Table 6.

Table 6: Polyolefins from white goods – selected analytical results 1, element contents (all values in mg/kg)

Description	Mg	Si	Ca	P	Cl	Cr	Br	Cd	Pb	Hg
Input fraction										
Input SHF < 20 mm	1,495	33,280	121,900	53	1,798	1,009	643	n.b. < 5	954	n.b. < 5
Side fractions										
Fine fraction < 5 mm	1,670	30,230	139,200	78	2.061	764	55	n.b. < 5	1,054	n.b. < 5
Sorting rest Laser	2,063	8,425	13,440	454	635	54	963	n.b. < 5	26	n.b. < 5
Sorting rest density	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Target fractions										
Styrol(co-) polymers	134	1,038	2,995	142	648	79	136	12	8	n.b. < 5
Polyolefins	2,252	9,516	29,960	104	16	111	442	n.b. < 5	12	n.b. < 5
CreaSolv® Polyolefins	461	1,231	62,000	14	17	47	7	n.b. < 5	n.b. < 5	n.b. < 5
CreaSolv® sediment	6,475	20,620	343,700	101	51	n.b. < 5	79	n.b. < 5	n.b. < 5	n.b. < 5

The specific flame retardant analysis of the styrene (co)polymer fraction shows low levels of TBBPA (111 ppm) and HBCDD (8 ppm), so there is no legal limit which would hinder the marketing of the regrind. The chlorine content of approx. 650 ppm cannot be attributed to the presence of dechloranes (e.g. Dechlorane Plus); the contents of this chlorinated flame retardant were below the limit of determination. It is therefore suspected that small amounts of PVC particles were missorted into the polystyrene fraction. With TBBPA, BTBPE, DecaBDEthane and DecaBDE contents of less than 150 ppm each, the polyolefin product also has marketable regrind qualities from a pollutant law perspective.

An examination of the fractions of specific polybrominated flame retardants reveals that the highest TBBPA, BTBPE and DecaBDE fractions are present in the sorting residues fraction, which also explains the low residual contents in the target fractions.

The analysis of bisphenol A and phthalates only shows traces below 50 ppm. Interesting is a bisphenol A value of 16 ppm in the sorting fraction polystyrene, which could indicate PC/ABS shares, because bisphenol A is a typical monomer in polycarbonate (PC) production. DEHP contents below 50 ppm in the polystyrene and polyolefin regrinds are considered to be less critical and could be explained by soft PVC contents or PVC-containing coatings.

Analytical results of the contents of selected flame retardants are shown in Table 7.

Table 7: Polyolefins from white goods – selected analytical results 2 – flame retardants (all values in mg/kg)

Description	HBCD	TBBPA	BTBPE	Deca-BDEthan	BDE-209	Dechloran	BPA	DEHP
Input fraction								
Input SHF < 20 mm	n.b. < 5	11	n.b. < 5	n.b. < 10	n.a.	n.a.	n.a.	n.a.
Side fractions								
Fine fraction < 5 mm	n.b. < 5	n.b. < 5	9	n.b. < 10	n.b. < 10	n.a.	n.a.	n.a.
Sorting rest Laser	n.b. < 5	222	229	184	482	n.b. < 20	n.a.	n.a.
Sorting rest density	n.b. < 5	n.b. < 5	n.b. < 5	n.b. < 10	n.b. < 10	n.a.	n.a.	n.a.
Target fractions								
Styrol(co-) polymers	8	111	n.b. < 5	n.b. < 10	n.b. < 10	n.b. < 20	16	27
Polyolefins	n.b. < 5	30	49	144	46	n.a.	3	48
CreaSolv® Polyolefins	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
CreaSolv® sediment	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

The series of tests shows a way to produce a mechanically recyclable regrind fraction from separately shredded white goods - after separation of fines, fluff and heavy materials such as metals, glass and stones - via spectroscopic plastic type sorting, which can be further refined in re-compounding.

3.3.2 Dry mechanical sorting of WEEE plastics of collection group 5

At the end of their useful life, the collection and primary treatment of WEEE in CG 5 entails a mixture of plastic qualities containing and not containing halogenated flame-retardants from different components and appliances. The recycling of plastics is a special challenge due to the high material flow heterogeneity and pollutant load and the high proportion of polyolefin and styrene (co-)polymer qualities that can be recycled. In the WEEEsense project funded by the Federal Ministry of Education and Research (funding code 033RK063), the project partners set themselves the goal of producing high-quality ABS, PS and PC/ABS plastic compounds from WEEE via a dry-mechanical process chain. The synergies with this project were used to carry out a material flow analysis on the sorting fractions of the process chain.

Concept

Plastic-rich sorting fractions > 10 mm were generated from 104 kg of first-treated small household appliances and 396 kg of consumer electronics appliances, which represent the input of the spectroscopic process chain considered here. Thus, a total of 79 kg of plastic-rich fractions > 10 mm were obtained via primary treatment, shredding, metal removal and screening.

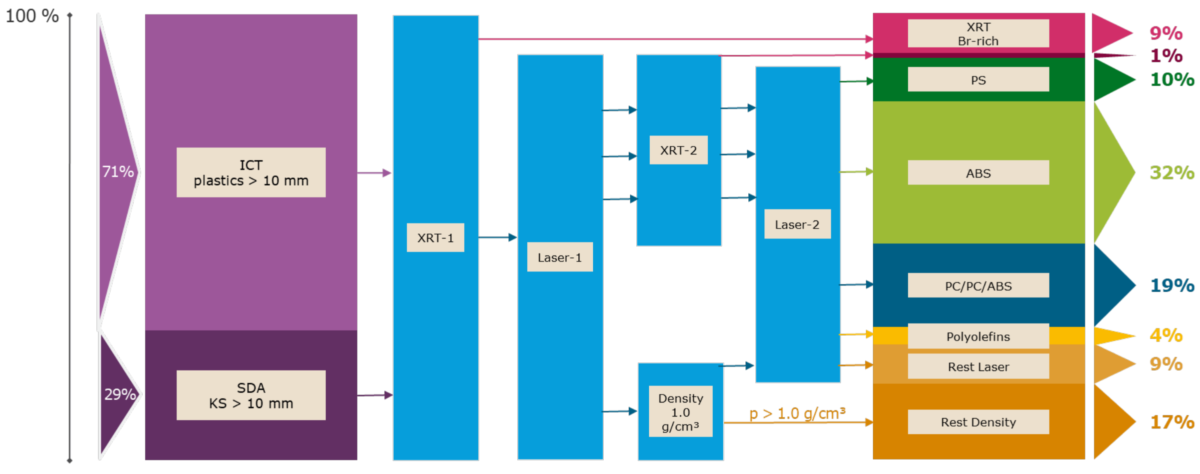
The sorting objective of the dry mechanical treatment was the targeted removal of brominated-flame retardant plastics and the production of high-quality, unmixed ABS, PS and PC/ABS regrind fractions. For this purpose, bromine-rich plastics were depleted via a two-stage XRT sorting process. The generated low-bromine output fractions were each sorted separately by laser-induced fluorescence spectroscopy. From the sorting residue of the first plastic type enrichment, the polyolefins were recovered via density separation. Finally, the target plastic-rich sorting fractions were post-purified via a second sorting stage using laser-induced fluorescence spectroscopy.

The analysis of pollutants and interfering substances accompanying the tests includes the quantification of element contents, contents of specific brominated, chlorinated and phosphorus-based flame retardants, phthalates, PFAS, BPA and PAH.

Results and Discussion

Across the entire process chain, a total of 32 % ABS, 10 % PS, 19 % PC+PC/ABS and 4 % polyolefins were recovered as unmixed regrind. A total of 10% of the plastics accumulated in the bromine-rich XRT rejects, while a further 26 % accumulated as residues from sorting via laser-induced fluorescence spectroscopy or density fractionation. The following figure shows the mass balance.

Figure 12: Collection group 5 – mass balance



ICT: devices of information and communication technology , SDA: small domestic appliances

Source: own illustration Fraunhofer IVV

In the test series, PC/ABS as well as low-bromine and high-bromine ABS and PS regrind fractions were enriched via a dry-mechanical process chain. Polyolefins were recovered via a density separation cut; the sorting task could also be integrated into the spectroscopic process chain.

One advantage of the dry-mechanical process chain is the flexibility of the sorting units used. Spectroscopic XRT sorting is also suitable for halogen depletion of other sorting streams (e.g. PVC separation) and for metal sorting. Laser-induced fluorescence spectroscopy can be used flexibly for diverse target plastics.

Another advantage lies in the targeted concentration of pollutant-contaminated qualities to feed them into a pollutant-appropriate treatment. The solution-based CreaSolv® process enables the recovery of bromine-free ABS and PS qualities through a special purification process for halogenated contaminated additives (Wagner & Schlummer, 2020). A sharper calibration in both the first and second sorting stages could increase bromine depletion without the need for another XRT sorting step to achieve target values < 1,000 mg/kg bromine for the target plastic fractions ABS, PS, PC/ABS and polyolefins.

PC/ABS sorting via laser-induced fluorescence spectroscopy opens the possibility of further increasing WEEE plastic yields. An integration of laser-induced fluorescence spectroscopy into the state-of-the-art process chain can provide or support the additional recovery of PC/ABS, as well as ABS and PS from a bromine-contaminated density fraction $\rho > 1.08$ g/cm^3.

The samples from the reprocessing trials of plastics from CG 5 of the WEEE collection were subjected to a broad spectrum of analyses. At the beginning, XRF analyses were carried out again, which primarily detected high bromine contents of 250-67,000 ppm and chlorine contents of 10 - 4,150 ppm. Phosphorus was also conspicuous with concentrations of 19 - 3,180 ppm. In contrast, the levels of chromium, cadmium, lead and mercury were lower and in many cases below the limit of quantification. Overall, the contamination with heavy metals is assessed as low.

Based on the analytical values of specific brominated flame retardants, it can be confirmed that the process developed within the framework of the SME innovative project WEEE Sense (FKZ: 033RK063) and analytically monitored here via dry XRT sorting achieves a comparably good separation of brominated flame retardants as the technology established in Europe via wet sorting in aqueous sealing solutions.

The phosphorus concentrations are not increased in the XRT rejects and there was a shift to the target fraction PC/ABS with about 3,000 ppm. This is also confirmed in the specific analysis of phosphorus-containing flame retardants. Of the seven substances investigated, only triphenyl phosphate (TPP) could be determined in relevant concentrations and here, too, the accumulation of TPP in the PC/ABS was easily traceable. TPP could degrade under the thermal stress of re-extrusion and thus impair the mechanical properties of the recyclate. The contents of bisphenol A and phthalates are in the lower ppm range, only DEHP reaches the value of 540 ppm in one input sample. Due to the low concentration in the final products, the relevance of both substances/classes of substances is considered to be low.

Furthermore, perfluorinated and polyfluorinated substances were analysed. For this purpose, the input samples from consumer electronics and small household appliances as well as PC/ABS were focused on, the former to assess the initial exposure situation, PC/ABS because of the known use of PTFE as an antidrip agent. The results generally show values below the limit of quantification of about 1 ppb. Levels in the upper ppb range were only determined for perfluorobutane sulfonic acid (PFBS), with values up to 870 ppb measured in PC/ABS. The source of this PFBS amount is unclear, postulated on the one hand is cross-contamination in the shredding process through contact and abrasion of printed circuit boards (the use of PFBS is known in the semiconductor industry) or thermally induced new formation from PTFE, which is used as an anti-drip agent in PC/ABS, during re-extrusion. So far, however, only the formation of short-chain perfluorinated carboxylic acids in thermally loaded PTFE has been determined (Schlummer et al., 2015). Teflon sources or Teflon abrasion are also suspected as the source for the low PFPeA load. All in all, however, the low ppb values are classified as harmless.

Table 8 and Table 9 show analytical results for selected elements and flame retardants.

Table 8: Collection group 5 – selected analytical results 1 (all values in mg/kg)

Description	P	Cl	Cr	Br	Cd	Pb	Hg	HBCD	TBBP A	BTBPE	Deca-BDEthan	BDE-209
Input fractions												
Entertainment electronics Plastics > 10 mm	1,192	227	35	14,550	7	n.b. < 5	n.b. < 5	n.n. < 5	15,650	13	361	234
small household appliances Plastics > 10 mm	274	297	66	2,429	n.b. < 5	38	n.b. < 5	n.n. < 5	2,510	5	184	65
Side fractions												
XRT1 - bromine rich plastics from small household appliances	514	702	302	23,440	6	n.b. < 5	n.b. < 5	n.n. < 5	19,850	54	112	632
XRT1 - bromine rich plastics from entertainment electronics	226	4,148	n.b. < 10	67,110	12	n.b. < 5	n.b. < 5	n.n. < 5	41,500	89	120	544
XRT2 – Recovery bromine rich	158	1,600	132	54,260	10	n.b. < 5	n.b. < 5	52	30,060	81	102	2,288
XRT2 - ABS bromine rich	63	2,543	82	56,100	13	n.b. < 5	n.b. < 5	n.n. < 5	40,420	209	554	1,599
XRT2 - PS bromine rich	19	937	63	55,230	8	n.b. < 5	n.b. < 5	n.n. < 5	11,630	17	n.b. < 10	741
Target fractions												
PC/ABS regrind	3,183	n.b. < 10	13	1,050	n.b. < 5	n.b. < 5	n.b. < 5	n.n. < 5	266	n.n. < 5	10	n.b. < 10
ABS regranulate	137	10	n.b. < 10	844	n.b. < 5	n.b. < 5	n.b. < 5	n.n. < 5	n.n. < 5	n.n. < 5	n.b. < 10	n.b. < 10

Description	P	Cl	Cr	Br	Cd	Pb	Hg	HBCD	TBBP A	BTBPE	Deca-BDEthan	BDE-209
PS regranulate	106	n.b. < 10	50	1,545	n.b. < 5	7	n.b. < 5	n.n. < 5	n.n. < 5	n.n. < 5	n.b. < 10	n.b. < 10
Polyolefins regranulate	30	78	31	254	n.b. < 5	19	n.b. < 5	n.n. < 5	276	n.n. < 5	31	n.b. < 10

Table 9: Collection group 5 – selected analytical results 2 (Values in mg/kg; PFPeA und PFBS in µg/kg;)

Description	Dechloran (syn)	Dechloran (anti)	TPP	BPA	DEHP	16 EPA PAK	PFPeA	PFBS
Input fractions								
Entertainment electronics Plastics > 10 mm	n.a.	n.a.	1,324	24.7	173	n.b. < 10	n.n. < 0,2	606
small household appliances Plastics > 10 mm	9	42	250	9.9	542	n.b. < 10	23	211
Side fractions								
XRT1 - bromine rich plastics from small household appliances	193	703	381	n.b. < 2	n.a.	n.a.	n.a.	n.a.
XRT1 - bromine rich plastics from entertainment electronics	n.a.	n.a.	n.a.	n.b. < 2	n.a.	n.a.	n.a.	n.a.
XRT2 – Recovery bromine rich	35	116	n.a.	n.b. < 2	n.a.	n.a.	n.a.	n.a.
XRT2 - ABS bromine rich	112	44	n.a.	n.b. < 2	n.a.	n.a.	n.a.	n.a.
XRT2 - PS bromine rich	n.a.	n.a.	n.a.	n.b. < 2	n.a.	n.a.	n.a.	n.a.
Target fractions								
PC/ABS regrind	n.a.	n.a.	2,347	49.7	n.b. < 4	3.14	n.n. < 0,2	868
ABS regranulate	n.a.	n.a.	399	16.2	24	1.75	n.a.	n.a.
PS regranulate	n.a.	n.a.	672	3.9	7	1.6	n.a.	n.a.
Polyolefins regranulate	n.a.	n.a.	n.n. < 0,4	2.1	31	n.b. < 10	n.a.	n.a.

The test series shows that PC+PC/ABS as well as low-bromine and high-bromine ABS and PS regrind fractions can be sorted via a dry-mechanical process chain. Sorting brominated-flame retardant plastics by plastic type makes these fractions accessible for pollutant-compatible recovery via solvent-based recycling. Polyolefins can also be sorted spectroscopically.

3.4 Development of separation and recycling strategies - WEEE

Separation and recycling strategies were developed against the background of the available project results.

Concrete options were developed and evaluated in terms of feasibility and effectiveness. From a combination of options considered to be reasonable, higher-level separation and recycling strategies are derived.

As already described in previous chapters, CG 1 (heat exchangers), CG 2 (display screen equipment), CG 4 (large appliances) and CG 5 (small appliances) are in the focus of the closer examination of this study. The following figure shows the status quo of the separation and recycling of the mentioned collection groups of WEEE.

3.4.1 Possible options to increase recycling

The question of where and by what means the total amount of plastic recycled from WEEE can be increased can be considered from several angles:

- What steps do recyclers already take that could possibly be improved (optimisation potential for mechanical recycling of plastics)?
- At which points are plastics lost for mechanical recycling?
- Why are existing (technical) possibilities not being exploited?

As already mentioned in chapter 3.2 manual removal of pollutants and, in some cases, the dismantling of certain components or extraction of certain appliances takes place in the collection groups. Due to the large number of different types of equipment within individual collection groups, plastic enrichment is mostly carried out using PST after the fractions have been crushed and broken up several times. CG 2 (display screen equipment) is an exception here. Further statements can only be made specifically for individual collection groups. Therefore, the following subchapters were structured according to collection groups.

Specifically, the following options were discussed on a collection group basis:

- CG 1
  - Early separation of loose plastic parts
  - Removing flame retardants from plastics containing bromine
- CG 2
  - Separation of PC/ABS from the heavy fraction
  - Removing flame retardants from plastics containing bromine
- CG 4
  - Separate treatment of white goods
  - Processing of filled and contaminated plastics from the heavy fraction

- CG 5
  - Early separation of certain equipment groups before mechanical disintegration
    Separation of PC/ABS from the heavy fraction
  - Remove flame retardants from plastics containing bromine.

3.4.2 Combination of options for developing separation and recycling strategies

By combining individual options in a meaningful way, strategies can be developed. From the individual options for each collection group, it can already be seen that many options can be applied to most collection groups. In this chapter, the possible opportunities and challenges for the individual strategies are described. The technical and economic prerequisites and framework conditions are also described.

3.4.2.1 Early separation of plastic components or equipment groups

In order to promote plastic recycling in the WEEE waste stream, certain groups of appliances or parts of appliances can be separated at an early stage. In this way, certain types of plastic that are specific to the type of appliance or appliance part can be enriched, which means that fewer impurities are present in the recycling process. The higher quality of the input stream achieved in this way then enables the targeted recycling of certain types of plastic and generally higher yields. The recyclate obtained is then also of a higher quality and can thus be reused in high-quality applications. The earlier certain plastic parts or streams are separated in the recycling process, the higher yields and qualities can be achieved, but this is always associated with additional costs (expert opinion workshop).

In general, the degree of separation depends on the respective collection group. In the case of collection groups with a small number of different types of equipment, individual frequently occurring equipment parts can be removed and the plastics of these parts can thus be enriched. In today's practice, for example, cables, housings and PMMA discs are already removed manually from CG 2 and then passed on to subsequent processors. In the case of CG 1, a pre-treatment is also carried out, whereby the coolant is extracted. As part of this process, frequently occurring plastic parts such as drawers and compartments could also be removed in order to create sorting fractions with a low content of impurities.

In the case of collection groups with a high number of different appliance types, the effort to remove individual appliance parts is comparatively high, which is why the approach of separating certain appliance types is considered more effective here. In doing so, the plastic types of this type of appliance can be enriched, which can facilitate downstream recycling. In the case of CG 4, for example, the white goods could be separated and treated separately, as this type of appliance is currently combined with the ELVs and processed together in Germany. For CG 5, before the introduction of the new German collection groups in December 2018, IT and telecommunication equipment was already separated ahead of time and treated separately, which could again be carried out.

Collection groups 3 and 6 were not considered here, but this strategy could also be applied to these collection groups.

In general, the aim of this strategy is to create purer fractions, which simplifies the downstream recycling process and increases the yield and quality of the recyclate. However, due to the variety of types in the individual parts and types of equipment, this strategy cannot produce pure fractions, which means that post-treatment is still necessary.

For separation, however, storage space would first have to be created to store the sorted parts. For example, the refrigerator and freezer drawers and compartments require a relatively large storage area due to their design. The same applies to sorted white goods or IT and telecommunications equipment. Furthermore, the sorting process creates a time burden for the EBAs. Since some dismantling processes are already established (e.g. removing coolants from freezers), further sorting steps could simply be integrated into them. In addition, in the example of freezers and refrigerators, the drawers and compartments can be removed without additional unscrewing or dismantling. In the case of the other collection groups, the sorting rate does not have to be 100% either, because even a waste stream with a clearly defined type of appliance can simplify recycling.

In CG 1 in particular, the removal of drawers and compartments is already considered state of the art. Work is currently underway on VDI 2292, which sets out the state of the art in the treatment of refrigeration appliances. According to experts, this also includes the removal of drawers and compartments, which is why it can be argued that this strategy will not result in any additional work for CG 1. However, some EBAs said that the removal would not be worthwhile because the plastic parts are very large but weigh very little, which would result in high transport and storage costs. The removal would therefore not be worthwhile, especially since recyclates with good qualities can already be produced without the removal (expert opinion workshop).

After separation, further reprocessing of the removed parts and equipment is nevertheless necessary, as the components consist of different types of plastic and quick and clear identification is not always possible during the sorting process. Compared to the reprocessing of the mixed fractions, however, less effort can be expected here, as there are fewer interfering materials, fewer sorting cycles are needed, fewer pollutants are present, etc.

The separate development of individual components or groups of devices results in fractions with a low pollutant content, or the contaminated fractions can be separated more easily. On the one hand, this increases the quality of the recyclate, but on the other hand it also creates security for the recycling companies and their customers to establish such process chains. Currently, there is uncertainty in the legal situation regarding the pollutant limits in recyclates. These are frequently re-evaluated, which means that in the long term it cannot be guaranteed that the recyclate may be marketed. If it can be guaranteed in the long term that a recyclate fraction has a minimum pollutant concentration, this also creates an incentive to establish process chains for it.

Due to the strict legal requirements, the producers also have high demands on the recyclates. On the one hand, they must have pollutant contents below the limit values and on the other hand, they must not lose too much of their quality over their usually long lifetimes. This makes it easier for manufacturers to use virgin materials for their products than to rely on recyclates, which means that no stable sales market develops. For recyclers, this means that a lot of time and resources must be used to bring the quality of the recyclate to a marketable level. However, this also increases the price, which means that the recyclate cannot compete with virgin material. The creation of more pure fractions could help to increase the quality in the long term, which would also establish a permanent sales market. However, this is not the case for every collection group. For example, the PP of CG 4 still contains specific additives (talc and glass fiber) after the recycling process, which hinder further use. Thus, due to the additives, this PP can in turn only be used in white goods, which severely restricts the sales market.

In general, recycling capacities are lacking in Germany. For large printers, for example, there is a lack of capacity at the EBAs in Germany, which is why they are mostly exported abroad (expert opinion workshop). Most traders for plastics from WEEE are located in Asia, which means that there is little competition in the European market. By expanding European capacities, competition could be promoted on the one hand and on the other hand the recycling rate could be increased, which could also develop a stable sales market.

In an expert interview, it was also mentioned that the redefinition of the collection groups has made recycling more difficult. In CGs 4 and 5, the variety of plastics was increased, which is not conducive to recycling. It was criticised that the division according to edge length does not make sense, as the plastic types are decisive for recycling (expert opinion workshop). At present, some devices from CG 4 are sorted out and fed into the CG 5 stream. According to the experts, it would make more sense to develop collection groups that match in terms of materials. This is already being done with refrigerators, for example, which makes downstream recycling much easier because the variety of plastics is limited. However, the collection is limited by the space available at the recycling centers, which is why only a limited number of collection groups can exist.

This strategy is only designed to separate individual appliance parts or appliance types at an early stage and treat them individually. The rest of the collection group must still be treated, but even with the standard treatment of the collection group, the yield of certain fractions can be improved, which will be discussed in the following chapters.

3.4.2.2 Separation of pollutant-free plastic fractions through post-shredder technology beyond the status quo

Another possibility to increase the recycling yield is to separate pollutant-free plastic fractions in the PST process. The idea here is to separate pollutant-free plastic fractions from the SHF and reprocess them further, as these are currently used for energy recovery together with the other pollutant-laden plastics from the SHF.

Currently, the mixed plastic fractions from the EBAs are first separated by means of a density cut at 1.08 g/cm^3. In this process, materials with a higher density, such as glass, metals and brominated and other heavy non-brominated plastics sink, while lighter plastics such as polyolefins and certain ABS and PS rise to the top. The heavy fraction (HF) obtained in this way is then separated again by means of a water table into metal and glass residues and a plastic fraction. Metals and glass of the HF are recycled, but the plastic fraction is used for energy recovery, as it usually contains a relatively high proportion of harmful plastics. The plastics are thus removed from the cycle, whereby the non-polluted plastics are also destroyed, although they could be separated and recycled. The fraction of non-polluted plastics to be separated in this strategy depends on the collection group.

In CG 1, the HF tends to make up only a small proportion, which is why this strategy is not considered here. In CG 2 and CG 5, ABS and PC/ABS blends can often be found in the heavy plastic fraction. These tend to be free of pollutants and could be recycled.

For CG 5, the strategy could be used especially for certain types of equipment such as printers (information based on expert interviews). However, no uniform statement can be made for CG 5, as the recycler market is very diverse.

In CG 2, it was mentioned in the workshop that the separation of PC/ABS blends is already being strived for, as the PC/ABS share in this collection group will increase. In Austria, for example, there is already a plant for reprocessing PC/ABS, but it is difficult for German companies to export their plastic waste there due to European legislation. Efforts should therefore be made to build up such facilities and capacities in Germany (expert opinion workshop).

Since CG 4 contains a wide range of equipment types, PC/ABS can also be found in the heavy plastic fraction here. However, the approach of this strategy for CG 4 is also based on the early separation of the white goods (see chapter 3.4.2.1) and the subsequent separation of the talcum and glass-fiber filled polyolefins (especially PP). These are used in this product group because they have a high strength on the one hand and on the other hand contribute to the appearance of the products which gives them their name. Filled PP can account for 50-62 % of the total amount of plastic used. Separate treatment of the white goods enables these plastics to be enriched in the recycling process and thus selectively separated for separate reprocessing. However, since most of the recovered PP still contains additives such as talc and glass fibers, manufacturing companies can only use it in new products to a limited extent. For example, one expert stated that the plastics recovered from CG 4 could be used in new refrigerators, but that manufacturers are rather reluctant to using them and are losing interest (information based on expert interviews). In addition, recycled polyolefins in particular have only a low market value and can generally only compete poorly with virgin materials. It is therefore proposed to process these plastics further by means of solvent-based recycling and to separate them from their additives (see Error! Reference source not found.).

Existing technologies can be used for the separation. To separate PC/ABS, spectroscopic methods such as fluorescence spectroscopy could be used to sort the fraction with density >1.08 g/cm^3. This can separate ABS like PC/ABS, but also other plastics like HIPS.

In the case of CG 4, in the experiment (see chapter 3.3.1), the white product was first subjected to a primary treatment and then shredded. The fraction with a particle size < 20 mm was then further sorted into polyolefins, ABS and PS by means of sieving, density separation and subsequent laser-induced fluorescence. The polyolefin fraction thus obtained was again separated into a high-talcum and a low-talcum fraction by means of a density cut at 1.0 g/cm^3.

However, the exact process steps for both types of plastic would first have to be determined and established by means of practical trials. In addition, there are storage, transport and personnel costs. The investment costs required for this are high despite the existing technologies, further, the sales market for plastic recyclates is not yet very pronounced in Germany.

According to experts, recycling companies also lack quality awareness. For example, the same price can be achieved for a PS with 80% purity as for a PS with 95% purity. Manufacturers therefore only pay a low price, which in turn further reduces the price of the recyclates.

In principle, this strategy would benefit from a redefinition of the collection groups. The 2018 recast increased the diversity of materials in CG 4 and CG 5, which made recycling activities more difficult. By grouping appliance types with similar plastic composition/interior, fractions could be created that have a higher proportion of certain plastics (e.g. PP in white goods) and less plastic diversity, which could facilitate recycling.

Regarding pollutants in new products, two further points can be of importance. European as well as national legislation sets strict requirements for products to be placed on the market and the limit values to be complied with may be subject to change. For companies in the recycling sector, this represents a certain uncertainty, as stricter limit values can prevent the use of previously permitted materials. One consequence can be a reluctance to invest in new facilities and technologies. In addition, manufacturers are subject to information obligations regarding the substances in the materials used. If recycled materials are used in production, information on pollutants and composition must also be available. If manufacturing companies feel too much uncertainty about secondary raw materials, they tend to use primary raw materials. The use of recycled materials may thus be further inhibited.

In general, the use of PC/ABS in modern small appliances is increasing, which would increase the yield of this strategy in the future. Likewise, the separation of this fraction would create a reliable supply of PC/ABS, which could promote the expansion of recycling capacities in Germany.

3.4.2.3 Processing of polluted plastics (from the heavy fraction) through post-shredder technology

The last separate strategy discussed here is the reprocessing of polluted HF plastics. The second strategy (see chapter 3.4.2.2) aims at the reprocessing of HF plastics free of pollutants, while polluted plastics are to be reprocessed here.

The plastic fractions from the EBAs are first separated into a heavy and light fraction in the recycling companies using a density cut at 1.08 g/cm^3. In the light fraction, plastics such as polyolefins, but also certain types of PS and ABS can be found. In the HF fraction, on the other hand, plastics such as PC and PMMA are found, but also plastics that have been mixed with additives. The additives increase the density of the polymers, which is why they sink during density separation. Particularly plastics that have been mixed with brominated flame retardants such as DecaBDE and HBCDD have a high density because the bromine atoms have a high molecular mass.

The HF is currently recycled for energy, as legislation sets limits for the destruction of polluted plastics and the reprocessing of these is currently not carried out due to the high costs involved.

In recent years, however, some solvent-based mechanical plastics reprocessing processes have been established and already competitively launched on the market. Some examples are the CreaSolv® process from the Fraunhofer Institute and the Newcycling® process from APK. These use solvent and solution parameters specifically adapted to the target plastic. This can selectively dissolve the desired plastic, with all other plastics and additives precipitating as solids and accumulating at the bottom. By separating the solid and evaporating the solvent, the purified target plastic can again be obtained. The evaporated solvent is then returned to the process. The target plastic can achieve very high qualities through this process, as virtually all impurity materials are removed in the process.

The process is limited by the proportion of the target plastic in the input, as the solvent can only dissolve this. Which plastic should be dissolved depends on the collection group.

In CG 1, mainly PS is used, but the HF only accounts for a share of ~5-10 % here, which means that only a comparatively limited yield can be achieved. One expert stated that CG 1 does not contain any brominated plastics, which is also confirmed in DIN EN 50625-1. However, this point was challenged, as studies have shown that brominated plastics can nevertheless be found in the heavy plastic fraction (Norwegian Environment Agency, 2021). In CG 2, ABS can be found especially in computer screens, while HIPS is more commonly used in televisions, which means that both plastics could be possible target plastics here. In addition, ABS is already collected separately (information based on expert interviews). Similar to the second strategy for processing pollutant-free plastic fractions of the HF (see Chapter 3.4.2.2), the filled PP can be further processed in CG 4. If the white goods are treated separately, a large proportion of talcum and glass fiber-filled PP would be produced, as this can make up 50 – 62 % of the plastics in the white goods. Since the glass fibers and talc also precipitate as solids in solvent-based recycling, the PP could also be reprocessed in this way. In the opinion of experts, ABS would have the greatest potential for solvent-based recycling in CG 5. In addition, a relatively large number of flame-retardant plastics can be found in CG 5.

For solvent-based recycling, however, a plant would first have to be built and the process adjusted to the input stream. This involves very high investment costs and a longer period without profits. One advantage, however, is that several recyclers could supply one plant. Since the input stream should be enriched with the target plastic, production waste from industry, for example, is suitable for this, or several recycling companies that process the plastics of the white goods could supply a plant for processing the polyolefins.

In general, care should be taken to combine similar input streams to achieve maximum yield. For example, a plant designed for ABS should not receive input from white goods recyclers.

However, a major problem with this recycling method is the market value of the recyclate. Polyolefins have only a low sales price, which means that there is no great financial incentive for recycling companies to build such a plant. In addition, manufacturers are generally reluctant to use recyclates because of the strict legal requirements. However, the solvent-based recycling processes can remove the added additives, including flame retardants, in very high proportions, which means that the recyclates have a high degree of purity. In the long term, this ensures that manufacturers are allowed to market the products, which gives them an incentive to use the recycled materials. In general, however, it must be noted that there is no sales market for recycled products in Germany, which means that recyclers have no incentive to establish new production chains.

This strategy would benefit from a redefinition of the collection groups. According to experts, the current separation according to collection groups is not expedient, as the variety of plastics in CG 4 and CG 5 was increased by the new version in 2018 (expert opinion). It would be better to combine devices with similar plastic compositions/interiors in one collection group, as this would allow the plastics to accumulate in the recycling process. Since solvent-based recycling can achieve a higher yield the higher the target plastic content in the input stream, recycling streams with fewer impurities would be an incentive to build such plants.

3.4.2.4 Combination of early separation, separation of pollutant-free plastic fractions and processing of polluted plastics by post-shredder technology

The last strategy combines the previous strategies and discusses the resulting challenges.

Already, up to 92.5 % of the weight of WEEE is recycled, which proves that effective recycling is possible. To further promote plastic recycling, some appliance groups or plastic components can be separated at an early stage. By removing individual components, fractions with a high degree of sorting purity can be created (such as by removing the drawer runners and compartments from freezers in CG 1) and by separating and then treating entire appliance groups separately, waste streams with fewer interfering materials and similar plastic types can be created (e.g. the separation of white goods in CG 4).

For the EBAs, this can initially mean extra work, such as in the example of separating the vegetable compartments in the refrigerators. In addition to the personnel costs needed for the separation, there are also storage and transport costs, but this step can be integrated into the already established pre-treatment and dismantling steps. On the other hand, some equipment groups are already sorted out in the EBAs, such as the white goods of CG 4, which are then fed into the end-of-life vehicle waste stream. However, these could be reprocessed as a separate waste stream, which would enrich the plastics of this type of appliance and allow tailored downstream recycling.

Separating these types of appliances/plastic components not only creates fractions with little impurities, but the plastics in these fractions are also removed from the rest of the waste stream. However, the quantities removed are probably not significantly large enough to generate a noticeable difference.

This strategy also shows that grouping plastic parts/equipment categories with similar plastic types or inner workings significantly simplifies downstream plastic recycling. Some experts said that it would make sense to divide the collection groups not by edge length, but by appliance type, so that certain plastics can be enriched in the recycling stream and interfering materials can be avoided.

The second strategy aims at separating the pollutant-free fractions in the heavy plastic fraction. This is currently recycled for energy, which could increase the recycling rate through separation. For CG 2 and 5 this is mostly PC/ABS and in CG 4 the talcum and glass-fibers filled PP, which ends up for the most part in the HF due to its high density. For CG 4, this strategy can only be used in combination with the first strategy (separation of the white goods), otherwise the filled PP cannot be enriched. In general, however, the recycled plastics have only a low market value and the manufacturers are reluctant to use them, which means that there is no incentive to separate these fractions.

The last strategy also refers to the heavy plastic fraction, but here the polluted plastics, which are currently also incinerated, are to be processed and recycled. Solvent-based recycling processes can be used for this purpose. These use a solvent adapted to the target plastic, which can selectively dissolve it. All other plastic types and additives remain as undissolved residue and can be separated. After evaporation of the solvent, a product with high purity can be obtained. The yield here depends largely on the proportion of the target plastic in the input stream. The higher the proportion, the more plastic can be purified and recycled by the solvent. Depending on the collection group, different polymers are suitable for solvent-based recycling. According to the experts, ABS and PS are the most suitable in CG 2 and CG 5, while PS is more common in CG 1. In the case of the white goods in CG 4, PP could also be used. Instead of the mechanical recycling of the second strategy, the additives can be removed, resulting in a recyclate of higher quality.

In particular, the second and third strategies have a good synergy. If the pollutant-free plastic fractions are separated in the second strategy, the polluted plastics can be enriched in the HF, which leads to a better yield. Through the combination, a proportion of the hitherto untouched heavy plastic fraction can be returned to the cycle.

If the first strategy of early separation is also integrated, the recycling rate can be increased again. By separating individual types of appliances or plastic components, the variety of plastics in downstream recycling can be reduced even further. This is already being done for some components and appliance types but can be further established if the collection groups are redefined.

3.4.3 Summary and recommendation separation and recycling strategies for WEEE

Three basic separation and recycling strategies can be derived for WEEE:

1. Early separation of plastic components or equipment groups for mechanical recycling
2. Application of extended PST for mechanical recycling of plastics by separating pollutant-free plastic fractions in the PST process beyond the status quo
3. Application of extended PST for mechanical recycling of plastics by processing polluted plastics (from HF) in the PST process.

These individual strategies can also be combined into a fourth combination strategy in which all three strategies are applied. Here, plastic components or equipment groups are separated at an early stage and subjected to an extended PST process for mechanical recycling of plastics.

By separating certain appliance components or groups at an early stage, high recycling rates and purities can be achieved. This strategy is already being implemented in CG 2 and 4, for example by separating the PMMA panels of flat screens in CG 2 and the white goods in CG 4 at an early stage. In order to be able to increase the recycling rate even further, pollutant-free plastic fractions can be separated from the heavy plastic fraction or polluted plastic fractions can be processed. The recycling rate can be maximised by combining all strategies.

Early separation of certain components or equipment categories would lead to high recyclate yields with good quality. In the case of CG 1, for example, drawers and compartments can be removed at an early stage, whereas in the case of CG 4 and CG 5, entire appliance groups are separated (white goods in CG 4 or IT and telecommunications equipment in CG 5). The separation of entire groups of appliances has the advantage that fewer impurities are present in the downstream recycling process, which simplifies recycling and allows better yields to be achieved.

In the subsequent treatment, plastic fractions can also be separated that do not contain any pollutants, such as the PC/ABS plastic blends that can be found in CG 2 and 5. This is a plastic fraction that has not yet been tapped into, the separation and processing of which could further increase the recycling yield. However, further process steps and plants would have to be established for this, which would involve high investments.

Finally, the polluted plastic fraction can also be processed by means of solvent-based recycling processes. Solvent-based recycling requires the construction of a separate plant and the recycling process can be adjusted to only one target polymer. The additive and residual polymers precipitate in the process and can be separated, resulting in a recyclate with high quality. This strategy can be promoted in particular by combining it with the separation of the pollutant-free fraction, as this allows the polluted fraction to be enriched.

Measures to promote the combination of early separation and the use of an enhanced PST process as a promising strategy are developed in chapter 5.

4 Vehicles

The following chapters provide an overview of the use of plastics in vehicles and the volume of plastics in the end-of-life vehicle stream. The status quo of end-of-life vehicle waste management in Germany and existing process chains for recycling plastics from ELVs are also presented. In two practical test series for end-of-life vehicle plastics, new recycling options that go beyond the state of the art were tested. Based on these results and the findings of the status quo and thus current challenges of end-of-life vehicle plastics recycling, separation and recycling strategies were developed.

4.1 Presentation of the use of plastics in vehicles and the amount of plastics in the end-of-life vehicle stream

4.1.1 Use of plastics in vehicles

Unless otherwise specified, the following description of the use of plastics in vehicles considers vehicles that fall under the category of passenger cars (M1) and light commercial vehicles (N1).

According to the Federal Statistical Office (2019, p. 566) 5.02 million passenger cars (M1) were produced in Germany in 2018. Commercial vehicles (N1) are not included in these statistics. The number of vehicles newly registered in Germany is significantly lower. In 2018, 3.4 million passenger cars (M1) and 278,286 commercial vehicles (N1) were registered, corresponding to a total of 3.71 million new vehicle registrations.

In the automotive sector, plastics are increasingly replacing components that were previously made of metal. According to SPI (2016) the volume of a vehicle consists of up to 50 % plastic, whereas the weight share is significantly lower. Since 1995, the use of plastics in passenger cars has increased significantly.

Based on information and opinions from experts, which were requested in the form of interviews, as well as random internet research[8] with manufacturers, the proportion of plastic polymers in M1 vehicles is currently between 16-25 % on average, with a proportion of elastomers of 3-5 %. This results in a current average polymer share of 20 %. The share of thermoplastics is currently around 16 % (contrary to the forecast of 26.5 % by (SPI, 2016)).

For commercial vehicles (N1), no specific values for the proportion of plastics in the vehicle could be found. It can be assumed that the proportion of plastic used here depends very much on the interior design of the vehicle. This was confirmed by interviews conducted, although exact data is lacking.

Plastics shares by production volumes (for 2017 and for 2021)

According to Conversio (2018), a total of 1.6 million tonnes of plastics were processed in vehicles in 2017, and around 1.23 million tonnes in 2021 (Conversio Market & Strategy GmbH,

[8] Daimler: Share of polymer materials between 16 and 25 %: https://www.daimler.com/nachhaltigkeit/umweltzertifikate/. Accessed 14.07.2020

BMW: plastics share approx. 18 % ((of which: 12 % thermoplastics, 4 % elastomers (e.g. tyres, sealing rings), 2 % duromers); https://www.bmwgroup.com/content/dam/grpw/websites/bmwgroup_com/responsibility/downloads/de/2020/2020-BMW-Group-SVR-2019-Deutsch.pdf; accessed 14.07.2020

Audi: plastics share approx. 19 % (18.6 % polymers and elastomers, 1.3 % process polymers); https://www.audi.com/content/dam/gbp2/company/sustainability/downloads/sustainability-reports/Audi-Nachhaltigkeitsbericht-2017.pdf; accessed 14.07.2020

Skoda: Plastic share 19.6 %; https://cdn.skoda-storyboard.com/2019/10/Sustainability-Report_17_18_EN.pdf; accessed 14.07.2020

Groupe PSA (Citroën, DS, Opel, Peugeot and Vauxhall): Polymer share 21.4 %; https://www.cotecorp.com/Groupe_PSA_2019_CSR_Report.pdf; accessed 14.07.2020

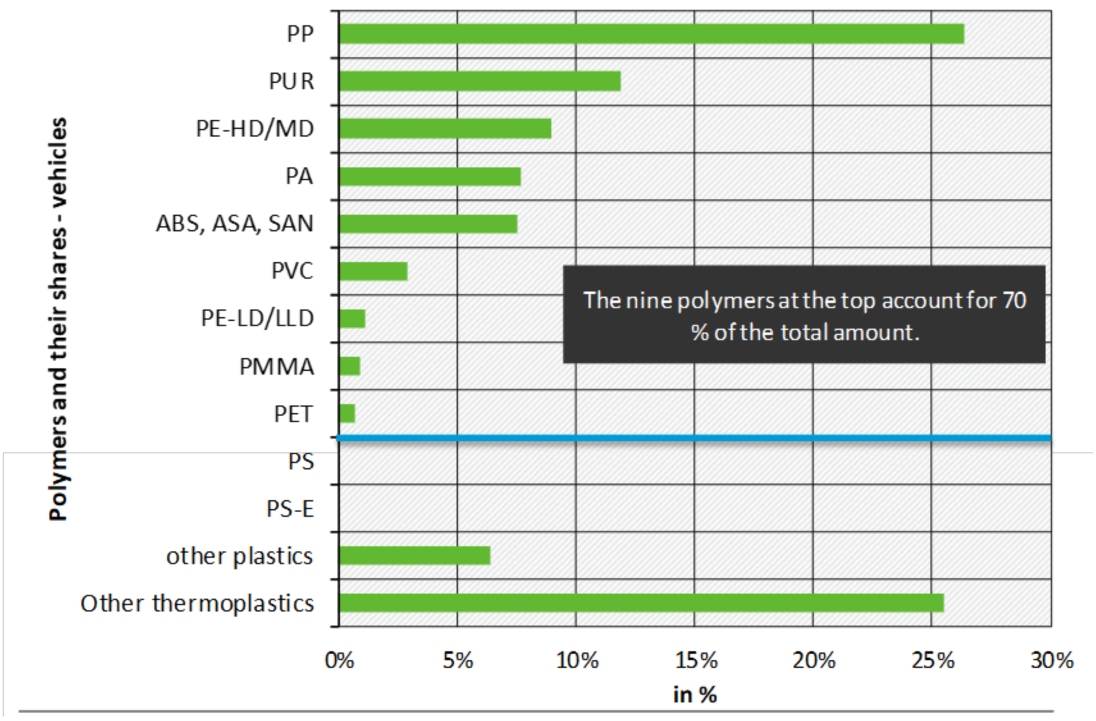
2022). A total of 0.86 million t of plastics were consumed in the vehicle sector in Germany in 2021, resulting from an export surplus. In terms of volume, this makes the automotive industry the third largest sector in terms of plastics consumption in Germany (after packaging and the construction sector). Of the quantity consumed in Germany, 0.26 million tonnes are exported (Conversio Market & Strategy GmbH, 2022).

Plastic composition and field of application

Figure 13 shows the variety of polymers used in the automotive industry. The volume of plastics processed in 2017 of around 1.6 million t (2021: 1.23 million t) was distributed across at least eleven polymers (including polymers reported as mixtures / other) (Conversio Market & Strategy GmbH, 2018).

The largest shares are made up of PP, PUR, PE, PA and the polymer group ABS, ASA, SAN. Other thermoplastics, with a share of 25 %, are the second most frequently used polymers in vehicles. However, this group combines a large number of different polymers and therefore, similar to the category "Other plastics", cannot be limited to a specific polymer type.

Figure 13: Overview of polymers processed in the automotive sector in Germany (in % for the year 2017)



Source: Ramboll modified according to (Conversio Market & Strategy GmbH, 2018)

The range of uses of the processed plastics amounts to the following typical applications (Conversio Market & Strategy GmbH, 2018):

- Interior (including trim and dashboards): 53.5 %;
- Exterior (including bumpers): 17.5 %;
- "Under the hood" applications (including engine linings, encapsulations, tank): 15 %; and
- Electrical / Lighting: 14 %.

4.1.2 Use of plastic recyclates in vehicles

The plastics recyclates used in the automotive sector in Germany in 2017 (post-consumer and production and processing waste) are low in relation to other sectors (agriculture, construction and packaging) with a share of 4.8 % of the total processing volume. In 2021, the share of recyclates and by-products used is 5.7 % (Conversio Market & Strategy GmbH, 2022). Of the plastic waste processed into recyclate, 66 % comes from production and processing residues and 34 % from post-consumer waste[9](Conversio Market & Strategy GmbH, 2018). At European level, only 3% of processed plastic recyclate comes from the automotive sector (PlasticsEurope, 2019b). According to Schönmayr (2017, p. 66) the low willingness to use recyclate is based, among other things, on the poor image of recycled plastic and the mismatch between quality, price and volume.

Whether plastic waste is processed into recyclate depends primarily on the processing depth and the quality of the pre-sorted plastic fraction. In the case of plastic mixtures, a lower yield can be expected (Wilts et al., 2016). An important factor for the use of recycled plastics in automotive engineering is that they have the same technical properties as virgin plastics. In Maier & Schiller (2016) it is pointed out that an important quality feature is processing and thermostability. This can be produced by post-stabilisation. Recycled PP can compete with virgin material in this way and be reused in exterior and interior parts.

Overall, the data on the use of plastic recyclates in the automotive sector in Germany is deficient. On the one hand, no specific information is provided on the type of recyclate. For example, it is often unclear whether the information is about recyclate from post-consumer waste or production and processing waste. Furthermore, often only individual values are given for individual models. The use of recyclate in an entire fleet, on the other hand, is difficult to determine.

However, current developments allow the conclusion that manufacturing companies increasingly intend to use recycled materials within the framework of a circular economy.

4.1.3 Plastics in the end-of-life vehicle waste stream

General information on end-of-life vehicle recycling

The "Annual report on end-of-life vehicle recycling rates in Germany in 2018" shows that in 2018, approximately 560,455 ELVs were accepted by the recognised ELV recyclers (1,154 dismantling companies) in Germany. An end-of-life vehicle had an average weight of 1,063 kg and was on average between 17 and 18 years old (BMU and UBA, 2020). The total waste volume was thus approx. 595,760 t.

The share of plastics in the end-of-life vehicle waste stream of 2018 originates from vehicles produced on average in the years 2000 and 2001. The mass share of plastics for vehicles produced in 2000 and 2001 was between 10 % and 14 % (average 12 %,). This results in a share of plastics in an end-of-life vehicle of about 128[10] kg. The total potential of plastics in ELVs was 71,490 t in 2018.

The waste stream of plastics in the area of ELVs in Germany is composed, on the one hand, of the partial manual dismantling of large plastic parts such as bumpers, tanks, radiator grilles and

[9] Post-consumer waste according to Conversio: "End-use waste generated after use (both short-lived and long-lived) from both commercial and household end-use sectors. This includes waste generated during installation, fitting, assembly or laying, etc. (e.g. pipes, cables, flooring, tarpaulins, etc.)" (Conversio Market & Strategy GmbH, 2018).

[10] According to the literature values, the plastic content for vehicles built in 2000 and 2001 ranges between 133 kg and 187.6 kg.

water tanks, and, above all, the treatment of the residual bodies in shredding plants (Martens & Goldmann 2016)[11].

The dismantling process can consist of up to five steps. Some steps are obligatory, such as the proper removal of pollutants, while other steps depend on the recycling and sales opportunities of the dismantled parts (Martens, 2011; Martens & Goldmann 2016). According to section 3.2.3.3 of the Annex to the AltfahrzeugV, operators of dismantling facilities should remove large plastic components (such as bumpers, hubcaps and radiator grilles) before transferring the stripped vehicle to a shredder or other facility for further treatment and priorities reuse or recycling. This does not apply, if the relevant materials are separated during or after the shredding process in a way that enables recycling. However, the dismantling of large plastic components hardly ever takes place in practice.

According to BDSV (2012) the stripped vehicle pass through various processes in the shredder plants (pre-treatment, main treatment, post-treatment) and, after shredding and using various technologies, the following main fractions are generated.

- Ferrous scrap;
- Shredder heavy fraction (SHF) - Non-ferrous (NF) fraction (containing NF-metals and non-metals[12]); and
- Shredder Light Fraction (SLF) - Non-metallic fraction.

The proportion of the individual fractions varies depending on the input of the shredder[13] .

In the annual report on end-of-life vehicle recycling rates of 2018 (BMU and UBA, 2020, p. 52) a distinction is made between ferrous scrap (306,877 t), non-ferrous materials (47,935 t), SLF and other non-metallic shredder residues (91,485 t) and plastics separated in the shredder plants (545 t).

Plastic content in the waste stream

In current ELVs, the following proportions of polymers[14] are found in the components listed below:

- PP (approx. 25% of plastic content); typical components: Dashboards, brake fluid reservoirs, interior trim, cable insulation, radiator grilles, wheel arch liners, headlamp and rear lamp housings, bumpers;
- PA (approx. 15 % of plastic content); typical components: Airbag bags, exterior trim, brake fluid reservoirs, bushings, cams, bearings, fuel systems, fan wheels, air filter housings, engine covers, hubcaps, seat backs, underbody components, water tanks, weatherproof coatings, gears;
- PUR[15] (approx. 14 % of plastic content); typical components: electrical potting compounds, suspension bushings, hard plastic parts, foam in seats and upholstery, foam insulation panels;

[11] However, the manual dismantling of large plastic parts is not carried out for all ELVs (see text below).

[12] According to (Martens, 2011) the SHF consists of 50 % non-ferrous metals and their alloys and 50 % non-magnetic steel as well as plastics, rubber, glass and wood,

[13] This input is not just from ELVs; most of the time, stripped vehicles are processed in the shredder plant together with WEEE for example (Martens & Goldmann 2016).

[14] Polymer shares calculated from vehicle weight and plastic share and use Polymers for vehicles manufactured in 2005

[15] Limited mechanical recyclability

- ABS/ASA/SAN (approx. 8 % of plastic content); typical components ABS: dashboards, exterior trim, interior trim, radiator grille, ventilation systems, centre consoles, mirror housings, bumpers, door handles; typical components ASA: exterior trim, radiator grille, air intake;
- PVC (approx. 6 % of the plastic content); and
- PE-HD/MD (approx. 4 % of plastic content); typical components: Brake fluid reservoirs, fuel tanks, water tanks.
- Other thermoplastics (approx. 12 % of the plastic content) with polymers such as POM (typical components: dashboards, interior trim, fuel systems), PC (typical components: PBT (typical components: bumpers, door handles, carburetor components) and polymer blends;
- PMMA (approx. 2 % of the plastic content);
- PE-LD/LDD (approx. 1 % of the plastic content); and
- PS (approx. 1 % of the plastic content).

If one wants to use these plastic potentials for recycling, criteria such as accessibility/dismantling capability[16] , weight relevance of the target components[17] , content of pollutants, fillers and reinforcing materials, presence of composites, coatings, effort and technical obstacles in sortability or in the recycling process must be considered.

The dismantling of large plastic parts for further recycling envisaged in the legislation hardly seems to be implemented in practice at present. From BMU and UBA (2020) show that in 2018 on average only about 3 kg of plastics were dismantled per end-of-life vehicle and thus the vast majority ends up in shredder plants. The figures from BMU and UBA (2020, p. 51) show that of the total of 1,702 t of dismantled plastics, 9% were reused, 86% recycled and 5% disposed of.

In principle, the dismantling companies remove what is legally necessary and economically possible (selective dismantling). Components of ELVs that cannot be marketed consequently remain in the vehicle. This also affects plastic components inside the ELVs.

Plastics in shredder input

After treatment of the ELVs in the shredder, plastic is found in smaller quantities in the SHF, but predominantly in the SLF. However, the composition always depends on the type of shredder input and the technology used (BDSV, 2012).

a) Shredder heavy fraction

In addition to non-ferrous metals such as aluminium, steel, copper and zinc, non-metallic residues such as stones, glass, rubber and plastics are also found in the SHF (BDSV, 2012) (Sander et al., 2020). According to Sander et al. (2020), the proportion of plastics in the SHF is 34.8 %. This share is partially separated (2.09 % within the SH; this corresponds to a subset of the plastics contained). The remaining part of the plastics is assumed to be in the fraction of substitute fuels (share of 32.7 % within the SHF). According to the data, the plastics fraction is recycled, while the substitute fuels fraction is recovered for energy.

b) Shredder light fraction

[16] only relevant for the above mentioned option 1 of dismantling large components

[17] most of the time, residual car bodies are processed in the shredding plant together with e.g. old electrical appliances (Martens & Goldmann 2016).

SLF is a mixed fraction and includes, for example, textiles, foams, plastics and plastic films as well as broken glass, paint residues and wood (BDSV, 2012). According to BMU and UBA (2020) a total of approx. 80,000 t of SLF was generated in the shredding of ELVs in 2018.

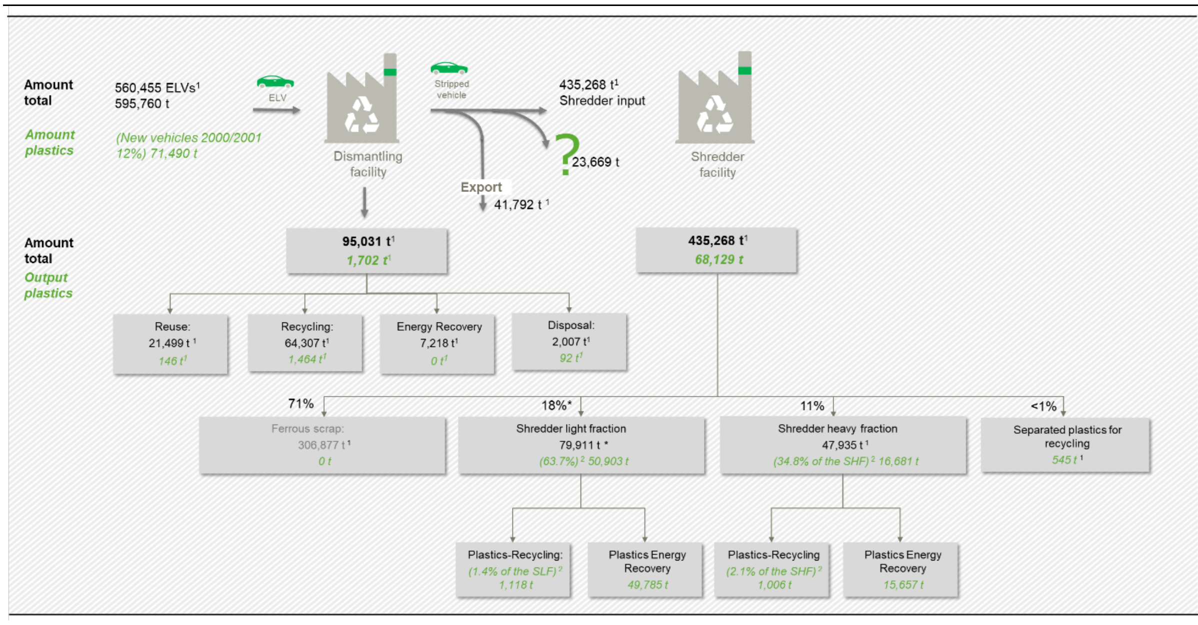
According to the tests by Sander et al., (2020, p. 224ff), plastics and elastomers were found with a share of around 73 % in the SLF[18] (< 18 mm). Overall, it can be assumed that plastics from shredder residues are not currently being fed into high-quality recycling (Sander et al., 2020, p. 330). Within the shredder fraction, only a small proportion of plastics (1.4 %) is separated and recycled. The remaining 98% of plastics in the SLF are energetically recovered.

Furthermore, BMU and UBA (2020, p. 52) state that 545 t of plastic were separated in the shredder plants in 2018. According to the report, these have been recycled.

Summary

In summary, the mass flow of plastic fractions from ELVs in Germany based on the available data is shown in Figure 14 for the year 2018. Figures on waste generation from BMU and UBA (2020), Sander et al. (2020) as well as information from the literature mentioned above serve as the basis for calculation. It should be noted that this is a purely mathematical representation of the mass flow and may not be complete.

Figure 14: Mass flow diagram of waste plastics from ELVs (2018)



Source: Own illustration according to 1: (BMU and UBA, 2020) 2: (Sander et al., 2020)
*18 % or calculated from 435,269 less ferrous scrap, SHF and separated plastics.

4.1.4 Pollutants in the end-of-life vehicle plastic waste stream

Mechanical recycling may only be carried out under the premise that no pollutants or impurities above permitted concentration limits are carried over into the new product life cycle. Experts cite the potential contamination with pollutants and interfering substances as the main obstacle to recycling plastics from ELVs. The following pollutants are particularly relevant in the area of ELVs: brominated flame retardants (PBDE, HBCDD, TBBPA), heavy metals (e.g. cadmium, lead) PFAS, SCCP, DP, fiber composites such as carbon fiber reinforced plastic (CFRP) and MOHs. The challenge lies on the one hand in the long service life of vehicles (substances that are not

[18] The SLF from this company is further processed in the PST treatment (Sander et al. 2020).

restricted as pollutants in their use during manufacture may already be restricted as pollutants at the end of the life cycle; this concerns or could concern e.g. DecaBDE and other brominated flame retardants, phthalates, HBCDD, heavy metals, SCCP, PFAS) and on the other hand in the financial expense of completely eliminating pollutants and interfering substances. In addition, the composition of the different components is often not known (exception: components that are listed in the IDIS database and contain labels). A complete testing of all components for pollutants and impurities is not economically viable (expert opinion workshop).

It should be noted that pollutants in plastics from the automotive sector are not only present due to the use of additives, fillers or reinforcing materials. Some components come into contact with other pollutants during the product life cycle and can therefore be contaminated with these substances in the end-of-life vehicle. This particularly affects plastic-containing components that come into contact with pollutants in a non-dismantled state, such as:

- Batteries (lead);
- Fuel tanks (hydrocarbons);
- Flame-retardant plastics, e.g. in the engine area;
- Cables (PVC);
- Galvanised plastics (chrome VI); and
- carbon fiber reinforced plastic components (carcinogenic when crushed).

4.2 Existing process chains for end-of-life vehicle plastic recycling

An end-of-life vehicle contains a large number of plastic-rich components. Similar components often have similar plastic qualities, types of composites, pollutant loads, signs of wear, etc.

In addition to polyolefins, the thermoplastic plastic types PA, ABS, ASA, SAN, PP/EPDM, PC, PC/ABS and PBT are used in particular. PP and PP/EPDM are often available in mineral-filled qualities. Some plastics are glass-fiber or glass-ball reinforced to meet technical requirements. Over the last decades, polyolefins were developed into plastics that meet higher technical requirements and therefore now find a wider range of applications than was common in the past.

Composites, are achieved by clipping, clamping, gluing and welding, with clipping and clamping being the preferred methods. Gluing is common for foam-skin-support composites, for example, and was also used for bumpers in the past.

The proportions of plastic, the composition of plastic types and the types of composite found in individual ELVs depend on various factors such as manufacturer, model and year of manufacture.

4.2.1 Pre-treatment and dismantling of ELVs

ELVs are pre-treated and dismantled in recognised dismantling facilities. At present, hardly any dismantling and sorting of thermoplastic-rich components takes place in dismantling companies. The removal of all vehicle components down to the bare residual body is time-consuming. In the past, there were a few companies that implemented a high level of dismantling on dismantling lines, but this practice has not become established (Mosselaar Autorecycling en Autodemontage b.v., n.d.). Instead, the dismantling of ELVs is usually carried out using standard workshop tool sets, dismantling stations and excavators in order to remove components containing pollutants and particularly valuable materials such as the catalytic converter (information based on expert interviews).

If necessary, the tank is dismantled after extraction to allow residual fuel to evaporate. Whether the tank is dismantled in individual cases also depends on the accessibility of the tank. There are no profitable sales opportunities for separately collected tanks. Some dismantling companies remove bumpers for mechanical recycling and separate foreign materials that have been carried along to make bumper plastics available for mechanical recycling.

Although the plastic parts are easy to dismantle with standard workshop tools, the time required is not economically justified in the opinion of the dismantling companies surveyed. Zimmermann et al. (2022) determined net costs of €93 per end-of-life vehicle for the separation of bumpers (front and rear) and wheel arch liners for a dismantling company that handles ~500 ELVs per year.

IDIS contains disassembly information on individual components, including large plastic parts. Regular evaluation of the database before, during or after each dismantling of a component would be too time-consuming in everyday dismantling practice. Plastic type identifications are very rarely used in current dismantling practice and depth. Observing the IDIS information and the markings is partly possible and helpful when dismantling and sorting larger plastic-rich components. Through practice, experience and routine, a skilled dismantler can often dispense with reading out the plastic type identification or the IDIS database and fall back on it in case of uncertainty (information based on expert interviews).

4.2.2 Processing of the residual car bodies by shredding companies

Residual car bodies are pressed and handed over from dismantling companies to shredding companies (Sander et al., 2016) (information based on expert interviews) and broken down by them in the shredder. Mixed input streams are processed, so that the plastic-rich shredder fractions also consist of materials not related to ELVs (Martens, 2011). The share of ELVs in the input of a shredder plant, for example, is between 5 % and 20 %. ELVs represent the most plastic-rich input of shredder operations, followed by WEEE of CG 4. However, plastics and non-plastic materials from other inputs are also introduced into shredder residue fractions from construction and demolition waste or from can scrap.

The removal of tanks and bumpers prior to shredding can also be done in shredding operations. A skilled excavator operator would need a few minutes to mechanically dismantle and sort these two components. Disposal costs can be reduced by separating bumpers and reselling them to recycling companies. The separation of tanks can avoid deflagrations in the shredder caused by fuel residues in tanks, but at the same time is associated with increased disposal costs if they are sent for separate disposal (information based on expert interviews).

During shredding, wind sifting takes place, enriching flyable materials in the SLF, this accounts for about 40 % of the pure end-of-life vehicle shredder residue (Sander et al., 2018; Kummer, 2008). According to the investigations of two SLFs carried out by Sander et al. (2018), the combined plastic and elastomer content is about 74 %, and almost 90 % of the plastics and elastomers accumulated in particle sizes > 10 mm. The SLF contains a proportion of fine particles (< 10 mm) of 30 % to 50 % (Martens, 2011). Polyolefins and foamed materials, for example, accumulate in the SLF from mixed scrap.

Iron and ferrous parts as well as non-ferrous metals are removed from the heavy fraction, the remaining residue results in the residues of the SHF. Small non-ferrous metals, minerals and non-flammable plastic parts accumulate in this residue. In the SHF-residues from ELVs, the non-metallic fraction determined by Sander et al. was about 50 %. The combined plastic and elastomer fraction in particle sizes < 2 mm was 4%. In a fraction < 18 mm, a plastic content of 22 % was determined. By sieve classification it was shown that 85.6% of this was in the particle size range > 10 mm.

A plastic and elastomer content of more than 70 % was determined from a SLF < 180 mm via manual sorting. The determined plastic and elastomer content of a manual sorting of the SHF residues < 2 mm of a shredder operation is 4 %. The plastic and elastomer content determined via manual sorting for the fractions of SHF residues < 18 mm was between 21 and 23 % (Sander et al., 2020).

The real share of plastics in SLF and SHF from mixed scrap depends significantly on the share of ELVs in the total input. Both SLF and SHF are screened to enrich the mineral content in a fine fraction that is suitable for backfilling and landfilling.

4.2.3 Post-shredder enrichment of plastics from plastic-rich SLF and SHF residues

Residual metal recovery from SLF and SHF is becoming increasingly important. SHF is often passed on to special reprocessors for the recovery of the residual metals it contains. These use classic mechanical processes, but also state-of-the-art sensor technologies, to recover metals. Plastics continue to accumulate in the sorting residue, and these are generally not processed by type. The SLF contains fewer residual metals and is therefore often not further processed (information based on expert interviews). The recovery of metals from SLF and SHF can also already take place in shredder plants (Sander et al., 2020).

Various approaches have been developed to further enrich the plastics contained in SLF and SHF including the VW-SiCon, TBS, Scholz and SRTL processes. Plastics-rich fractions can be enriched by combining classic processing steps such as shredding, magnetic separation, eddy current separation, density separation (e.g. at 1.5 g/cm^3 and 3.2 g/cm^3), air classification, screening and sensor-based sorting. All processes produce metal-rich, plastic-rich (granulate, fluff) and mineral-rich fractions. SLF processing, for example, can use screen classification and two-stage air classification to break up and loosen tangles and fine-grained adhesions to produce a metal/plastic/rubber mixture. SHF can be achieved via multi-stage screening, residual metal recovery and density separation (Schubert et al., 2020). In Germany, metal recovery from SHF extends to the enrichment of low-chlorine RDF plastic fractions (Scholz Recycling & SRW metalfloat, 2019).

4.2.4 Mechanical recycling of plastics from ELVs

Mechanical recycling of dismantled bumpers

The core technology of bumper processing is the enrichment of PP and PP/EPDM by density separation. The overall process can include, for example, manual sorting out of older bumpers that are visually judged not to be PP/EPDM, as well as shredding stages, metal removal, floating-sink separation and mechanical drying. Paint stripping is possible and is used sporadically (Sparenberg, 2021).

The PP and PP/EPDM sorting fraction can have purities > 99 %. A recyclate yield of 90 % to 92 % is achieved (information based on expert interviews).

Few bumper recyclers take the bumpers collected by dismantlers and shredders in Germany and supplement their input with workshop collections or even inputs that do not come from the post-consumer sector and feed them into high-quality recycling.

Mechanical recycling of plastic-rich shredder residues

Process chains for plastics processing from shredder residues have hardly been established in Germany so far. One recycling company interviewed stated that it processes polyolefins from SLF for mechanical plastics recycling (information based on expert interviews).

In other countries, mechanical recycling of plastics is already more advanced and process chains for the treatment of plastic-rich shredder residues have been implemented that are similar to the process chains used for the treatment of WEEE plastics. Shredder residues may also be treated on the same process line as WEEE. Density separation is a central process step in process combinations used today, supplemented by other processing methods depending on the sorting and target fraction (information based on expert interviews).

Reported qualities vary and range from recyclate qualities in need of improvement (VanderHeijden Communications, n.d.). to recyclate qualities that are reused by the automotive industry. If the tanks are not dismantled beforehand and treated with polyolefins from the shredder residues, the fuel residues can lead to higher VOCs during extrusion (information based on expert interviews).

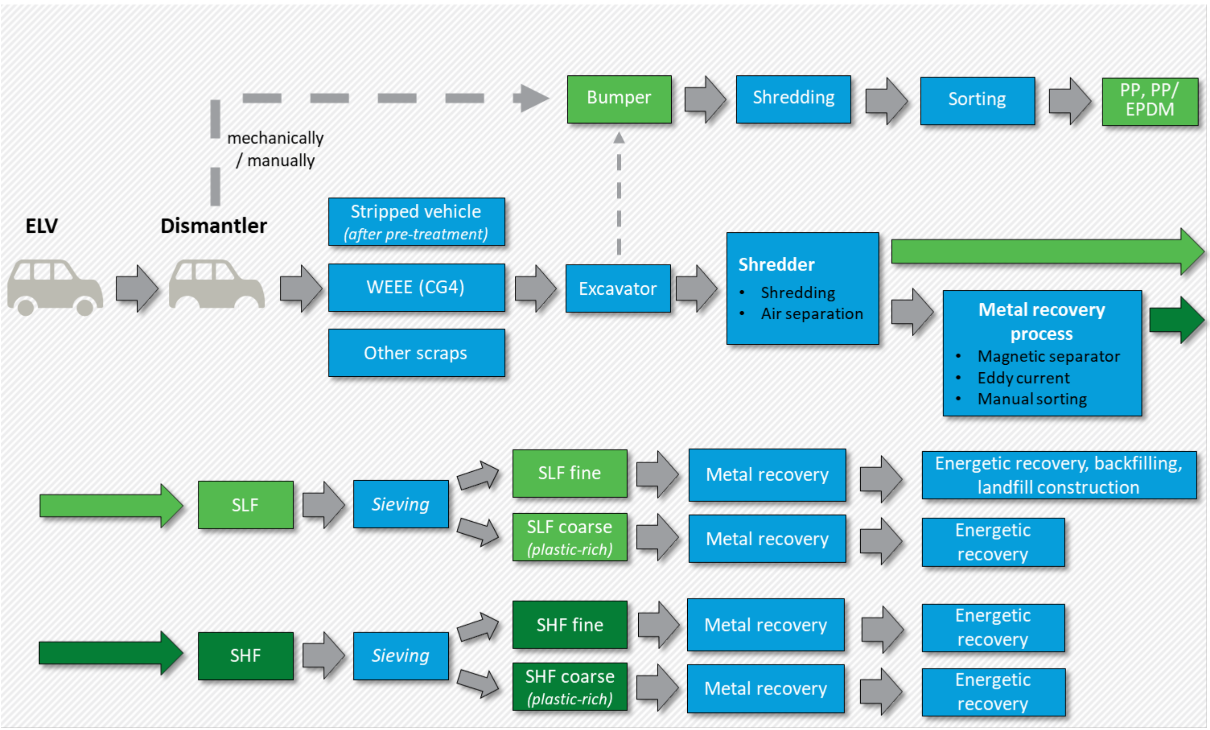
In a large-scale shredding trial involving the Scholz Group, the BMW Group and Galloo Plastics S.A., among others, 501 pre-series vehicles (BMW and MINI models) built between 2004 and 2007 were processed. The vehicles were dismantled and sorted to a high degree of depth, so that a total of 24 % of the existing plastics and elastomers were already separated before shredding. By screening, magnetic separation and multi-stage sifting, a sorting fraction rich in plastics was produced from the SLF. A sorting fraction rich in plastics was produced from the SHF via the process steps magnetic separation, sieve classification and eddy current separation. These plastic-rich sorting fractions were further enriched by a density cut at 1.5 g/cm^3. The light fraction contained 41% of the plastics present in the total input. From this plastic-rich sorting fraction with a density < 1.5 g/cm^3, 21.5 % of the materials could be recovered as unmixed plastic fractions for mechanical recycling (Kummer, 2008).

Recyclate qualities were produced that could be used again in the automotive sector (information based on expert interviews).

4.2.5 Barriers and obstacles of end-of-life vehicle plastics recycling

An overview of the status quo of the path of the plastic is shown in a simplified way in the following figure:

Figure 15: Simplified illustration of the fate of the plastic fraction in the status quo of the separation and recycling of ELVs



CG 4 = German collection group 4 of the WEEE collection; SLF = Shredder light fraction; SHF = Shredder heavy fraction; Source: own illustration, Ramboll/Fraunhofer IVV

The recycling of ELV plastics in Germany is not yet very advanced. Only in isolated cases are plastics from ELVs dismantled and recycled. In 2018, approximately 0.6 to 0.7 % of plastics were recycled in relation to the total mass of ELVs. In terms of the proportion of plastics, this corresponds to a rate of 5 to 6 %, even though there is considerable plastic potential available in ELVs for mechanical recycling. Furthermore, only small quantities of recyclates were used in the vehicle sector. In 2017, the recyclate use rate was 4.8 %, with only 1.6 % coming from post-consumer recyclates.

Various reasons/inhibiting factors are cited in the literature and discussions with stakeholders as reasons for the comparatively low recovery of recyclates from post-consumer waste from ELVs as well as a low recyclate use rate in vehicles:

- Poor image of recycled plastics;
- Mismatch of quality, price and volume (primary plastics versus secondary plastics) and thus lack of economic efficiency;
- Insufficient quality (e.g. with regard to material properties, pollutant content, impurity content, etc.);
- Lack of availability of data on recyclates (e.g. to indicate substance contents for the SCIP database);
- Insufficient communication between producers and recyclers;
- Logistical problems in dismantling large plastic parts from ELVs (dismantlability, storage, transport, lack of know-how to identify polymer types, etc.);
- Diversity of polymers;

- Mixing of plastic fractions in large shredders;
- Lack of separability of fractions containing pollutants, composites, coated plastics, unusual polymer blends, reinforcing materials;
- Insufficient availability in consistent quantity and quality;
- Lack of demand;
- Lack of recycling capacities (e.g. insufficient sensor-based technologies for identification and separation);
- High investment costs combined with legal uncertainty and consequent lack of willingness to invest; and
- Uneven framework conditions within the EU and the handling of hazardous waste that complicate or hinder intra-European trade

Furthermore, the German AltfahrzeugV waives the obligation to separate large plastic parts at an early stage, provided that the corresponding materials are separated during or after the shredding process in a way that enables recycling (number 3.2.3.3, Annex AltfahrzeugV). This means that there is no need for actors along the recovery chain to look for solutions. For plastics processors, there is no incentive to use more recyclates. For this, car manufacturers would have to demand higher recyclate use quotas from their suppliers.

4.3 Practical tests to derive suitable separation and recycling strategies - vehicle tests

Two test series for end-of-life vehicle plastics were derived from the technical issues of separation for plastics from ELVs identified in the exchange with experts, in order to specifically gain new knowledge that goes beyond the state of the art for the derivation of separation strategies and recommendations for measures:

- HFC removal and recovery of HDPE from plastic fuel tanks; and
- Sorting of polyolefins from SHF metal recovery from mixed scrap.

4.3.1 Mechanical recycling of plastics from fuel tanks

Diesel and petrol fuel tanks from ELVs are usually HDPE-rich components, some of which contain a fluorinated, PA-based or EVOH-based barrier to prevent the escape of volatile components. Over the lifetime of a vehicle, MOHs diffuse into the polymer matrix. Fuel tanks must be emptied of residues during pre-treatment, and fuel tanks can also be dismantled prior to treatment of the residual body in the large-scale shredder in order to allow residual fuel to evaporate. Woidasky et al. reported to have achieved depletion rates of more than 95 % for MOHs via entrained flow extrusion using supercritical CO_2 (Fraunhofer ICT, 2004). In Germany, there are still no mechanical recycling options for plastic fuel tanks.

Concept

The series of experiments aimed to deplete the MOHs from HDPE container plastics by deodorisation to produce high quality HDPE recyclates.

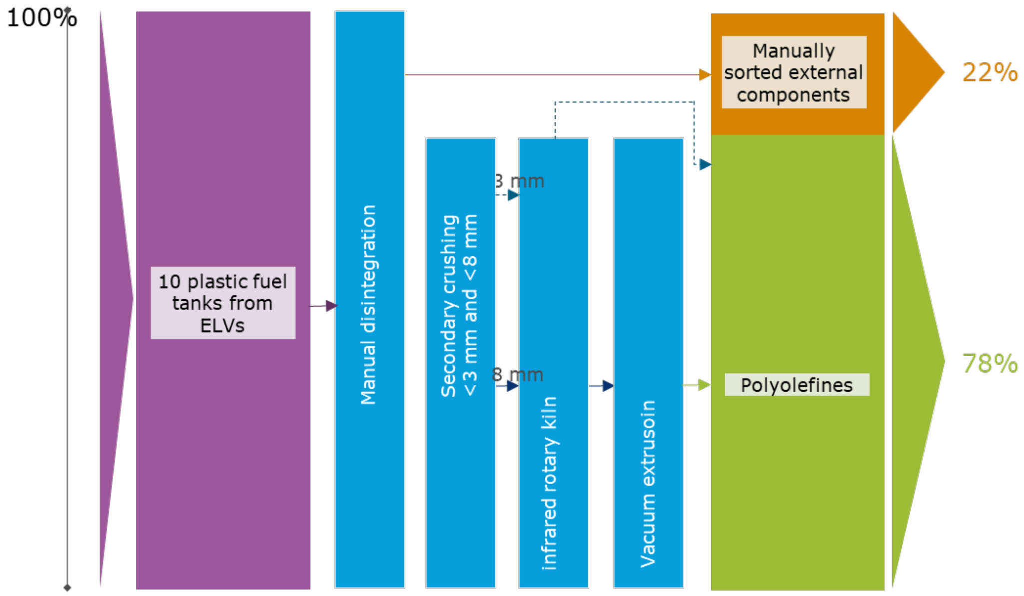
Ten fuel tanks (77 kg in total) from ELVs delivered at random to a dismantling company were drained, dismantled and collected separately by the dismantling company. Components that were not part of the tank were cut off manually using a pneumatic saw. The container plastics were shredded to < 8 mm and < 3 mm. The < 8 mm fraction was deodorised using infrared rotary kiln (IRK) technology in combination with subsequent 2-hour thermal treatment, followed by vacuum extrusion and regranulation to increase the depletion of volatile components. HFCs were depleted from the fraction < 3 mm via a 20-minute IRK treatment without subsequent thermal post-treatment.

The pollutant analysis accompanying the test includes the quantification of element contents, BPA, phthalates, PFAS, PAH, volatile organic compounds and the sum of the four individual substances benzene, toluene, ethylbenzene and xylene (BTEX).

Results and discussion

Figure 16 shows the mass balance of the manual sorting and the process chain used for the removal of MOHs.

Figure 16: Plastic fuel tanks – mass balance



Source: own illustration Fraunhofer IVV

The recycling of PE from plastic fuel tanks has various advantages. On the one hand, the good, achievable quality and, on the other hand, the removal of this MOH-contaminated fraction from shredder residue fractions should be emphasised. Fraunhofer ICT achieved high MOH removal rates by means of entraining agent extrusion and named high energy costs as an obstacle to industrial implementation (Fraunhofer ICT, 2004).

Therefore, an alternative process chain was evaluated in this test series in order to remove MOHs via IRK technology. Due to the small amount of randomly considered plastic fuel tanks in this test series, a higher complexity is to be expected in real recyclable material streams, especially since PA is also occasionally introduced through plastic fuel tanks manufactured according to the Selar RB process (Fraunhofer ICT, 2004). The volume of tanks containing PA or fluorinated container plastics is declining. As the number of ELVs with electric drives increases, the number of plastic fuel tanks in the end-of-life vehicle stream will decrease.

The separation of non-container and non-PE components can be fully automated and does not have to be carried out manually as in this project. For this purpose, e.g. demagnetisation and spectroscopic purification or density-based PE purification (preferably after deodorisation) can be evaluated.

The high-quality long-chain PE quality of the reprocessed tanks allows a wide range of outdoor applications. Whether the material is also suitable for the original purpose remains to be tested, although a high depletion of MOHs occurred.

The analysis data show that the tanks contain hydrocarbons from fuels that have migrated in (naphthalene, BTEX). The hydrocarbons were significantly reduced by the recycling processes. In the case of toluene, by a factor of about 800; a similarly high cleaning effect is postulated for the more volatile benzene. For the more volatile ethylbenzene and xylene, the purification efficiencies were a factor of about 200, for naphthalene probably well over 30; more precise calculations fail due to the detection limits of the methods used.

A PFBS load below 500 ppb was detected in the deodorised and regranulated sample. The low load is assessed as harmless, but warrants further verification in further technical process chain development and scaling.

The following table shows analytical results for selected substances.

Table 10: Plastic fuel tanks – selected analytical results (Values in mg/kg; VOC in mg Tol-Ä./kg; PFBS und PFBS after TOP Assay in µg/kg)

Explanation	BPA	VOC	Benzol	To-luol	Ethyl-benzol	Xylol	Naph-thalen	16 EPA PAK	PFBS	PFBS nach TOP Assay
Input fraction										
10 plastic fuel tanks, shredded	n.b. < 0,1	27.5	59	722	194	381	27.3	35	n.b. < 10	n.b. < 10
Intermediate fractions										
8 mm, IRK > 2 h + vacuum extrusion	n.a.	0.8	n.b. < 1	4	6	22	n.a.	n.a.	n.a.	n.a.
3 mm IRK < 30 min	n.a.	16.7	n.b. < 1	2	9	37	n.a.	n.a.	n.a.	n.a.
Target fractions										
8 mm, IRK > 2 h + vacuum extrusion + regranulation	6.8	1.5	n.b. < 1	n.b. < 1	n.b. < 1	2	3.0	5.2	414	254
3 mm IRK > 2h + Regranulation	n.a.	n.a.	n.b. < 1	n.b. < 1	n.b. < 1	2	n.a.	n.a.	n.a.	n.a.

The results show high quality regrind and high volatile matter removal rates. They also indicate that even higher HFC removal rates can be achieved via IRK treatment of small particle sizes in combination with vacuum extrusion.

4.3.2 Mechanical recycling of polyolefins from SHF metal recovery

In Germany, SHF is mostly produced from mixed scrap and contains valuable non-ferrous metals that are recovered industrially as well as many plastics that are not recycled in Germany. The dominant polyolefin qualities come from ELVs and white goods, so that fiber-reinforced and highly filled qualities are also to be expected.

Concept

The aim of the test series is the recovery of light and heavy polyolefins ($\rho < 1.0$ g/cm^3 and $\rho > 1.0$ g/cm^3) from mixed scrap from a plastics-rich sorting fraction of the SHF non-ferrous metal recovery.

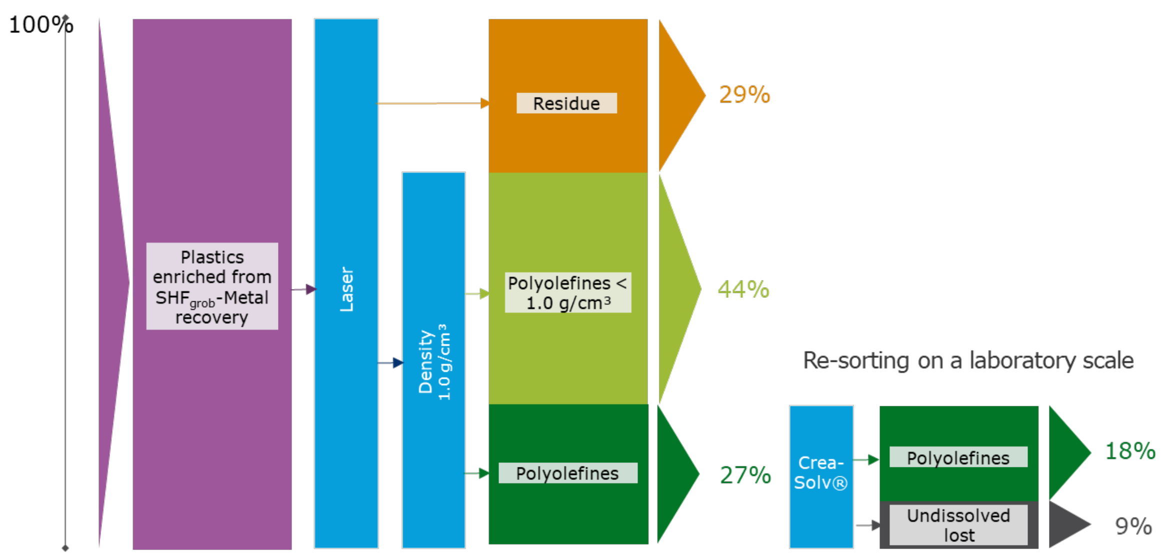
A polyolefin-rich sorting fraction of the SHF non-ferrous metal recovery was post-shredded and the polyolefins were sorted via laser-induced fluorescence spectroscopy. In order to produce sufficient material for the mechanical evaluation and the CreaSolv® test series with the filler-rich fraction, the test series had to be repeated with a larger quantity. CreaSolv® results and product evaluation of the high-filler polyolefin fraction refer to the input of the second test series.

The pollutant analysis accompanying the polyolefin sorting includes the quantification of element contents, contents of specific brominated and chlorinated flame retardants, phthalates, BPA, PAH and the analysis of volatile components. The three elements silicon, magnesium and calcium were determined as indicators for typical polymer fillers such as talc (magnesium silicate hydrate) and calcium carbonate.

Results and discussion

A pure polyolefin regrind fraction was first sorted from the input fraction using laser-induced fluorescence spectroscopy. The polyolefin yield of the sorting is 72 %. The sorting residue accounts for a total of 29 %. A heavy fraction was produced via density separation at $\rho = 1.0$ g/cm^3. Filler and fiber fractions were removed from this heavy fraction via sedimentation in the solvent-based CreaSolv® process. The mass balance is shown in Figure 17

Figure 17: Polyolefins from shredder residues – mass balance



Source: own illustration Fraunhofer IVV

Dark, filler-rich polyolefin grades are not yet separated from complex plastic-rich recyclable material streams on an industrial scale according to the state of the art. The reason for this is the increased density due to fillers and fiber reinforcements.

By means of spectroscopic sorting via colour- and density-independent laser-induced fluorescence spectroscopy, it was possible to generate a polyolefin regrind fraction with high purities containing both low-filler and high-filler polyolefins.

Subsequent density separation made it possible to produce low-filler regranulate qualities that can be further modified in application-specific re-compounding. The high-filler polyolefins show mechanical properties in the expected range of filled polyolefin qualities. The odour of the regranulate should be further optimised, for example by using deodorisation technologies which should be evaluated in the process chain. Fillers could also be separated from the filler-rich fraction by means of solvent-based recycling via sedimentation.

The X-ray fluorescence analysis shows increased contents up to the single-digit percentage range for silicon and calcium and somewhat lower values in the per mille range for magnesium, bromine and chlorine. This shows that the magnesium, silicon and calcium contents in the sorted polyolefins of the fraction with a density greater than 1 g/cm^3 are higher than in the fraction smaller than 1 g/cm^3 by factors of 2.5, 6.3 and 7.7. The observed distribution of the elements thus proves the success of the methodical approach of separating spectroscopically presorted polyolefins into high and low filler polyolefin fractions via density separation, the latter with Mg, Si and Ca contents of about 860, 4,000 and 7,800 ppm being far below typical filler contents of e.g. 30 %. Using density fluids with densities below 1 g/cm^3 could possibly achieve even greater effects.

The observation of the bromine concentrations and loads shows a clear enrichment of bromine in the sorting residues (>85 %). The specific analysis for brominated flame retardants showed only low levels of flame retardant contamination. The sorting routine applied and the focus on polyolefin regrinds make it possible, on the basis of these data, to recover regrind fractions with low flame retardant levels that reliably meet the current legal limits.

The contents of bisphenol A, phthalates and PAHs were in the lower ppm range and are assessed as being of low relevance. An exception is the DEHP value of over 1,000 ppm in the higher density polyolefin regrind. As DEHP is not a typical PP or PE component, there may be contamination with soft PVC particles or soft PVC-containing surface coatings. Since DEHP contents above 1,000 ppm are to be reported according to REACH, the content must be considered more closely in large-scale implementations of the proposed sorting routine. However, the authors expect that the DEHP content can be significantly reduced during further processing of the pellets into PE, PP or PE/PP pellets by methods such as electrostatics.

Table 11and Table 12 show analytical results for selected substances.

Table 11: Polyolefins from shredder residues – selected analytical results 1 (all values in mg/kg)

Description	Mg	Si	Ca	P	Cl	Cr	Br	Cd	Pb	Hg
Side fractions										
Sorting rest 1	499	1,922	18,830	30	220	20	2,744	n.b. < 5	28	n.b. < 5
Sorting rest 2	1,356	2,071	27,790	134	264	21	2,638	n.b. < 5	78	n.b. < 5
Target fractions										
Polyolefin regrind $\rho < 1.0$ g/cm³	859	4,002	7,826	46	67	118	160	n.b. < 5	40	n.b. < 5
Polyolefin regrind $\rho > 1.0$ g/cm³	2,131	25,380	60,210	65	260	177	183	n.b. < 5	26	n.b. < 5
CreaSolv® Polyolefins	660	2,202	23,460	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
CreaSolv® sediment	14,110	47,170	212,430	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

Table 12: Polyolefins from shredder residues – selected analytical results 1 (values in mg/kg; VOC in mg Tol-Ä./mg)

Description	HBCD	TBBPA	BTBPE	BDE-209	Deca-BDE than	Dechlor an	DIBP	DBP	BBP	DEHP	BPA	VOC	Naph-thalen	16 EPA PAK
Side fractions														
Sorting rest 1	55	669	11	20	92	n.b. <20	n.b. <2.5	2.1	n.b. <5.6	157	47	14.6	n.b. <1	-
Sorting rest 2	n.b. <5	n.b. <5	n.b. <5	0	n.b. <10	n.b. <20	n.b. <2,5	2.5	n.b. <5.6	42	63	7.2	2	6
Target fractions														
Polyolefin regrind ρ < 1.0 g/cm³	n.b. <5	85	n.b. <5	1	n.b. <10	n.b. <20	7.4	5.7	n.b. <5.6	40.5	n.b. <0.5	4.8	n.b. <1	2
Polyolefin regrind ρ > 1.0 g/cm³	n.b. <5	178	n.b. <5	0	n.b. <10	n.b. <20	6.4	4.3	n.b. <5.6	1,060	n.b. <0.5	2.3	n.b. <1	3
CreaSolv® Polyolefins	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
CreaSolv® sediment	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

The test series shows that unfilled and mineral filler-containing polyolefins can be sorted by laser-induced fluorescence spectroscopy with high purities and low contaminant levels. Density separation enables the sorting of low-filler and high-filler polyolefin grades.

4.4 Development of separation and recycling strategies - Vehicles

In this chapter, separation and recycling strategies are developed considering the state of affairs regarding the increasing legal requirements for materials, the use of plastics from vehicles, the technical principles of separation and the results of the practical tests.

Concrete options were developed and evaluated in terms of feasibility and effectiveness. Overarching separation and recycling strategies were derived from a combination of options that were deemed sensible.

4.4.1 Possible options to increase recycling

The question of where and by what means plastics recycling can be increased in ELVs can be considered from three perspectives:

- What steps are dismantlers/recyclers already taking that could possibly be improved (optimisation potential for mechanical recycling of plastics)?
- At which points are plastics lost for mechanical recycling?
- Why are existing (technical) possibilities not being exploited?

As already described, hardly any dismantling and sorting of thermoplastic components takes place at present.

This raises the question of how this loss of plastics can be prevented. The following starting points can be derived:

- Early separation
  - of plastic parts that are particularly well suited for mechanical recycling
    - By dismantling parts that have not been taken into account so far, or by more consistent implementation of previous practices
    - The pretreated residual body by the excavator.
    - Specifically, the early separation and recycling of headlights, hubcaps, dashboards, radiator grille, fluid reservoir and bumpers was considered
  - plastic parts that contain hazardous substances by dismantling parts that have not been taken into account so far, or by implementing previous practices more consistently.
    - Specifically, the early separation and recycling of plastic fuel tanks was considered.
- Use of extended PST for
  - the SLF
    - Specifically, the processing of particularly promising types of plastics was considered: Polyolefins, ABS/ASA/SAN
  - the SHF

- Specifically, the processing of particularly promising types of plastics was considered: Polyolefins, ABS/ASA/SAN

These starting points result in concrete options for increasing plastic recycling from ELVs. A sensible combination of individual options results in possible separation and recycling strategies. In the following, different combinations of options are shown that should contribute to achieving the overarching goal of increasing high-quality recycling. The expected opportunities but also challenges of the separation and recycling strategies are described and the technical, economic and legal prerequisites are explained. Based on this information, a "simple" and a "sophisticated" strategy are selected, which are then compared with the status quo.

4.4.1.1 Strategy 1: Early separation and joint processing of components of the same plastic type

In order to make the recycling of plastic parts more effective and thus more profitable, components of the same plastic type could be separated during dismantling[19] and stored together to enable plastic-specific recycling. A pure sorting fraction and selective pre-selection of plastics rich in target plastics fundamentally enable high qualities and high yields. The recyclate obtained from this can be used for high-quality applications.

The strategy envisages, for example, dismantled hubcaps, dashboards, bumpers and radiator grilles made of ABS or hubcaps, dashboards, bumpers, radiator grilles and liquid containers made of PP being collected and processed together (components can be extended as required).

As a matter of principle, potentially contaminated components such as fuel tanks should be stored or collected separately to keep the costs of the treatment processes low and to achieve a high-quality recyclate. A considerable advantage of early separation and separate collection of fuel tanks is that odour contamination of the entire shredder fraction as well as disruption of the shredding process (through potential sparking) can be prevented.

Components or plastic types that cannot be recovered by the usual separation processes of the extended PST (e.g. PC from headlights) can be kept in the cycle by early separation. However, this depends on the type of sorting.

Before or during dismantling, it is therefore necessary to check which component is made of which type of plastic (different materials from different manufacturers are used for the same components).

This presupposes the availability of relevant and easily accessible information on the types of plastic used in the components concerned - for each vehicle model. According to experts, valuable information is available through the labelling obligation and the IDIS database and the plastic types used for the individual plastic components of the specific manufacturers tend to be the same, but this data retrieval is not always complete and it would be helpful for dismantling companies to be provided with this information even more quickly and specifically (expert opinion workshop) (see paragraph on the digital database 6.3.3.3)

Since the components consist (for the most part) of the same type of plastic, but can have different properties, additives and composite materials, further sorting is necessary. In the case of components such as dashboards, which usually consist of a hard-substrate composite, the composite would have to be dissolved before joint processing.

Manual pre-sorting, e.g. to remove cables, follows the dismantling of the plastic components.

[19] The following also includes shredder operators who (can) separate components at an early stage.

In addition, sufficient storage capacity must be planned and the material logistics of the companies involved may have to be adapted. Due to the low bulk density, large plastic volumes are to be expected. One possible solution would be to compact and shred the material in a separate processing plant, provided that the buyers also accept shredded plastic components (which makes it more difficult for the processors to check the material). Furthermore, additional time must be expected for the dismantling companies. However, since the dismantling of specific parts (battery, operating fluids, etc.) is carried out by the dismantling companies in any case, this process is basically already established and would only have to be expanded accordingly. Work could be made easier by reducing the requirement that components be dismantled non-destructively and not necessarily to 100 %, if this appears too costly for technical reasons or accessibility. Components of which only 80% or 70% are separated from the end-of-life vehicle already make a significant contribution to early separation.

Subsequent shredding and sorting are considered necessary, as components can also consist of different materials or a clear identification of the plastic type is not always possible.

Compared to the processing of SLF and SHF, however, higher yields and higher qualities[20] are expected with less effort (less material variety; fewer sorting cycles to achieve a high degree of purity; reduction of possible pollutant contamination).

In addition, there is clear transparency for buyers of plastics regarding the origin of the plastic/recycled material[21]. Manufacturers note that the SCIP database must be filled out for products (and thus also for recyclates used) (expert opinion workshop). In order to be able to guarantee that no substances of concern are contained in the product/recycled material, this can only be done with complete transparency about origin and ingredients, which is facilitated by early separation.

On average, only about 3 kg of plastics per end-of-life vehicle were dismantled in Germany in 2018. The fact that these separated plastic parts from ELVs are effectively recycled is shown by the current figures in Germany: of the total 1,702 t of dismantled plastics, 9 % were reused, 86 % recycled and 5 % disposed of (BMU and UBA, 2020). The high recycling rate of 86 % proves the potential for effective recycling from dismantling. In total, the recycling and reuse rate for separated plastics is 94%.

The technologies for further processing should already exist. However, capacities would have to be further expanded.

Since end-of-life vehicle dismantling companies in Germany are primarily small companies with low ELV throughputs, each company can only dismantle and resell small quantities of plastic components. Profitability will increase if more plastic components are marketed or if dismantling companies cooperate and develop appropriate structures. The prerequisites for this are buyers and suitable economic framework conditions such as competitive prices that take into account the additional effort of the dismantling companies.

Furthermore, it must be noted that a dismantling company is paid by weight for the remaining bodywork at the shredding company. Due to the premature removal of plastic components, this reduces the profit and must be compensated accordingly by the profit (revenue from plastic components - effort/cost). As already described, a study by the Federal Environment Agency assumes that the dismantling company (treatment of ~500 ELVs per year) incurs costs of €93 per end-of-life vehicle due to the removal and resale of bumpers (front and rear) and wheel arch

[20] Depending on component-specific additivation

liners, taking into account all costs and revenues incurred in the process (Zimmermann et al., 2022). However, one expert at the workshop states that the removal and resale of bumpers would be profitable.

The study "Plastic Parts From ELVs" (Aigner et al., 2020) compares ten relevant life cycle assessments that deal with the environmental impacts of dismantling. However, the LCAs provide very different results with large uncertainties[22] . There is therefore no clear, generally valid conclusion on the environmental benefits of early dismantling compared to separation by PST based on LCAs. Conclusions depend largely on the underlying assumptions, data and processes. For example, it depends on the extent to which the LCAs focus exclusively on the calculation of plastic recycling or, if applicable, also include metal recovery. However, even if LCAs do not allow any clear conclusions to be drawn, it is nevertheless assumed, as already mentioned above, that recycling costs are lower due to early dismantling, as fewer sorting cycles and possibly less effort in re-compounding are required to achieve high purities due to the existing grade purity.

The strict consideration of the strategy assumes an early separation and no extended PST process to enrich the plastics. However, since it is not possible to separate all plastics before the shredding process, additional plastics treatment after the shredding process also makes sense. This combination of options is described in 4.4.1.4 described. Nevertheless, the amount of plastics in SLF and SHF is reduced according to the preceding plastic dismantling and the economic efficiency of plastics processing by extended PST may be affected.

4.4.1.2 Strategy 2: Early separation and joint processing of identical plastic components

Another possibility is to dismantle as completely as possible and reprocess the same (large and easily accessible) plastic components together.

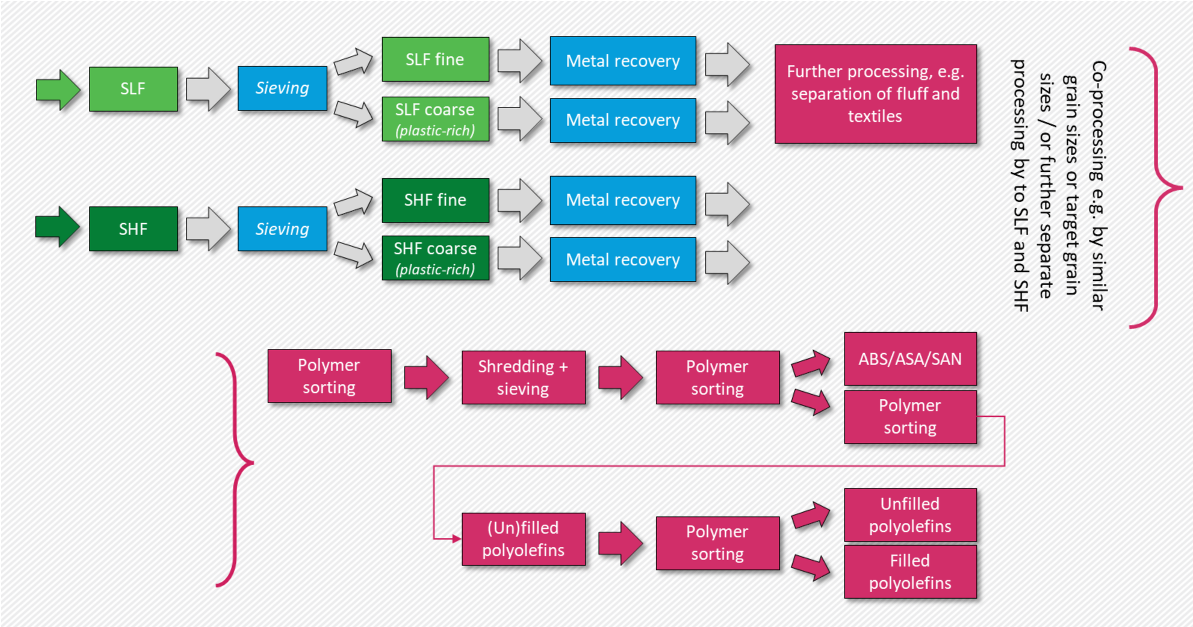
If plastic components are made of the same type of plastic, it is assumed that the preparation is relatively simple (similar properties and additives) and the output is of high quality. However, a plastic component is not made of the same type of plastic in every vehicle model. Therefore, components would then have to be further collected according to plastic type (e.g. bumpers made of ABS separately from bumpers made of PP).

If the components are available separately and separated according to plastic types, the same process steps and the same opportunities and challenges as well as preconditions apply as with strategy 1 (see 4.4.1.1).

4.4.1.3 Strategy 3: Expanded post-shredder technology and recycling of ABS/ASA/SAN from SHF and SLF or polyolefins from SHF and SLF

Another possible strategy is the (possibly joint) reprocessing and recycling of ABS/ASA/SAN from SHF and SLF or polyolefins from SHF and SLF without upstream, early separation of plastic parts. The focus of plastic separation and recycling is therefore after shredding (post-shredder) at the end of the recycling chain (see Figure 18).

Figure 18: Focus on advanced PST and recycling, illustrated by the combination of different options



SLF = shredder light fraction; SHF = shredder heavy fraction;
Source: own illustration, Ramboll/Fraunhofer IVV

Eliminating the step dismantling of large plastic parts means a reduction in the workload for dismantling companies. The quantity to be shredded should in principle not represent an additional burden for the shredding companies.

For plastic type sorting, foams and textiles should be separated from the plastic-rich SLF or SHF fractions. Depending on the sorting technology used, an optimal particle size range should be produced (e.g. by post-shredding and/or screening). Sorting fractions from SLF and SHF with similar material composition and particle size distribution could be recombined for plastic type sorting. Technologies that enable the enrichment of the target plastics polyolefins and ABS/ASA/SAN from such enriched plastic fractions are density separation (possibly in combination with electrostatics) or laser-induced fluorescence spectroscopy (possibly in combination with density separation).

A density cut at about 1.1 g/cm^3 allows polyolefins, ABS/ASA/SAN and, if present, PS to be enriched in the LF. A density cut at 1.0 g/cm^3 enables the enrichment of unfilled or low-filled polyolefins (mineral filler < 15 %) and PP/EPDM blends in the LF. A density fraction between 1.0 g/cm^3 and 1.1 g/cm^3 thus contains not only styrene-containing plastics but also polyolefins that are mineral-filled or fiber-reinforced (with mineral or GF content usually < 25 %). Polyolefins and plastics containing styrene can be enriched via electrostatic sorting processes. According to experts, filled polyolefins are problematic (expert opinion workshop). Foreign materials such as wood or paper or unusual plastic blends with similar densities can also be contained in the density fractions, so that additional purification steps are necessary. Heavy foreign materials (e.g. metals, minerals and foreign plastics) accumulate in the HF.

Laser-induced fluorescence spectroscopy allows sorting by plastic type independent of the filling level. In a first sorting cycle, an enrichment of the target plastic of usually 80 % to 90 % can be achieved. Post-sorting is therefore necessary in order to be able to produce high-quality regranulates. If not all mechanical composites have been completely broken down before the first sorting, re-shredding in combination with metal removal steps may be necessary. Depending on the desired reuse range of a recyclate, it may be useful to combine laser-induced fluorescence spectroscopy with density separation methods, e.g. to separate filled or reinforced target plastics from filler/reinforcement-free plastics.

The choice of the processes and technologies or process combinations to be used should be left to the recycling operators; the strategy should be implemented in a way that is open to technology.

As shown above, an extended PST process for the recovery and recycling of plastics is already more advanced in other countries. This shows that practical feasibility is given. Nevertheless, experts state that a comparable quality of recyclate from PST processes with the quality of recyclate from separated plastic components is difficult to achieve. On the one hand, this is due to the heterogeneous and fluctuating material composition and input qualities as well as potential impurities, pollutants and cross-contamination. This may lead to the necessity of additional treatment steps or processes. These have to be determined for each input to be processed (and the types and proportions of plastics contained) (expert opinion workshop).

Experts mention plastic tanks, composites or glass-fiber reinforced plastics as interfering materials in the application of PST, which can lead to problems in further processing and must therefore be sorted out (if possible). Closed-loop recycling or other high-quality recycling is therefore difficult to implement (information based on expert interviews; workshop). Recyclate is more likely to be used in components with lower requirements.

Furthermore, certain plastics (e.g. PC and PBT) cannot be enriched via the usual density cuts (due to their high density) and can therefore not be recovered by usual PST processes (depending on the sorting technology used). A solution to this problem would be the following strategy 4.

In principle, the large quantities of plastics in SHF and SLF speak in favour of enriching, sorting and recycling plastics after the shredding process. In this way, plastics that cannot be separated during dismantling can also be recovered. The technologies for further processing should already be available. However, capacities would have to be further expanded.

In addition to life cycle assessments on the dismantling of ELVs, the study "Plastic Parts From ELVs" (Aigner et al., 2020) evaluates a further five relevant LCAs relating to extended PST processes, although it is not always clear here whether the evaluation relates to plastics or other materials. As already mentioned, there is no clear, generally valid conclusion on the environmental benefits of early dismantling compared to PST separation; this depends largely on the underlying assumptions and data.

4.4.1.4 Strategy 4: Combination of early separation and advanced post-shredder technology and recycling of plastics

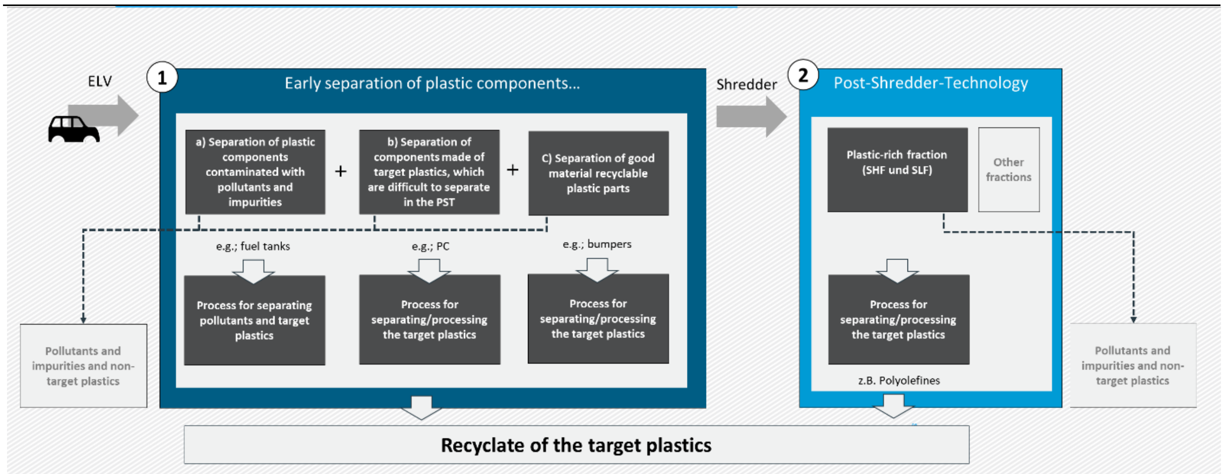
This strategy is a combination of the strategies presented above. This strategy attempts to respond to the challenges of strategies 1-3.

The current recycling rate of 86 % of early separated plastics from ELVs proves the potential for effective recycling from dismantling. This potential should be further exploited, which is why promoting the early separation of (large) plastic parts from target plastics is considered target-oriented (see Figure 19, point 1c) to increase recycling rates in the end-of-life vehicle sector. Components that are difficult to separate by means of the usual PST processes but also contain target plastics (buyers and market available) should also be separated (see Figure 19 point 1b). The separated components are then further processed in separate processes. Closed-loop recycling can thus take place for most components and recyclates can be used in high-quality applications (taking into account legal requirements and limit values).

However, since not all plastic components can be dismantled effectively and with reasonable effort, there will still be enough plastics in the shredder fractions. Consequently, the plastic-rich fractions (from SHF and SLF) must be further processed (see Figure 19, point 2). In order to prevent contamination or restriction of further treatment processes, contaminated plastic components or interfering materials should be removed at an early stage before the shredding process (see Figure 19, point 1a). This applies, for example, to fuel tanks, carbon fiber reinforced plastics or composites. This is only possible if the relevant information on the potential pollutant content or properties and material composition of the components is known.

The early separation of (flame-retardant) textiles is seen as positive by the plastics reprocessors of the shredder fractions, but the effort required for this is too high for dismantling companies (expert opinion workshop).

Figure 19: Combination of early separation and advanced post-shredder technology and recycling of plastics



Source: own illustration, Ramboll/Fraunhofer IVV

The removal of large components from target plastics will reduce the proportion of target plastics for processes of the extended PST. This must be taken into account. Nevertheless, even after the separation of several components, experts still see a large plastics potential for the application of advanced PST (expert opinion workshop).

For dismantling companies, this strategy means an additional effort, as well as the need for additional storage capacities and logistics structures and the challenges already mentioned under strategy 1.

The aim of strategy 4 is to recycle plastics (components) in the most appropriate process without hindering or limiting other processes. Thus, a significant increase in the plastics recycling rate is expected. To achieve this, it is necessary to further expand recycling capacities and create a corresponding market for plastic recyclates.

For this strategy, too, it is important to leave the choice of technologies to be used to the reprocessors (applies to early separation as well as extended PST)

4.4.2 Summary and recommendation Separation and recycling strategies for ELVs

In the area of **ELVs, the following** were identified and evaluated as possible separation and recycling strategies:

- The early separation and joint preparation of components of the same plastic type;

- The early separation and joint processing of identical plastic components;
- A focus on the application of extended PST and recycling of ABS/ASA/SAN or SHF and SLF polyolefins; and
- A combination of early separation and application of extended PST and recycling of plastics.

The combination of individual technical options results in integrated separation and recycling strategies.

It became clear that early separation and processing of plastic parts already achieves a high recycling rate today, which is why this potential should be further exploited. However, to further process plastics that are not suitable for early separation (because they are too ineffective or too difficult to implement), the extended PST process is considered a sensible supplement to early separation in order to promote the recycling of ELVs. A combination of these two processes thus appears to be the most effective.

The evaluation shows that the effectiveness and feasibility of early recycling and reprocessing strongly depends on the components and plastic types.

In the field of extended PST and reprocessing, feasibility and effectiveness depend on the types of plastics to be separated, as well as on the composition of the shredder input (which always varies).

The evaluations of the previous chapters and the practical tests, allow to conclude that the early separation and reprocessing of bumpers is considered simple as well as effective, as these have a high target plastic content and a high component weight, among other things. The implementation of early separation and reprocessing of hubcaps, fuel tanks and liquid containers is considered neither easy nor difficult. The effectiveness is rated as adequate for fuel tanks and liquid containers (high target plastic content and high component weight). Wheel covers, on the other hand, are assessed as less effective due to the small quantities involved. The separation and reprocessing of dashboards, headlamps and radiator grilles are considered more demanding in terms of feasibility (whereby dashboards and radiator grilles are considered effective due to the high plastic potential, among other things). For a better or real assessment, however, these material flow-specific processes would first have to be developed and evaluated.

The early separation of all components that interfere with the processes of the extended PST (e.g. components contaminated with pollutants, carbon fiber-reinforced plastics or composites) is also considered challenging.

An easier feasibility in the field of extended PST is achieved with the reprocessing of the SHF (since this has already been enriched with plastics through metal removal). Thus, the feasibility of processing plastics from the SLF is considered somewhat more complex than from the SHF but offers great plastics potential, especially for polyolefins.

Measures to promote the combination of early separation and the use of an enhanced PST process as a promising strategy, are discussed in chapter 5 developed.

5 Derivation of measures to improve mechanical plastics recycling from WEEE and ELVs

Measures and recommendations for action are developed on the basis of the knowledge gained in the project, in particular the evaluation of the legal framework, and the strategies derived. The aim is to implement the technically necessary measures to improve the recycling of plastics from WEEE and ELVs and to create framework conditions and incentives for the separation of "mechanically recyclable" from "non-mechanically recyclable" plastics, other materials, pollutants and contaminants.

The focus of the project is on measures that achieve the realisation of the technically necessary measures in terms of improving plastic recycling from WEEE and ELVs and create framework conditions and incentives for the separation of "mechanically recyclable" from "non-mechanically recyclable" plastics, other materials and pollutants and impurities.

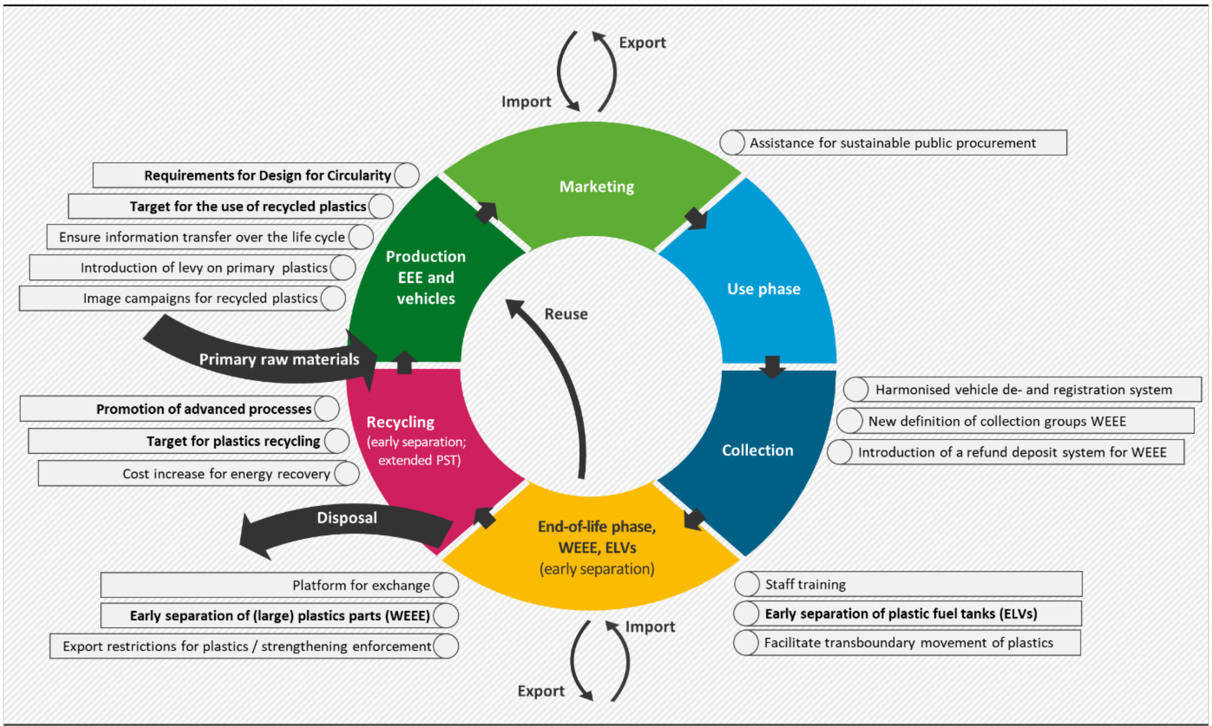
Against this background, some measures have been identified that are important for the realisation of the technically required measures for separation in the phase of recycling as well as production and marketing, because they directly support the separation and recycling strategies (strategy-specific measures):

- Target for plastics recycling
- Early separation of (large) plastic parts from WEEE
- Early separation and recycling of plastic fuel tanks
- Promoting advanced practices
- Target for plastic recyclate use (recycled content ratio)
- Design specifications for circularity

It is in the nature of the circular economy that changes at one point in the cycle also necessitate changes at other points in the cycle. Measures are only effective if suitable complementary measures are also taken in other phases of the cycle. Specifically, targeted measures in the recycling phase (with the aim of increasing the supply and quality of secondary plastics) must be complemented by measures in the production and marketing phase (with the aims of increasing the demand and quality of secondary plastics and improving the recyclability of products) and also by measures in the use and waste collection phase (with the aim of improving the quality and quantity stability of the waste input). Only if these measures are implemented in a coordinated manner can cycles be effectively closed by stimulating the supply of high-quality recyclates on the one hand and ensuring the demand for such recyclates on the other.

This makes it clear that in addition to the above-mentioned strategy-specific measures, other measures can also be useful, which, however, can only be derived and justified more or less directly from the analysis of the results of the present project, but which can create suitable framework conditions and incentives that are prerequisites for realising the objectives pursued. Such "complementary measures" are also presented in the following sub-chapters. The selection of measures was limited to those that address the specific objective of increasing the recycling of plastics in the area of WEEE and ELVs and can counter current obstacles and challenges to higher recycling rates of plastics in the area of WEEE and ELVs, but also have the potential to increase the use of recyclates in EEE and vehicles.

Figure 20: Illustration of strategy-specific and complementary measures based on the life cycle



EEE = Electrical and Electronic Equipment; WEEE = Waste from Electrical and Electronic Equipment; PST = Post Shredder Technology; ELV = End-of life vehicle

Source: own illustration Ramboll / Fraunhofer IVV

5.1 Waste phase and recycling

5.1.1 Strategy-specific measures

Target for plastics recycling

The recycling of plastics is to be promoted through a legally prescribed, weight-based recycling targets. The recycling targets can be achieved by means of secondary plastics, which primarily originate from high-quality mechanical recycling or also from chemical recycling. It is essential that the resulting secondary plastics are used to replace primary plastics. To this end, recycling targets are proposed for WEEE categories and ELVs. Target corridors with clear timeframes and recycling targets are intended to provide planning security. This contributes to the European Plastics Strategy target of recycling 50% of all plastic waste by 2030. Against this background, the following recycling targets are proposed (percentages based on the total mass of WEEE or ELVs):

- WEEE:

Table 13: Targets for plastics recycling (WEEE)

Category	Target for plastics recycling
Category 1 (heat exchangers):	2024: 5 %, 2027: 10 %, 2030: 15 %.
Category 2 (display screen equipment):	2024: 5 %, 2027: 7 %, 2030: 10 %
Category 4 (large appliances):	2024: 5 %, 2027: 7 %, 2030: 10 %
Category 5 (small appliances):	2024: 5 %, 2027: 9 %, 2030: 13 %

- ELVs:

Table 14: Targets for plastics recycling (ELV)

Category	Target for plastics recycling
ELVs	2024: 0.7 %, 2027: 2.0 %, 2030: 3.3 %.

Implementation requires the availability of sufficient recycling capacities. This requires considerable effort and corresponding investments. On the other hand, the possible savings in primary raw materials and the associated follow-up costs mean that considerable savings can be made in economic terms and the measure makes an essential contribution to achieving a circular economy.

The concrete implementation of such a target requires a considerable regulatory effort and the achievement of the target would have to be reviewed after its introduction. Existing reporting obligations for the waste statistics survey of primary and secondary treatment facilities should be used and, if necessary, adapted to determine the share of recycled plastics per WEEE category or for ELVs as an annual average. For primary and secondary treatment facilities in the area of WEEE and ELVs, a horizontal verification of the fulfilment of the recycling target per reporting year should be established.

In the future, plastics recycling targets should be regularly adjusted to the waste composition and the state of the art of recycling, under the premise of high-quality mechanical recycling.

Early separation of (large) plastic parts from WEEE

It is proposed to include a requirement for the early separation of large plastic parts, such as drawers and compartments in refrigerators, with subsequent mechanical recycling in the EAG-BehandV if the corresponding materials are not separated and recycled during or after shredding. By separating large plastic parts at an early stage, it is possible to create fractions of higher purity or, in some cases, mono-fractions. Especially in the case of equipment that is currently already undergoing manual or semi-mechanical dismantling, companies can carry this out with little additional effort during dismantling.

Inclusion of early separation and recycling of plastic fuel tanks in EC End-of-Life Vehicles Directive

Through the practical tests and discussions with experts, the advantage of early separation with subsequent recycling of plastic fuel tanks was recognised. The main advantage is that odour contamination of the entire shredder fraction and disruption of the shredding process can be prevented. The practical tests confirmed the possibility of mechanical recycling. Therefore, the early separation with subsequent mechanical recycling of plastic fuel tanks made of PE is to be included in Annex I of the EC WEEE Directive, point 4, under a new indent, so that it reads:

"Removal of plastic fuel tanks before the shredding process and feeding them primarily for reuse or recycling".

This is also to be included in the AltfahrzeugV under point 3.2.3.3 of the Annex.

Investment aid and fiscal measures to promote advanced processes

The provision of low-threshold investment aid and tax measures are intended to specifically promote advanced processes, but also the expansion of process combinations existing on the market. By reducing the investment risk, the development of a comprehensive recycling infrastructure - in particular the development of sufficient recycling capacities - is supported. In addition, the use of the processes should increase the recyclable plastic content and improve the recyclate quality. There are several possibilities for practical implementation, which are not mutually exclusive and can be used in combination if necessary. For example, subsidy programmes have proven to be an adequate means for the targeted promotion of certain economic sectors, especially in economically uncertain times. In this way, the expansion of recycling infrastructure and capacities could be accelerated to achieve the desired goal. Existing funding programmes are currently either too broadly thematic or focused on other areas, so that the expansion of capacities for mechanical plastics recycling has not been promoted to the extent that it is needed. The state has further options in the form of investment aid, such as state participation or loan guarantees, and in the form of tax measures, such as improved depreciation options.

Implementation requires considerable investment in the expansion of capacities and advanced processes for the provision of secondary plastics in sufficient quantity and quality. On the other hand, the potential savings in primary raw materials and the contribution to climate protection and associated follow-up costs mean that considerable savings are possible in macroeconomic terms.

5.1.2 Complementary measures

Cost increase for energy recovery from plastics

The aim is to improve the economic efficiency of recycling. Improve the economic efficiency of plastics recycling compared to energy recovery by introducing a tax on the incineration of plastic waste.

Facilitate or enable cross-border shipments of plastic-containing fractions for the purpose of high-quality mechanical recycling in other EU countries.

The aim is to increase the supply and quality of secondary plastics. This measure aims at simplifying the intra-European shipment of plastic-containing fractions from WEEE and ELVs by further reducing bureaucratic hurdles, provided that the objective of the shipment is mechanical recycling.

Export restrictions or strengthening of enforcement for the export of waste containing plastics to non-European countries

The aim is to increase the supply and quality of secondary plastics. Currently, large quantities of plastic waste are still exported from Germany to non-EU countries. In order to reduce these exported quantities as well as illegal exports, it is necessary to discuss whether concrete, further export restrictions could be introduced or whether it would be sufficient to improve monitoring.

Training of personnel in dismantling companies

The aim is to improve the economic efficiency of dismantling and recycling. This measure obliges the owners of dismantling companies to train their staff in (non-destructive) dismantling and to establish the topic of sustainability or circular economy in the corporate culture.

Creation of a platform for the exchange of actors along the value chain

The aim is d to increase the supply and quality of secondary plastics. In order to establish and improve new cooperations between dismantling, shredding and recycling companies, a platform for better exchange is to be created. This should contain specific information on the concrete possibilities of dismantling, shredding or recycling. In addition to the creation of a network, the exchange of knowledge should also be promoted.

5.2 Production and marketing

5.2.1 Strategy-specific measures

Target for the use of plastic recyclates (recycled content ratio)

Currently, recyclers do not have a stable market for the recycled plastics. In order to oblige manufacturers to use recycled plastics, a target for the use of secondary plastics could be introduced. This would increase the demand for secondary plastics and provide a stable market for recyclers. The target refers to PCR plastics. The PC recycled content ratio (PC-RCR) is determined by the mass share of PCR plastic in the total plastic content of the product.

For EEE, a general PC-RCR of 5 %-10 % of total plastic use could be targeted initially (starting value of 2% in 2024 and a target corridor until 2030), with the aim of increasing this share in the further future. The proposed quota refers to EEE across all equipment categories. In certain product groups, comparatively high recyclate use rates are already possible. In the design of the PC-KREQ under the EC Ecodesign Directive, specific PC-RCR should be established for individual product groups.

For vehicles, a PC-RCR of 10 % - 15 % of total plastic use could initially be targeted (starting value 2%, target corridor until 2035, adjustment to approx. 10 % in 2030 and 15 % in 2035). It is recommended to relate the recyclate use rate to the mass share of PC-RCR plastic in the total plastic share of the vehicle fleets.

Implementation requires the availability of sufficient capacities to provide secondary plastics in sufficient quantity and quality. The availability of secondary plastics can be supported by a target for plastic recycling from WEEE and ELVs. This requires considerable effort and corresponding investment. On the other hand, the potential savings in primary raw materials and the associated follow-up costs mean that considerable savings can be made in macroeconomic terms.

The PCR content of a plastic cannot be determined analytically. To implement a PC-RCR, it is therefore necessary that the PCR recyclate mass from the recycler to the finished product is reliably balanced and verified. Approaches for a corresponding system already exist (Schischke et al., 2021) and can be used as starting points for the design of a detection system from recyclate production to use in products. In the long term, the information on the PCR recyclate content could be used for the realisation of the digital product passport for products made from these recyclates.

In order to review the achievement of objectives and as a basis for adapting the PC-RCR to the state of the art, corresponding reporting obligations would have to be prescribed and implemented.

Establishing a system for detection and monitoring requires considerable effort and time.

Design specifications for circularity in the area of EEE and vehicles

This measure aims to facilitate recycling with concrete specifications for design for circularity for EEE and vehicles, already during the manufacturing process, and thus also to improve the economic efficiency of dismantling and recycling. The aim is to avoid the use of potentially harmful substances that will be restricted in the future, to keep the variety of polymers to a minimum, to use polymers that are easy to recycle (such as polyolefins or ABS), well-tolerated and easy to separate (such as PE + PP; PC + ABS) and to avoid substances that hinder recycling (such as composites, fiber composites and blends (with the exception of recyclable blends). Furthermore, specifications were formulated for easy and effective dismantling.

The following points must be taken into account for the implementation:

- Dialogue between different stakeholder groups; consideration of results of Circular Plastics Alliance
- Effort for manufacturing companies: Modification of products/components and production; innovations may be necessary;
- Process for inclusion in directives: time-consuming process (for EC Ecodesign Directive description below);

5.2.2 Complementary measures

Ensure information flow over the entire life cycle

The aim of the measure is to improve the recyclability of products. In order to be able to ensure the flow of information over the entire life cycle, there are several possibilities: For vehicles: living IDIS database or simplification of the IDIS database for dismantling companies; for EEE: establish platform for EEE with manufacturer information on material inputs and dismantling; introduction of a digital product passport for EEE and vehicles; application of innovative technologies to deposit information on the product itself.

Introduction of a levy on primary plastics

The aim of the measure is to improve the economic efficiency of recycling. The introduction of a levy on primary plastics is intended to increase the use of secondary plastics. For reasons of competition, a levy should preferably be implemented EU-wide or internationally.

Assistance for the implementation of the preferential duty for public procurement

The aim is to increase the demand for products with secondary plastics. The obligation to give preference to sustainable procurement is anchored in § 45 KrWG. Since little experience has been gained so far, concrete assistance for sustainable public procurement should be developed. For example, in the form of a list of "quick wins products" containing product groups with a typically high proportion of secondary plastics.

Image campaign for the use of secondary plastics

The aim is to increase the demand and quality of secondary plastics. The aim of this measure is to raise the image of secondary plastics or products made from secondary plastics by using labels or providing corresponding information to educate consumers.

5.3 Use and waste collection

5.3.1 Complementary measures

Harmonised vehicle registration and deregistration within the EU

The aim is to improve the quality and quantity stability of the waste input. A common, improved framework for the registration and deregistration of vehicles within the EU is intended to counteract the illegal disposal of vehicles. Specifically, a distinction between temporary and permanent deregistration is recommended.

Introduction of a deposit system for various EEE/WEEEs

The aim is to improve the quality and quantity stability of waste inputs. This measure provides for the introduction of a deposit system for specific WEEE in order to increase the collection quantities and consequently also create quantity stability for plastics through WEEE or increase the quantities. Subsequent high-quality recycling must be a prerequisite.

Redefinition of the collection groups

The aim is to improve the economic efficiency of recycling. Classification of WEEE into collection groups based on material types instead of based on size of the appliance.

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