PolyCE

Post-Consumer High-tech Recycled Polymers for a Circular Economy

Project Duration: **01/06/2017 - 31/05/2021**

Deliverable No.: **D3.4**

Deliverable Title: Adaptation of EoL treatment of e-waste to enable sorting and separate collection of plastics without contaminations from other fractions of EoL treatment

Version Number: V1

Due Date for Deliverable: **15/03/2019**

Actual Submission date: **31/01/2019**

Lead Beneficiary: **Technische Universität Berlin**

Lead Author: Perrine Chancerel
Johanna Emmerich
Franziska Maisel

Deliverable Type: R

R = Document, report
DEM = Demonstrator, pilot, prototype, plan designs
DEC = Websites, patent filing, press & media actions, videos, etc.

Dissemination Level: PU

PU = Public
CO = Confidential, only for members of the consortium, including the Commission Services

Lead Author Contact: Johanna Emmerich
Technische Universität Berlin

Phone: +49 30 46403 748
e-mail: Johanna.emmerich@tu-berlin.de

Contributing Partners

List partners and / or co-authors contributing to this Deliverable

Luca Campadello	(ECODOM)
Alessia Accili	(ECODOM)
Nazarena Vincenti	(ECODOM)
Dr. Jef Peeters	(KU Leuven)
Alexander Boudewijn	(KU Leuven)

Disclaimer

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730308

Table of contents

Glossary

ABS	Acrylonitrile-butadiene styrene
BFR	Brominated flame retardants
CRT	Cathode ray tube
C&F	Cooling and freezing equipment
DSC	Differential scanning calorimetry
EEE	Electrical and electronic equipment
ELV	End-of-life vehicles
EoL	End-of-life
FR	Flame retardants
FT-IR	Fourier-transformed infrared
HIPS	High-impact polystyrene
LHA	Large household appliances
LIBS/LIPS	Laser-inducted breakdown-/ laser-inducted plasma spectroscopy
MDS	Magnetic density separation
MFI	Melt flow index
MIR	Mid-infrared
MIR-T	Mid-infrared thermography
NIR	Near-infrared
OEM	Original equipment manufacturer
PBB	Polybrominated biphenyls
PBDE	Polybrominated diphenylethers
PC	Polycarbonate
PCB	Printed circuit boards
PCR	Post-consumer recycled
PCs	Personal computers
PE	Polyethylene
PMMA	Polymethyl-methacrylate
POP	Persistent organic pollutants
PP	Polypropylene
PS	Polystyrene
RoHS	Restriction of hazardous substances
S/F	Sink/float
SHA	Small household appliances
sWEEE	Small waste electrical and electronic equipment
TVs	Televisions
UV	Ultraviolet
WEEE	Waste electrical and electronic equipment
XRF	X-ray fluorescence
XRT	X-ray transmission

List of figures an tables

Executive summary

The increased use of electrical and electronic devices leads to growing generation of waste electrical and electronic equipment (WEEE). WEEE is now the fastest-growing waste stream in the world and it is estimated that this waste stream reached 48.5 million tons in 2018. On a global scale, society treats only 20 % of WEEE appropriately and there is little data on what happens to the rest[1]. Today, the main economic driver for WEEE recycling comes from the recovery of metals. Recycling of WEEE plastics, on the other hand, still represents a major challenge from a technical and economic point of view. In order to ensure high quality recycling of WEEE plastics an efficient separation process is key.

The aim of this deliverable is to evaluate modifiable parameters in the WEEE plastics pre-treatment processes and to provide recommendations aimed at improving the volumes and quality of the plastics materials delivered to post-consumer plastics recycling facilities. For this purpose, different shredding technologies applied by WEEE pre-treatment operators and their output particle size as well as the sorting technologies used by recycling facilities and their required input particle size were investigated and analysed. An investigation of provided samples of plastic flakes from WEEE pre-processors was performed.

The results show that the different sorting technologies require different particle size ranges for efficient separation. The particle size distribution of pre-processors samples shows how challenging it is for pre-processors to get a homogeneous particle size range during the shredding step. The results suggest that a particle size between 10 to 20 mm increases the recyclability of the plastic fractions and minimizes the losses into fines.

The key recommendations for pre-processors and recyclers are to improve their communication, pre-sorting of the mixed plastics fraction in the pre-processing facility (e.g. pure plastic types/BFR/POP/dangerous or not), to standardize the particle size range to 10-20 mm and to find suitable recyclers with appropriate sorting technologies for the fine fraction instead of discarding it. Furthermore, the production of fine fractions should be kept low by reducing the number of shredding steps and the choice of an adequate shredding technology.

[1] https://www.weforum.org/reports/a-new-circular-vision-for-electronics-time-for-a-global-reboot

1 Introduction

Whereas Waste Electric and Electronic Equipment (WEEE) constitutes one of the fastest growing waste streams in the 21st century (Widmer, Oswald-Krapf, Sinha-Khetriwal, Schnellmann, & Böni, 2005), only little of the contained valuable materials such as metals and plastics is retrieved or recycled. Plastics account for roughly 10-30 % of WEEE material composition (Taurino, Pozzi, & Zanasi, 2010), making it a significant fraction available for recovery. Results from PolyCE deliverable 3.1 claim that waste stream from cooling and freezing (C&F) appliance contains 12.8 % of plastic; large household appliance (LHA) waste stream contains 6.82 % of plastic; TVs and screens waste stream contains 16.42 % of plastic and small household appliance (SHA) waste stream contains 36.4 % of plastic. Furthermore, the WEEE Directive[2] defines strict mass-based recycling quotas, which cannot be achieved with metal or glass alone due to the high percentage of waste plastics (European Union, 2012; Maris, Botané, Wavrer, & Froelich, 2015a). The lack thereof, in part, is due to a multitude of technological restraints such as the incompatibility of certain polymers and the deterioration of plastics' properties (Kistenmacher, 2003) as well as the sheer diversity of plastics (type of polymer and colours) found in WEEE (Martinho, Pires, Saraiva, & Riberio, 2012). In order to move closer to a circular economy for polymers in the electronics industry, improvements along the entire value chain should be put in place. The technologies applied throughout the entire recovery and recycling process must be reviewed and reformed.

Current sorting strategies still leave room for improving the segregation levels and the necessary removal of contaminants. The WEEE treatment pre-processors produce mixed fractions for both the plastic recycling industry as well as for energy recovery industry (Martinho, Pires, Saraiva, & Ribeiro, 2012). Considering the production of post-consumer recycled (PCR) plastics from WEEE treatment, the following factors influence the quality of the recycled product, i.e. plastic flakes: type of plastics, hazardous additives like brominated flame retardants (BFR) and material impurities. These parameters depend on the properties of the WEEE input material which cannot be influenced. To fulfil these parameters with a high quality, the sortability must be as high as possible. In order to achieve this, the plastic flakes must be separated with the minimum possible losses across the different sorting technologies. To ensure this, the various sorting technologies require different ranges of particle size to keep the scrap/losses as low as possible. Reasons for energy recovery or landfill fractions from WEEE are the mixed composition with impurities or additives which provoke high recycling costs. To keep this fraction as low as possible, the separation efficiency should be as high as possible. Sorting efficiency is a criterion for quality of sorting and means the yield of the recovered target plastic type(s).

[2] Directive 2012/19/EU on waste electrical and electronic equipment (WEEE)

1.1 Aim and scope of the deliverable

This report focusses on finding the modifiable parameters in the WEEE plastics pre-treatment processes and formulating recommendations aimed at improving the volumes and quality of the plastics materials delivered to post-consumer plastics recycling facilities. Considering that task 3.4 focuses on the improvements of the pre-treatment technologies, the hypothesis is that the input WEEE stream is stable, the only parameter that can influence the sorting activities, to keep the losses as low as possible, is therefore the particle size. In respect of other PolyCE tasks, the improvements of input material is performed in task 3.2. Therefore, focus is placed on the producing output particle size of the pre-processors and the required input particle size of the plastic recycler.

The recommendations produced in task 3.4 will be tested and validated in task 7.1.

2 State-of-the-art

A broad investigation of the available literature on the WEEE pre-processing and plastics sorting was conducted, including the sources listed below.

Table 1: Overview of literature review on WEEE pre-processing and plastics sorting

Source	Contents (general)	Mass flows	Waste Compo-sition	Recycling technolo-gy	Type of stream
(Maris et al., 2015b) (paper)	Focus on WEEE: waste streams polymer composition, additives, polymer characterization methods, contamination in recycling		x	x	WEEE
(Stenvall et al., 2013) (paper)	Focus on mechanically recyclable, BFR-free WEEE plastics: polymer composition of batch from recycling facility in Sweden		x		WEEE
(Kistenmacher, 2003) (presentation)	State of the art in packaging- / ELV- and EEE recycling, very vague, mostly general information	x			WEEE, ELV, Packaging
(Koehnlechner, 2016) (presentation)	State of the art in plastics waste treatment, detailed description of sorting technologies, complications, compatibility of plastics	x	x	x	WEEE
(Martinho et al., 2012) (paper)	All WEEE plastics, polymer composition of batch from recycling facility in Portugal, discussion of demands for manual recycling	x	x	x	WEEE
(Biddle et al., 1999) (report)	Focus on plastic bottles and general overview of developing plastics recycling industry (barriers, technologies)			x	Plastic bottles
(Schlummer, Gruber, Mäurer, Wolz, & van Eldik, 2007) (paper)	Characterisation of polymer fractions from waste electrical and electronic equipment (WEEE) and implications for waste management		x		WEEE
(Buekens & Yang, 2014) (paper)	Definitions of concepts and terms, plastics amounts of various EEE categories, overview of legal framework, design strategies		x		WEEE
(Bennett et al., 2009) (report)	Separation of mixed WEEE plastics - A series of demonstration trials on novel techniques for the separation of mixed WEEE plastics.		x	x	WEEE
(Frerejean et al., 2015) (report)	Technological information on mix plastic sorting and mechanical recycling equipment			x	WEEE, ELV
(Batanic et al., 2018) (paper)	Applied WEEE pre-treatment methods: Opportunities to maximizing the recovery of critical metals	x		x	WEEE
(Hyks et al., 2014) (report)	Shredder residues: Problematic sub-stances in relation to resource recovery		x	x	WEEE, ELV
(Freegard et al., 2007) (report)	Overview of WEEE Plastics Separation Technologies			x	WEEE

2.1 WEEE pre-treatment

To enable the separation and compounding of PCR polymers, the collected WEEE must undergo a number of pre-treatment measures (figure 1). This may include manual disassembly/ dismantling, a mechanical treatment process and a combination of manual and mechanical pre-processing (Batanic et al., 2018). Manual sorting may serve as a basic form of decontamination.

As a first technical step of the WEEE pre-treatment, particle size must be reduced in order to create particles where the separation based on their characteristics (Biddle et al., 1999). For pre-shredding of WEEE, cross-flow-shredder, rotary shredder as well as slow-rotating hammer mills or rotary shears can be used. For post-shredding, it is suggested using slow-rotating hammer mills or rotary shears, knife mills, rotary impact mills or granulators. The batch is then sieved in a spinning drum which allows the removal topical dirt (Christine Jeavens, 2008).

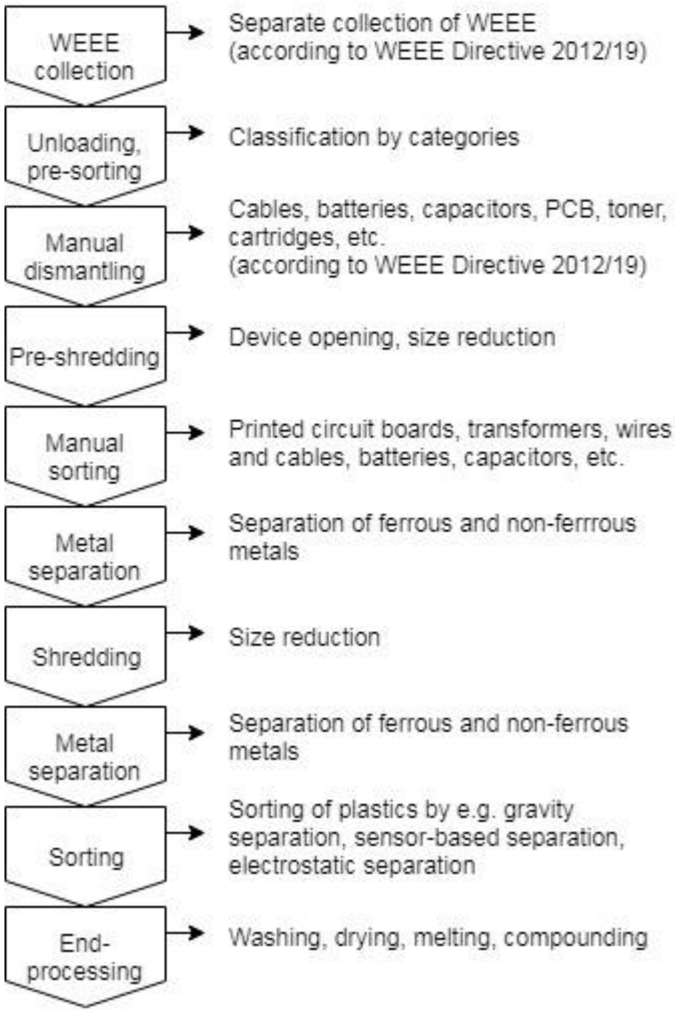
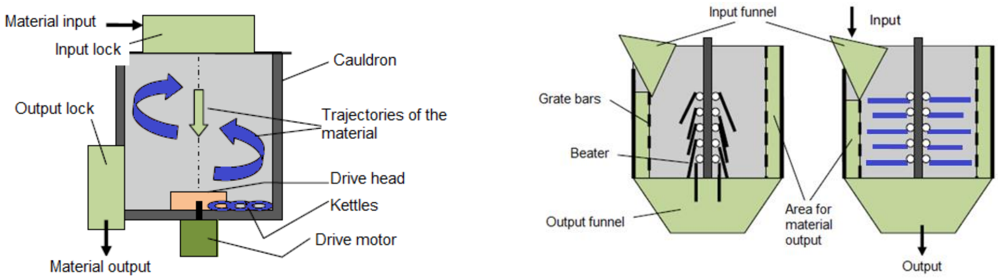


Figure 1: Multistep mechanical separation with following sorting and end-processing according to (Batanic et al., 2018; Chagnes, 2016; Ueberschaar, Geiping, Zamzow, Flamme, & Rotter, 2017)

The processing principle of a **cross-flow shredder** completely dispenses the WEEE with the use of knives and closes the feed material very gently and quickly by impact stress (ANDRITZ, 2016). This gentle cutting machine has been developed especially for WEEE. The machine consists of a boiler, on the bottom of which a rotating kettle is installed. The chain puts the WEEE in an intensive movement, which leads to a mutual impact stress (autogenous decomposition technique). As a result, the cross-flow shredder disassembles the devices in single components. (Martens & Goldmann, 2016)

The **rotary shredder** is optimally adapted to the task of decomposition with regard to the disintegration process result, the degree of shredding and the intensity of the stress. It consists of a vertical cauldron, a vertical shaft and movable elements arranged on it. Product discharge takes place via the cauldron wall designed as a gap grate. The processed product results from the fact that essential components are only detached from their composites, the same principle as the process of the cross-flow shredder. (Drechsel, 2006; Martens & Goldmann, 2016)

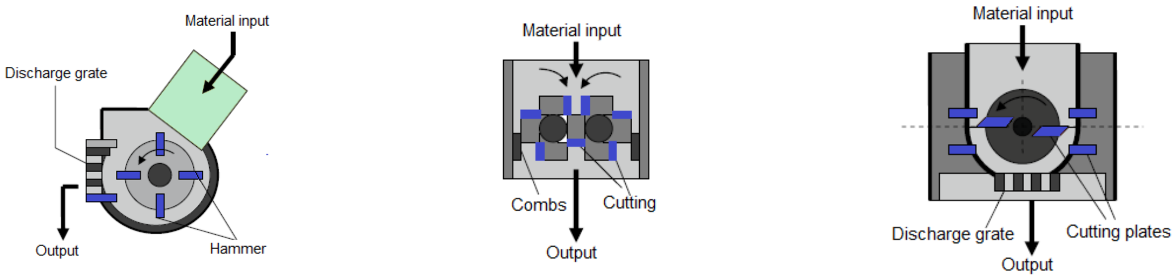
A schematic illustration of a cross-flow shredder (1) and a rotary shredder (2) is given in figure 2.



(1) Cross-flow shredder (2) Rotary shredder

Figure 2: Schematic illustration of a cross-flow shredder and a rotary shredder *[Martens & Goldmann, 2016]*

The **hammer mill** uses hammers capable of rotating around an axis for the size reduction (Veit & Bernardes, 2015). It is differentiated between horizontal and vertical hammer mills with flexibly mounted hammers (Bilitewski & Härdtle, 2013). The input material fed into the machine from above is picked up and shredded by the hammers. The operation of the hammer mill works so that the hammers are radially aligned when circulating by centrifugal forces. (Kranert, 2017)
The **rotary shears (shredders)** with rotor peripheral speeds of lower than 5 m/s (low-speed designs) and more than 20 m/s (high-speed designs) are of great importance in the field of scrap and waste shredding. (Woldt, 2004; Biddle, Dinger, & Fisher, 2003) Depending on the design of the crushing chambers and elements, the rotor shears can be subdivided into axial gap and radial gap rotary shears. (Woldt, 2004)
For the shredding of WEEE, especially for further shredding of soft materials like plastics, the **knife mill** is used as a common equipment (Veit & Bernardes, 2015). The shredding technique of a knife mill belongs to the cutting of the material using knives attached on two in opposite direction rotating shafts (Veit & Bernardes, 2015). Due to the opposite direction of rotation of the knife-mounted double- or single shaft against a cutting comb, the resting material is forcibly pulled. The shredding takes place between the cutting tools. The degree of shredding is determined by the choice of the distance of the tool blades. (Bilitewski & Härdtle, 2013) Schematic illustrations of a hammer mill (3), a rotary shear (4) and a knife mill (5) are given in figure 3.



(3) Hammer mill (4) Rotary shear (shredder) (5) Knife mill

Figure 3: Schematic illustration of a hammer mill, rotary shear (shredder) and a knife mill *[Martens & Goldmann, 2016]*

Granulators are modified knife mills, which realize a predominant tensile stress by using blunt knives (Bilitewski & Härdtle, 2013). Usually, these machines are used for post-shredding, because they are high speed moving with rotor speed up to 80 m/s and more and therefore can produce small particle sizes (Vegliò & Birloaga, 2018b).
The **rotary impact mill** is a high-performance vertical shaft shredder for use in WEEE

treatment. The unique racquet rotor in conjunction with the toothed ring armor causes an intensive use of the feed material. Material composites are selectively comminuted and separated, material matting is isolated and brittle-hard materials are very heavily comminuted. The size of the output fractions can be adjusted by the variable ring gap. (BHS, 2016)
A schematic illustration of a granulator (5) and a rotary impact mill (6) is given in figure 4.

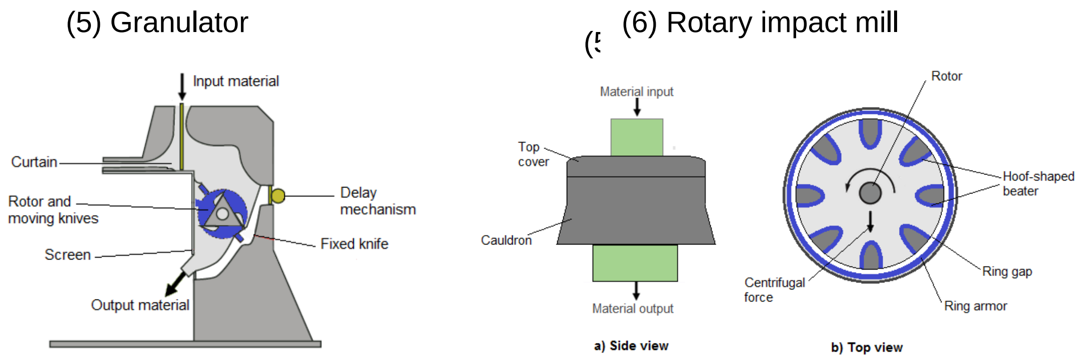


Figure 4: Schematic illustration of a granulator and a rotary impact mill *[WorkSafe, 2017; BHS, 2016]*

After size reduction, usually metal separation is performed by magnetic drum separation and electric conductivity-based separation techniques (Batanic et al., 2018). Ferrous metals (e.g. iron, steel, nickel) and non-ferrous metals (e.g. aluminium, copper) are separated from other materials in the WEEE stream like plastics or glass (Batanic et al., 2018).

A series of various sorting methods are then employed to produce the desired polymer fractions. To separate heavy objects, water baths are commonly used as a sink-float separation (Deloitte, 2017). Optical sorting methods such as spectroscopy technologies may further discriminate polymer types. Pure polymer fractions are further washed and dust is removed (Deloitte, 2017). For further compounding of the fractions the plastics have to be melted (Christine Jeavens, 2008).

2.2 Plastics sorting technologies

2.2.1 Sensor-based separation

Sensor-based sorting technologies all work with a signal source like infrared light, UV-light or X-rays. The sensors are set up on the particle transported by a conveyor belt and emit a signal to a detector. This signal is converted by a computer to a digital signal and the particle is removed due to software settings. Then, the material is split in two fractions, an eject fraction which is ejected by air jets in the machine and the reject fraction remaining on the belt. (Bennett et al., 2009)
Modern WEEE treatment facilities employ a variety of technologies to identify the type of polymer at hand, including **mid-infrared (MIR)** and **Fourier transform infrared (FT-IR) spectrometry**. FT-IR spectrometry is known for producing highly accurate results and the possibility of recognizing blends as well as differentiating between similar plastics e.g. high-impact polystyrene (HIPS) and acrylonitrile-butadiene styrene (ABS). (Stenvall et al., 2013)

When dealing with polymers of identical density, flakes may be separated on the basis of colour using **near-infrared (NIR) spectrometry**. NIR spectrometry, however, does not allow the recognition of dark-coloured polymers, as the dark colouring comes from carbon black which fully absorbs the radiated light and thus impedes reflection and moreover the detection of colour degrees. (Maris et al., 2015b) The other sensor-based separation technologies all can detect black plastics.

Polymer substances containing flame retardants (FRs) or fillers can be detected via density and **X-ray fluorescence analysis (XRF)** as well as several of the above mentioned spectroscopy technologies (Freegard, Tan, & Morton, 2006). A special attention is put on BFRs, given that the presence of bromine in plastics is restricted by the EU-RoHS Directive[3]. Brominated plastics can be separated from light ABS, polystyrene (PS) or polypropylene (PP) via X-ray. (Koehnlechner, 2016) The limit of the X-Ray detection is not identifying the polymer families, since they are composed of the same elements (Bezati, Froelich, Massardier, & Maris, 2015).

The principle of **X-ray transmission (XRT)** is based on X-ray measurements such as X-ray fluorescence analysis. The main difference between XRF and XRT is that the XRT uses the property of permeability of the material. The material is X-rayed and, depending on the density and material composition, the material is penetrated to different degrees, which leads to intensity differences. (Weiss, 2012)

Both NIR and XRT spectrometry detect the presence of flame retardants amounting to a mass fraction of 4-5 %; XRT, however, does not permit the differentiation between the detected flame retardants. Lower mass fractions of flame retardants may be detected via chromatography. The total mass of bromine present in a sample may be investigated via XRF spectrometry. (Delavelle, 2012)

The **laser-inducted breakdown- or laser-inducted plasma spectroscopy (LIBS/LIPS)** is a method to separate types of polymers and BFR from non-BFR plastics (Dimitrova, 2017). The advantage of this technology is the non-contact measurement, the detection of light atoms (not possible with XRT) and BFR (not possible with NIR) as well as different types of BFRs (Frerejean et al., 2015a).

The **polymer tracing** technique is based on the signature of a tracer instead of its intrinsic characteristics to identify a material. The working principle of the polymer tracing process is to irradiate the sample by a UV-light source and fit in the material a small concentration of a substance. Polymers suitable for the tracing process are dark-coloured plastics, plastics with similar density or having fillers altering their density and being incompatible for recycling when merged. But there is no industrial sorting for polymers and no characteristic spectra for polymers. (Maris, Aoussat, Naffrechoux, & Froelich, 2015)

The **Raman spectroscopy** is a sorting method to analyse the type of plastic and additives in the plastics to detect plastics containing BFR. The principle of the process is to irradiate a plastic sample with a monochromatic light and to detect the dispersed light. (Frerejean et al., 2015a) The limitations of this process are on the one hand the high costs (twice or three times more expensive than NIR spectroscopy) and the process needs development for usage in industrial scale (Frerejean et al., 2015b; Saimu Corporation, 2018).

[3] Directive 2011/65/EU on the restriction of the use of certain hazardous substances (RoHS) in electrical and electronic equipment

The **terahertz spectroscopy** is a method to identify the type of plastic including the detection of black plastics in a wavelength range of 100 µm to 1 mm. The process is based on the use of terahertz waves for sorting the plastics based on the determination of a spectrum, which is compared with a database with spectra of different polymers. (Tang, Daryoosh, & Iniewski, 2017)

High-speed laser spectroscopy for polymer sorting is a non-destructive foreign substance detection. It works with optoelectronic sensor technology by a combination of absorption, fluorescence and Raman spectroscopy. It is developed for the identification of substances in industrial processes, especially for the recycling industry. (Meyer, 2017)

Most technologies come with a set of conditions which need to be met during pre-treatment. The pre-concentration of plastics and a minimum particle size of 10 mm, for instance, is necessary for conducting sensor-based separation especially for NIR spectrometry (Hyks et al., 2014). MIR spectrometry requires samples that are flat and no larger than 10 mm (Maris et al., 2015b). Many WEEE treatment facilities opt to use a combination of several polymer detection technologies to provide reliable and successful results.

2.2.2 Gravity/density separation

Polymer fractions are also separated on the ground of their individual densities using the immersion method as prescribed in ISO 1183-1:2013 or **sink/float (S/F) separation**. The latter may separate polymer fractions up to a difference in density of $\Delta\rho=0.002$ g/cm^3, producing separate fractions of PP, talc-filled PP, PS, polyethylene (PE) and ABS with 97% purity (Delavelle, 2012). Brominated plastics may, for instance, be removed via density separation as their density ($\rho>1{,}08$ kg/dm^3) exceeds the one of salt-water (Koehnlechner, 2016).

Similar to the density-based principle of the sink/float separation is the **sink/float magnetic density separation (MDS)**. The difference between the two is that the MDS uses a liquid separation medium with a density gradient as opposed to a single density. Suspended in water are magnetic iron oxide particles with a size about 10-20 nm which vary the effective density of the liquid by applying an artificial gravity with magnetic force. In this way, plastic mixtures separate into different layers and particles of the same density float in the liquid at the same vertical height. (Hu, 2014)

The **hydrocyclone** separator works with the same sink/float principle to separate the heavy and the light fraction of the polymers. The separation of the different plastic fractions of a granulate mixture is caused in the hydrocyclone in a centrifugal force field (Billitewski & Härdtle, 2013). The **centrifugal** sorting process works similar as the hydrocyclone and is also based on density sorting (Frerejean et al., 2015a).

Other density separation methods are **air tables** and **wet shaking tables**, where the particles get separated on a vibrating table. The high-density particles are vibrated to the higher side and the low-density particles to the lower end (Dodbiba, Sadaki, Okaya, Shibayama, & Fujita, 2005).

2.2.3 Flotation

The principle of **flotation** is based on the fact that hydrophobic particles are wetted by air bubbles and rise to the surface where they form a foam layer, while hydrophilic particles are wetted by water. The process takes place in a flotation cell with the addition of flotation agents to the water medium such as depressants, activators, collectors or frothers. (Frerejean et al., 2015a)

2.2.4 Electrostatic/triboelectric separation

The **triboelectric or electrostatic separation** is a method to sort different types of plastics using their differences in electrostatic charges due to different densities. The approach of this separation technology is to collect the different plastic types by letting the plastic flakes fall through an electric field between two parallel electrodes that are charged oppositely. Particles with the higher dielectric constant have a positive charging and particles with the lower dielectric constant have negative charging. After the charging the electrostatic separation takes place through attraction of the positive charged particles by the electrode. (Frerejean et al., 2015b)

2.2.5 Dissolution technology

The **CreaSolv® process** is based on a solvent which dissolves a target polymer separately out of the waste stream and removes non-dissolved and co-dissolved materials (Schlummer, Wolff, & Maurer, 2016). The main advantage of this process is the separation of polymers by family and therefore the separation of BFR-rich fractions to fulfil the RoHS-directive (Frerejean et al., 2015b). However, CreaSolv® is not commercially available and the industrial feasibility is currently tested in two pilot plants in Indonesia and Netherlands (CreaCycle GmbH, 2018).

2.3 Sorting of pure and mixed plastics fractions

The separation technologies in sections 2.2 are used to sort pure or mixed polymer fractions from the WEEE stream. For example, sink/float separation is commonly used to separate different types of plastics, but also to separate metals from plastics as well as plastics with additives. Figure 5 shows an overview of the separation technologies used to sort mixed plastics fractions and pure plastics fractions from WEEE. To illustrate the difference between the principles of the sorting techniques colour framing is used. The technologies are divided in dry (white) and wet (grey) sorting technologies and in the different principles of sorting like metal sorting (orange), sensor-based sorting (yellow), gravity/density sorting (blue), floatation (red), solvent sorting (green) and electrostatic sorting (pink). The black framed technologies are currently not commercially available in the context of WEEE treatment.

It can be observed that the only technology sorting metals, BFR plastics and different types of plastics is the sink/float technology. For sorting metals and plastics by polymer, electrostatic sorting and a wet shaking table can be used. To sort BFR containing plastics from the stream, the sensor-based technologies XRF or XRT can be used as well as the wet technologies sink/float and centrifugal sorting. The processes LIBS/LIPS, Raman spectroscopy, hydrocyclone and CreaSolv® can also separate BFR plastics, but are not available commercially. For separating the different plastic types, NIR, high-speed laser spectroscopy, air table, electrostatic sorting, MDS, wet shaking table, sink/float, centrifugal sorting and floatation can be used. The other processes MIR/MIR-T, LIBS/LIPS, FT-IR, polymer tracing, terahertz spectroscopy, Raman spectroscopy, hydrocyclone and CreaSolv® which can sort by plastic type are not available for purchase. MIR/MIR-T, LIBS/LIPS and FT-IR are only purchased as handheld separators.

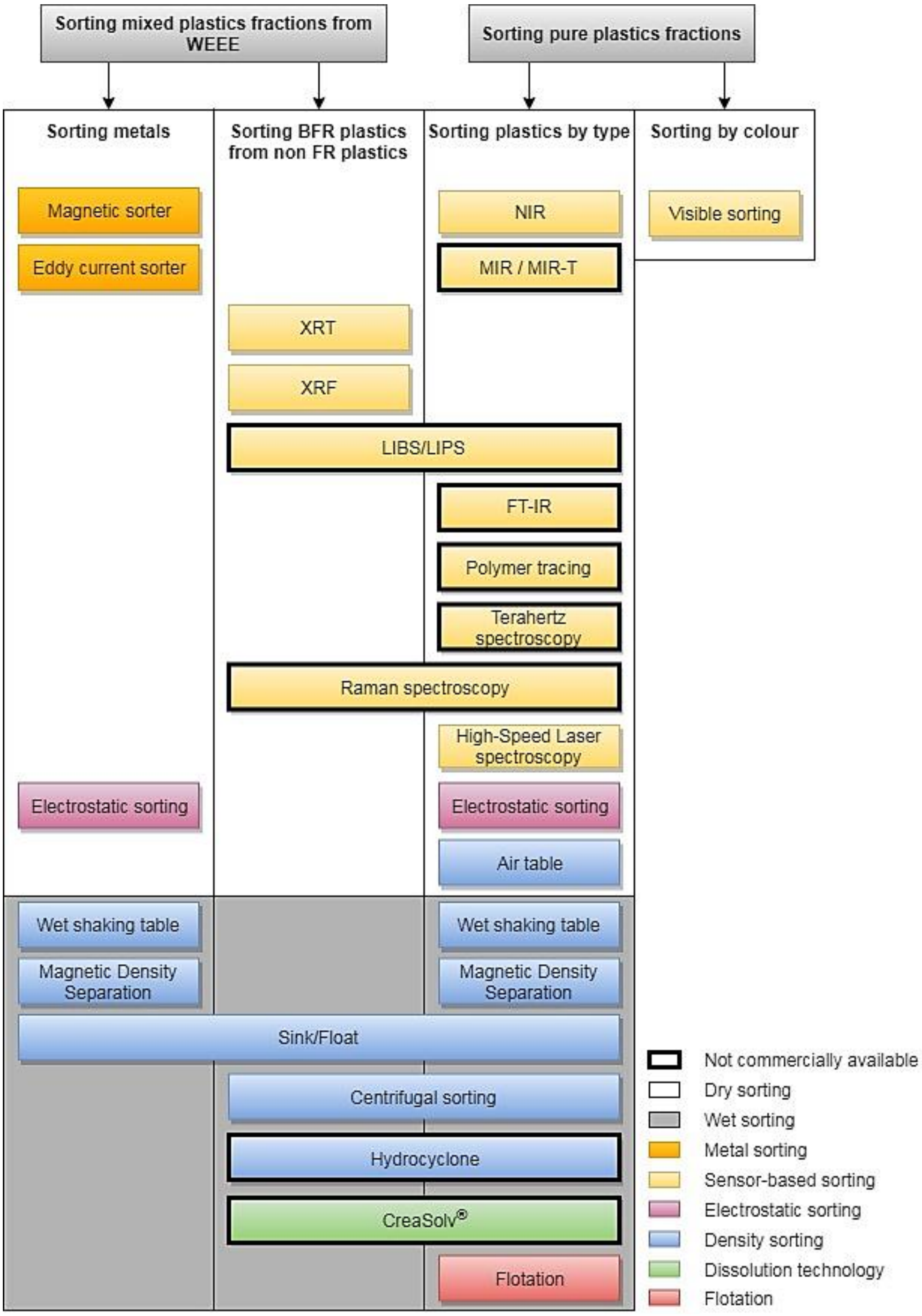


Figure 5: Sorting of mixed and pure plastics fractions from WEEE

In table 2, the sorting technologies are listed together with their characteristics and specifications of the process evaluated in section 2.2. The individual technologies are divided according to the sorting principles of density sorting, flotation, electrostatic sorting, solvent sorting and sensor-based sorting. The evaluated criteria of the techniques are the sorting principle, water treatment, commercial availability, slow or fast process and the sensitivity of density separation methods to small differences in material density.

Table 2: Overview sorting technologies with characteristics and particle size ranges

Sorting technique		Separation of BFR plastics	Separation of polymer types	Separation of metals	Separation by colour	Needs water treatment	Com-mercially available	Slow/Fast process	Sensitive/not sensitive to small differences in material density	Specifications of the technique
Density sorting	**Air table**	No	Yes	No	No	No	Yes	N/A	N/A	Difficulty of the separation of plastic from glass and aluminium, need dust removal system
	Wet shaking table	No	Yes	Yes	No	Yes	Yes	N/A	N/A	Only separation of copper
	Sink/Float	Yes	Yes	Yes	No	Yes	Yes	Slow	Sensitive	No separation of Soft PVC,
	Sink/Float Magnetic Density Separation	No	Yes	Yes	No	Yes	Yes	Fast	Sensitive	Need of specific system for recovering nanoparticles, cheap separation method (five different fractions in one step)
	Hydrocyclone	Yes	Yes	No	No	Yes	No	N/A	Not sensitive	No moving fittings, specific equipment could be expensive
	Centrifugal	Yes	Yes	No	No	Yes	Yes	N/A	Not sensitive	No moving fittings, specific equipment could be expensive
Flotation		No	Yes	No	No	Yes	Yes	N/A	Sensitive	pH modifier and chemical reactive substances, easy changeable separation parameters, permanent control of the bath properties
Electrostatic sorting		No	Yes	Yes	No	No	Yes	N/A	N/A	Need of dry and small particles without dust
Solvent sorting	**CreaSolv®**	Yes	Yes	No	No	Yes	No	N/A	N/A	Needs solvent treatment and regeneration

Sorting technique		Separation of BFR plastics	Separation of polymer types	Separation of metals	Separation by colour	Needs water treatment	Com-mercially available	Slow/Fast process	Sensitive/not sensitive to small differences in material density	Specifications of the technique
Sensor-based sorting	**XRF**	Yes	No	No	No	No	Yes	N/A	N/A	Measurement of heavy substances
	XRT	Yes	No	No	No	No	Yes	N/A	N/A	Measurement of heavy substances
	NIR	No	Yes	No	No	No	Yes	N/A	N/A	sorting of polymers, papers and wood in a mixed stream, No detection of black plastics
	MIR	No	Yes	No	No	No	No	Slow	N/A	Optical equipment can fouled with dirt
	MIR-T	No	Yes	No	No	No	No	N/A	N/A	Needed heat for the process
	FT-IR	No	Yes	No	No	No	No	N/A	N/A	Spectrum over a wide spectral range, only handheld technique
	LIBS/LIPS	Yes	Yes	No	No	No	No	Slow	N/A	Detection of light atoms and different types of BFR
	Colour sorting/ Visible sorting	No	No	No	Yes	No	Yes	Fast	N/A	N/A
	High-Speed Laser spectroscopy	No	Yes	No	No	No	Yes	Fast	N/A	Expensive process
	Polymer tracing/ UV fluorescence	No	Yes	No	No	No	No	Fast	N/A	Detection of tracers with spectra peaks close to each other
	Raman Spectroscopy	No	Yes	No	No	No	No	Fast	N/A	Expensive process
	Terahertz Spectroscopy	No	Yes	No	No	No	No	N/A	N/A	Low temperature for quantum cascade laser needed (difficult to develop emission sources)

N/A: Not available

2.4 Limitations of PCR plastics recycling related to WEEE processing

2.4.1 Technical limitations

The presence of several types of polymers (e.g. ABS, PP, PS), additives (e.g. BFRs) and impurities generated along the treatment phases (e.g. wood, glass) are influencing the recyclability and the achievement of a good quality of recycled plastic fractions.

Types of polymers

The necessity to discriminate polymer types results from the incompatibility of certain plastics for material recycling (Kistenmacher, 2003; Peeters, Vanegas, Tange, van Houwelingen, & Duflou, 2014). The mixture of different plastics leads to a quality decrease of the mechanical properties (Peeters et al., 2014). The limitations of the miscibility of the plastic types is shown in figure 6.

	ABS	ABS BFR	HIPS	HIPS BFR	PET	PC	PMMA	PC/ABS PFR	HIPS/PPE PFR
ABS	G								
ABS BFR	G	G							
HIPS	Y	Y	G						
HIPS BFR	Y	Y	G	G					
PET	O	O	O	O	G				
PC	G	G	O	O	G	G			
PMMA	O	O	O	O	Y	O	G		
PC/ABS PFR	G	R	O	R	R	G	O	G	
HIPS/PPE PFR	O	O	G	G	R	O	O	Y	G

G	Good miscibility (contamination>5%, properties>80%)
Y	Reasonable miscibility (contamination=2-5%, properties>80%)
O	Limited miscibility (contamination=0.1-2%, properties>80%)
R	Bad miscibility (contamination<0.1%, properties<80%)

Figure 6: Compatibility matrix of plastics (Peeters et al., 2014)

Different melting temperatures as well as chemical or physical immiscibility impede plastics compounding (Koehnlechner, 2016). From the figure it can also be seen that additives are used in many types of plastics that can endanger human health, such as BFR. These are also miscible with pure plastics fractions and thus can be recycled despite legislative constrains (see following section). As a result, mechanical recycling is limited to plastics from reliable sources which provide available information on presence or content of additives. (Buekens & Yang, 2014)

Additives

WEEE plastics containing BFRs are regulated under the WEEE and RoHS Directive and have to be collected separately (European Commission, 2011, 2017). The RoHS Directive limits the possibility to mechanically recycle plastics with BFRs such as polybrominated biphenyls and polybrominated diphenyl ethers (European Commission, 2011). Plastics containing more than 1000 ppm Pb, Hg or Cr^{6+} or 100 ppm Cd may not be recycled (European Commission, 2011). The Directive dates back to 2002, but WEEE being treated now can still contain restricted substances (Martinho et al., 2012).

The CENELEC-norm states that the separation of plastics containing bromine must be ensured if the content of bromine in these fractions is higher than 2000 ppm (CENELEC, 2016; Haarman & Gasser, 2016).

Since the year 2009 several flame retardants have been added to Annex I of the POP-regulation[4], which may only be used in products with a certain weight percentage. These include PBBs and PBDEs (tetra-BDE, penta-BDE, hexa-BDE and hepta-BDE) which may only be included in manufacturing and usage with 0.001 wt.-%. [European Parliament, 2004]

The flame retardants PBDEs are also listed in Annex IV which defines the concentration thresholds in waste that makes necessary a treatment or recovery listed in Annex V. The threshold of these flame retardants in waste or especially in waste plastics are set to 0.1 wt.-%. [European Parliament, 2004]

Sorting methods like X-ray fluorescence or sink-float must be used by the pre-processor or the recycler to fulfil the requirements.

Impurities

Another limitation for plastics recycling is the deterioration of plastics' properties occurring during (pre-)treatment processes (Kistenmacher, 2003).

Studies indicate that recycled plastics can have weaker mechanical and unpredictable rheological properties due to several recycling cycles or due to impurities. For instance, studies have reported that the impurity level and the type of impurities could influence some properties (e.g. elongation-at-break, impact strength) more than others (rheology and tensile yield strength) (Liang & Gupta, 2001). For this purpose, efficient sorting techniques are necessary to sort out these contaminants and to avoid these effects.

Problematic in the recycling process are also thin copper wires in electronics (about 100 µm), accounting for 1 % of input. They are problematic because wires create "braids" throughout the recycling process. (Koehnlechner, 2016)

Sortability

The above discussed parameters (types of polymers, additives and impurities) have a significant impact on the quality of recycling and depend on the input material of WEEE, which cannot be influenced during the treatment. For this reason the sortability must be as good as possible. In order to achieve this, the plastic flakes must be separated with the minimum possible losses across the different sorting technologies. To ensure this, the various sorting technologies require different ranges of particle size to keep the scrap/losses as low as

---

[4] Regulation (EC) No 850/2004 on persistent organic pollutants (POP) and amending Directive 79/117/EEC

possible. The limitations of the sortability are given by the different input particle size ranges of the different sorting technologies. If the input particle sizes are not met (e.g. too small or too large particles), this results in misthrows and the recyclability decreases.

Labelling

Regarding to the very few experiences of the manual sorting process, missing polymer signs or flame retardant marks lead to limitations in the pre-sorting process. For instance, previous study reports that 25 % of CRT monitors and 58 % of CRT televisions had polymer signs (Martinho et al., 2012). That is a reason why polymers must be separated by automated sorting processes.

Material characteristics

Limitations can occur during the material characteristics like colour, odour or food contact considerations (Kistenmacher, 2003).

In the polymer sorting process, NIR spectroscopy is mainly used for separating polymer types. As explained in chapter 2.2.1, one limitation of this technology is the detection of black plastics. It is estimated that around 50 % of dark grey or black plastics in WEEE devices cannot be detected with NIR spectroscopy. (Frerejean et al., 2015a).

The usage of recycled plastics materials and articles in contact with food can have several risks. This is caused due to contaminants of the input which are not suitable for food contact applications or incidental contaminations originating from previous use or misuse, chemicals used in the recycling process as well as degradation products of the polymer or of plastic additives. (European Food Safety Authority (EFSA), 2008)

2.4.2 Economic and market limitations

In addition to technical limitations, there are also organisational and economic barriers. These barriers are briefly explained below, but will not be discussed further in the results, as they can neither be improved nor optimized.

Collection

When it comes to organisational barriers, the waste collection scheme plays an important role. The factors that influence the current technological limits of the sorting activities is due to the fact that the amount of WEEE collected is low. Large amounts of WEEE are illegally exported into countries with no or inappropriate recycling procedures (Veglió & Birloaga, 2018a). Particularly in developing countries, the informal sector is often very strong and should be rather integrated into the formal collection system (Hobohm, 2017).

Collecting sufficient volumes of WEEE devices is fundamental for efficient recycling. Collection differs in the various countries, which is also reflected in collection efficiency like collection rates (Veglió & Birloaga, 2018a). Limitations due to the collection of WEEE can be caused by different factors, such as legislation, the collection system, the retailers, and the consumers. Stricter legislation will require individual stakeholders to comply with stricter recycling rates, recycling volumes or producer responsibility. Various studies show that the information on disposal options for WEEE must be brought closer to the end user in order to generate higher collection volumes (Hobohm, 2017). The integration of retailers for instance in the collection of WEEE leads to an increase in collection points and an intensification of coverage (Hobohm, 2017). Regarding to collection systems, adapted collection vehicles and trained staff must be used in order to ensure cost-effectiveness in the collection (Nowakowski, 2016). A study on the end of life of computers found out, that one of the main environmental impacts on EoL is the fuel consumption of the collection trucks (Choi, Shin, Lee, & Hur, 2006). For more details on clustering of WEEE and logistics see PolyCE Deliverables 3.2 and 3.3.

Economic barriers

When it comes to economic barriers, an investigation in deliverable 6.1 evaluated some price considerations due to virgin plastics and PCR plastics.

The price of virgin polymers is volatile and it reflects the changes (daily, weekly, monthly) in economic developments; virgin plastics prices are closely related to their raw materials (e.g. for virgin ABS the fluctuation of **styrene**, acrylonitrile and butadiene should be kept in check) and while the relationship between virgin plastic price and the oil prices is well known being one of the strongest influential factor, there are other factors that are relevant too: grid energy price, cost of additives, supply and demand of virgin plastics. (PolyCE Deliverable D6.1)

In general, the variations in the prices of virgin resins are reflected in the prices of recycled resins: recycled plastics are exchanged at prices that include a discount compared to virgin plastics.

The post-consumer plastic recycled market is smaller and more fragmented in comparison with the primary plastic sector and this puts the sector dealing with recycled plastics at a relevant disadvantage; moreover the global market for plastics waste is concentrated in few countries: China is responsible for two third of waste plastics imports during the last decade and the new Chinese policy on plastic waste import is the evidence of a vulnerable market.

Therefore the market for recycled plastics, although constantly developing, still remains fragmented and small in size compared to the virgin one. As a result, the prices of recycled plastics are not determined by the marginal costs of production, as is the case in an efficient market: the prices of recycled plastic pellets are primarily determined by the competing alternatives of virgin resins.

According to the analysis carried out, the demand of post-consumer recycled plastic is related to the unsatisfied demand of virgin plastics. (PolyCE Deliverable D6.1) It seems however that there isn't a parallel stable market for recycled plastics yet.

This could however change with an increasing awareness of both end-users and manufacturers who are starting to look for alternatives to the increasing price of virgin plastics. The price for virgin plastics is dependent primarily on the oil price and on the exchange rate of the dollar, both of which are quite unpredictable. Cost uncertainty is a challenge for manufacturers who would like to have less variance in their long-term contracts with suppliers. Gaining experience in using recycled plastic can lead to more resistance towards future bottlenecks in oil supply.

For manufacturers of electronic devices for instance, the added value of using PCR plastics is driven both from a cost perspective but also for better predictability of the price. (Emmerich et. al 2018).

Demand

Although the market for recycled plastics is developing rapidly, it is still small. This is due to the lack of demand for recycled plastics, for instance by manufacturers. As a result, investments in better separation technologies are met with reserve and large quantities of WEEE plastics remain unrecovered. (Vlugter, 2017) A shift from virgin to PCR plastics will remain difficult as long as the demand is low and product policy or ecolabels do not provide incentives to use respectively increase the content of recycled plastics in products.

As far as manufacturers are concerned, a factor is resistance to change. The manufacturers usually do not know about the advantages of recycled plastics such as more cost-effective material and ensuring a stable supply and many remain reluctant to try out alternatives due to lack of experience (Emmerich et. al 2018).

Stability and visibility

The stability and visibility of the plastic recycling market is not given, which makes marketing and efficient, high-yield recycling difficult.

The composition of the product changes too fast (see CRT, flat screens evolution). So, a clustering that makes sense today might not make sense tomorrow because different polymers and different blend will be used. The trend is that the number of polymers inside the products is considerably increasing. This makes the stability of the quality challenging.

An investment in increased recyclability or cost savings of a company requires market visibility. It must be sure that the investment is worthwhile in the long term, and not just over a certain period of time. This would not be economic for the company. Due to insufficient stability, companies are reluctant to invest. For this reason, the market must be stabilized. From today's perspective, it is not possible to predict how the market will change over the next 5 years (or 6 months).

The collection of EoL products is currently small in scale and widely dispersed. This makes it practically and economically challenging to source sufficient and stable volumes of waste plastics. It is difficult to anticipate when a specific product will reach the recycling stream, without a prearranged take-back scheme. For the example of a specific printer, it could be retrieved after only 2 years, but also after 10 or 20 years. (Vlugter, 2017) This makes a stability of volumes to a major challenge.

The prices do not only depend on plastics quality, but also on demand and offer. The creation of a strong PCR secondary market can create a major stability but there will be always external forces that will influence the prices. However, recycling depends on many factors including oil price or incineration price. These prices are volatile which cannot be prevented.

3 Methods

3.1 Interviews with pre-processors

In addition to the literature review a series of semi-structured interviews with WEEE and plastics recyclers were conducted. In preparation for these interviews, a tailored check-list was established (Annex A) containing questions left unanswered by the literature review. The questions were individually adapted according to the type of operations conducted in the pre-treatment facilities and the level of expertise of the interviewees. Questions arising from task 3.2 of the PolyCE project were added to the interview check-list to avoid having to conduct several interviews with the same operators.

In total, 18 interviews of operators of WEEE pre-processing facilities were conducted in Italy (by ECODOM), Germany and France (by TU Berlin). The interviews were conducted in the language of the country (Italian, German and French). It was agreed with the interviewees that the results would be aggregated and anonymized before publication.

3.2 Assessment of data from the recycling industry

In order to find out the particle size of shredding and sorting technologies, in addition to the literature review, interviews with plant manufacturers were conducted and plant-specific data sheets were queried. In total, queries were addressed to 21 manufacturers of shredder technologies and 16 producers of sorting technologies (Annex B). The plant manufacturers were contacted verbally and in writing and a questionnaire was compiled on the production plants determined in advance. At the IFAT trade fair in Munich on 16th May 2018, various manufacturers of shredders and sorting technologies were interviewed regarding the used particle size. Important parameters were the efficiency of the plants, the particle size and the material throughput. Based on the statements of the manufacturers, the particle sizes of the different technologies were evaluated and summarized in a comparison table. For shredding technologies, 231 machines were evaluated and analysed with respect to different characteristics like drive power, working width, rotor diameter, throughput and particle size. For sorting technologies, 43 machines were evaluated, analysing the throughput as well as input particle size (Annex D).

3.3 Sample analysis of plastics fractions from WEEE

Several samples of the plastics output fraction, each weighing 10 kg, from shredded WEEE from small appliances were collected. The pre-processors received a form to be filled out with detailed information about the plant, product category, equipment of the shredding and sorting processes and the sieving particle size of the materials transported to the recyclers (Annex E). Since it was not possible to take the samples in the treatment facility by ourselves, the samples were taken by the pre-processors. The pre-processors had been given the specification to take the sample from the full breadth of the conveyor belt, because fines tend to fall down on the sides of a pile.

Further sub-samples were taken from the 10 kg sample to examine the particle size and to set up a particle size distribution.

A computer vision system was used to analyse the mixed plastic samples in order to determine the shape of the single flakes. The program was developed during a master thesis at the KU Leuven within a Python environment with the support of open source computer vision algorithms (Antico & Beerten, 2018). This program was tested for the first time with the samples from the pre-processors.
The process behind the computer vision consists of taking a picture of the plastic flakes spread on a blue background plate, such that disturbances of the measurements are minimized as much as possible. In order to increase the quality of the images, the equipment was encased by a cover to avoid external influences like sunlight. For the calibration of the camera, a circle grid plate is necessary to define the intrinsic parameters. It compensates the distortion caused by the lens and the extrinsic parameters used to transform the pixel coordinates (pixel) to world coordinates (mm). As shown in figure 7, at least 10 images from the grid with a maximum of dispersion are required (Antico & Beerten, 2018).

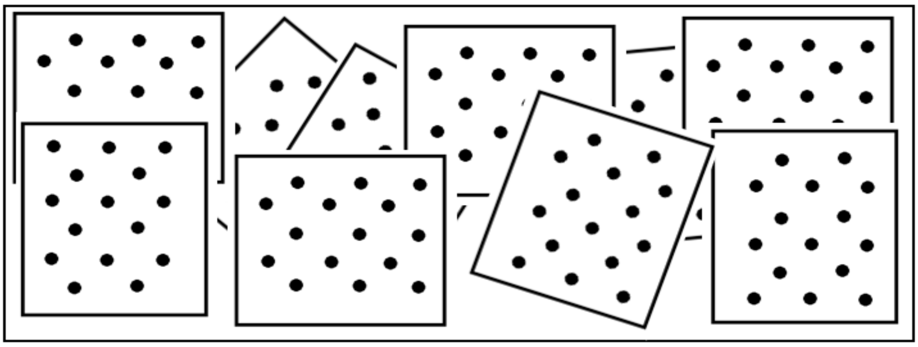


Figure 7: Calibration with the circle grid plate (Antico & Beerten, 2018)

After calibrating, images from the samples were taken. It was ensured that the plastic flakes do not overlap each other and were applied inside the blue screen. The overall process of the calculation is described in the following six steps and shown in figure 8 (Antico & Beerten, 2018):

1) After taking the picture with the camera (Canon D750), it is uploaded in the program. The image is undistorted with the initial calibration parameters.
2) Afterwards, the background is removed. This is done with a threshold to get only the useful information, which results in an image with only the coloured objects on a black background.
3) At the third step the image is ready for preparation using useful filters. The first filter used to find the contours is the grey scaling filter. With this filter, the image is converted from a red, green and blue image to a greyscale image. The second filter is a blurring filter for identification of the contours of each object by deleting the 'noise' in the image and it will also improve finding edges in there. In that case, noise means unwanted bright pixels caused by light reflections or variation across a pixel line.
4) The result can be seen in the edged picture.
5) In the edged picture, pixels inside are identified. This is done to check the pixels if the contour is correct. If the algorithm works, all these pixels are turned white.
6) After that first part of the program, all objects take with the camera are stored in an array with its contour and pixels.

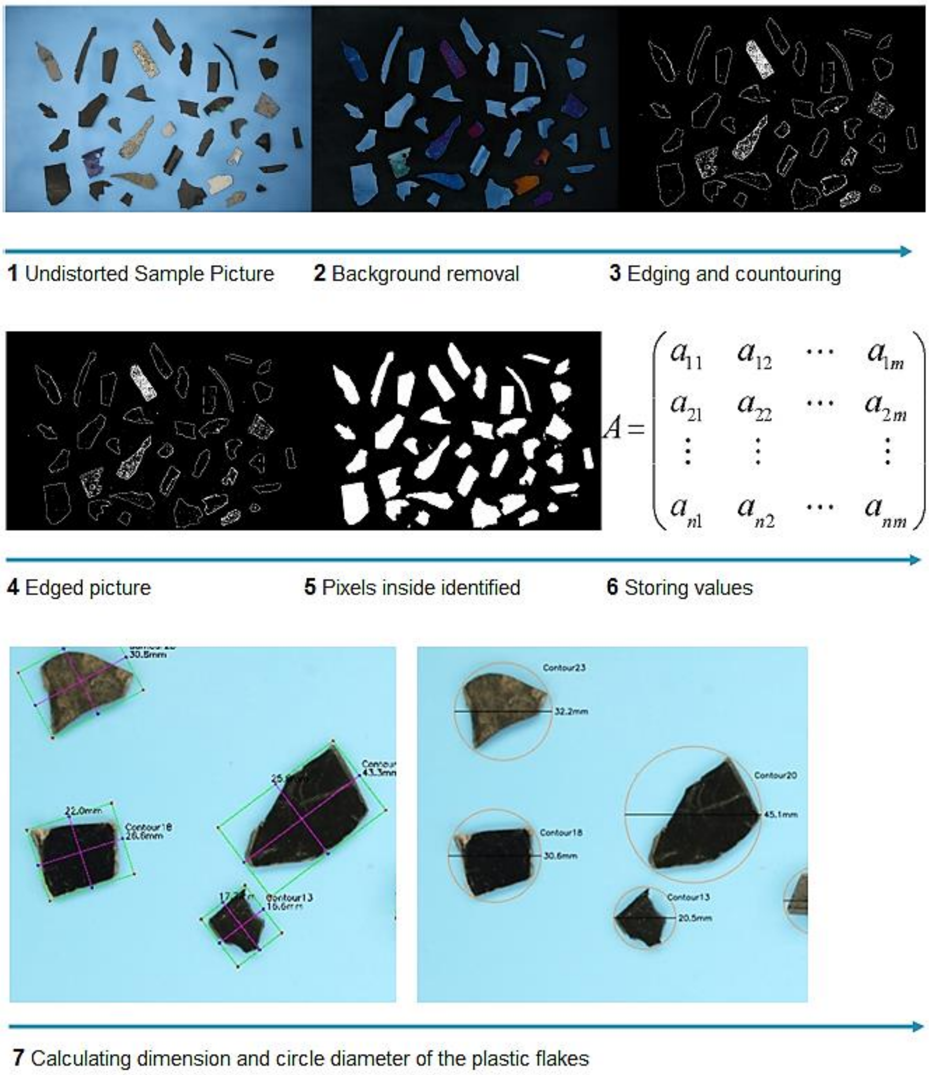


Figure 8: Flowchart of the identification of the plastic flakes with the computer vision system (Antico & Beerten, 2018)

The second part of the program used the stored information as input values and calculated the dimension and the circle diameter of the plastic flakes. To use and read the data easily, all calculated values are exported in an Excel file. The limitation of the program with respect to particle size is 0.5 mm, because a limit needs to be set to distinguish it from dust. (Antico & Beerten, 2018)

3.4 Scenario development

Three scenarios were developed to show combinations of shredding and sorting technologies that seem promising and most fitting in terms of particle size. The scenarios are divided into large particle size (20 to 50 mm), medium particle size (10 to 20 mm) and small particle size (6 to 15 mm). The size of the particles refers to the output fraction after treatment by the pre-processors and before transport to the recycler. Exemplary chains of the shredding steps, sorting technologies, transports as well as the size of the individual fractions are illustrated in figures 17-19. Subsequently, the advantages and disadvantages of the various scenarios are listed and discussed.

In the scenarios, an assumption is made that the plastic fractions with size ranges of 2 to 6 mm and 6 to 10 mm can be transported and recycled using suitable sorting methods. Only the fine fraction with a particle size of 0 to 2 mm is incinerated or landfilled, since no suitable sorting methods exist for this purpose.

4 Results

4.1 Technical outcomes

4.1.1 Input to pre-processing

The input material arrives in different collection groups which are treated separately, also because the WEEE compositions of each stream impose different treatment technologies. The input fractions arriving at the pre-treatment facilities mainly consists of:

- C&F appliances
- TVs and screens
- LHA
- SHA
- Lamps

For plastic fractions, there is no further pre-sorting. In some cases materials like glass, wood or seals are sorted out of the stream before entering the shredder. For C&F appliances, no material is removed before the shredding. But, depollution activities should be performed before shredding, including compressors removal. One company tried to remove internal drawers (transparent plastic), but this plastic flow was not valorised differently from the others, so it was economically not feasible. Another company performed also tests to remove drawers from fridges. However, this did not improve the quality of the output plastic (also the drawers resulted to be PS). For SHA, components as transformers, electronic circuit boards, suppliers and capacitors are removed from the flow.

Pre-sorting is only possible for one of the interviewed companies, which is linked to a high-quality collection system. Instead of throwing the devices in the container, they are carefully placed without damaging the equipment. For this reason the EoL devices are in a good state, e.g. the backlights of flat screens are usually not broken. They have one treatment line for fridges (only step 1 - depollution), for flat screens (manual dismantling) and get all types of small equipment. The person interviewed described the following depollution and separation steps:

- Personal computers (PCs)
- Laptops
- Tools
- Cathode Ray Tubes (CRTs)
- Flat screens
- Routers
- Modems
- Receivers
- Mobile phones (they remove the batteries)

The remaining depolluted SHA flow is sent to a WEEE shredder. The pre-sorted fractions are sent to downstream certified operators for further processing (including workshops for handicapped people, bigger WEEE recyclers and directly to copper smelters).

The pre-sorting is an important step performed primarily to produce clean plastic fractions for reuse and recycling. Furthermore, it enables cleaner plastics fractions. One of the interviewed recycling companies reported to remove some specific parts, e.g. lose printed-circuit boards (PCB) and batteries. One of the company's major obstacles is the recognition if the devices have a battery or not. The batteries are collected by the German battery compliance scheme (GRS), most of the other separated materials are given to bigger recyclers that process higher volumes and therefore have a better negotiation position to talk to the downstream acceptors. That applies for plastics from shelves and drawers in fridges, as well as the casings, foils and polymethyl-methacrylate (PMMA) from flat screen dismantling.

Statements on the polymers content across the different WEEE flows were very similar between the interviewed companies: C&F appliances have rather homogeneous material composition being mainly made of PS and small amounts of PP and ABS. The same is true for TVs and screens, which are mainly composed of ABS and PS.
In contrast, LHA and SHA have rather heterogeneous polymer composition. No analyses to identify correlations between product brands and plastics used have ever been performed by any of the interviewed companies. This is due to the high volumes to be treated and the related effort it would take.

4.1.2 Pre-processing technologies

The pre-processing technologies have large similarities. The main steps in pre-processing are:

1. Device opening
2. Depollution, manual sorting
3. For SHA: Liberation through shredding: Different technologies, different particle sizes. Enough liberation to get homogeneous particles, not too much to avoid the production of fines. Some facilities have narrow ranges of particle sizes (e.g. around 20 mm), others produce fractions with particles sizes ranging e.g. from 10-100 mm
   For screens: Manual or automated dismantling
4. Sorting: positive sorting of metals and other metal-rich fractions, plastics is usually a mixed "rest" fraction

Most of the time computers, TVs and screens are manually dismantled and the plastics are obtained at the beginning of the treatment. For SHA, some products are manually removed from the WEEE stream (toner, smartphones and batteries). Also, the fractions cables and capacitors are separated manually. Generally, the plastic parts are often difficult to manually separate from the other components because they are closely attached (time consuming activity).

After shredding, in the sorting step, the iron is removed through magnets. Aluminium, copper and brass are removed using eddy currents. The separation of plastics from the shredded fraction is always obtained by negative sorting. This means that plastic is the remaining fraction after the other separation. The pre-treatment facilities do not normally have optical sensors. Some facilities use sink-float separation for sorting remaining metals and brominated plastics fraction.

The main method used during the pre-processing of WEEE is mechanical treatment. A total of seven shredding technologies were identified, being able to crush WEEE and especially the plastic from WEEE. These technologies are:

- Cross flow shredder
- Rotary shredder
- Rotary shear (shredder), which can be single-, double-, three- or four-shaft
- Knife mill
- Hammer mill
- Rotary impact mill
- Granulator

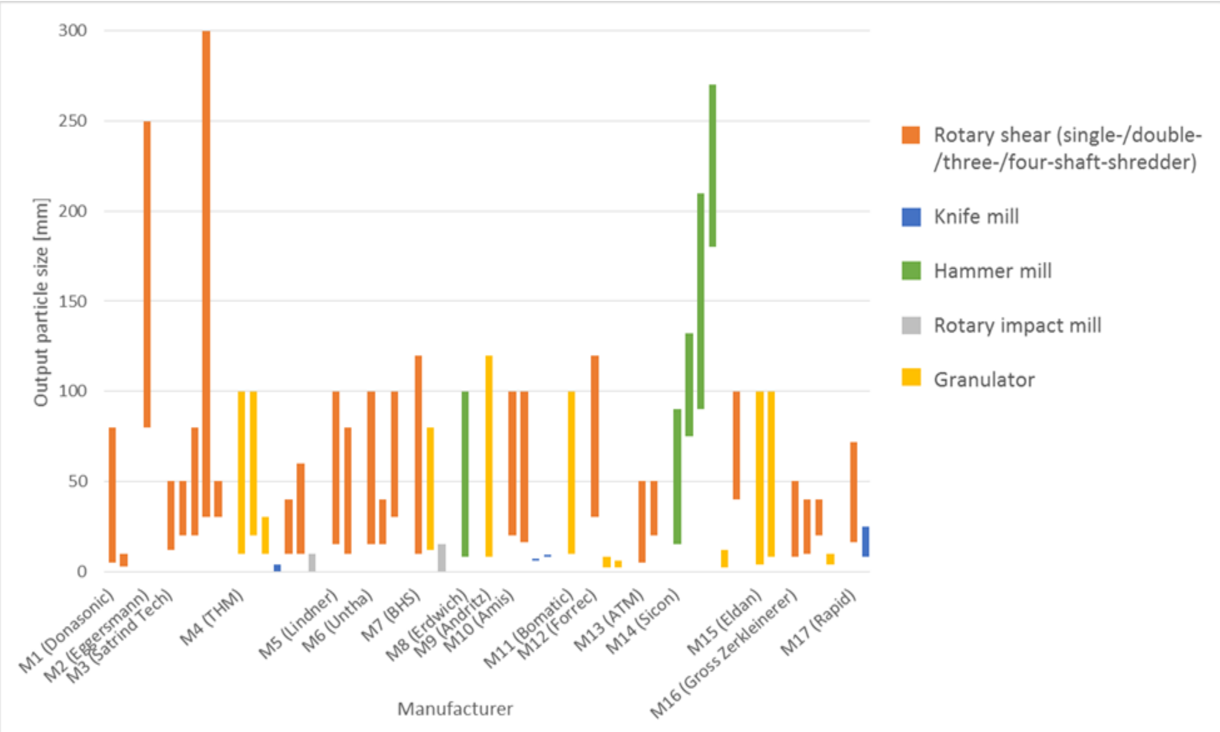


Figure 9: Output particle sizes produced by different shredding technologies

As shown in figure 9, the individual technologies can have a widely adjustable particle size range. For the technologies rotary shear, hammer mill, knife mill and granulator this can be ensured by an exchangeable shredding sieve with different mesh. For the cross-flow shredder, the particle size is generated by an output lock and for the rotary shear the output fraction is generated by an output funnel. The particle size of a rotary impact mill is adjusted over a gap width between 0-15 mm.
Cross-flow shredders and rotary shredders are only used for pre-shredding and therefore no homogeneous size ranges are produced. Only an indication of the maximum particle size is made, since only disintegration of the input material takes place during pre-shredding. That is why these two technologies do not show up in the figure above.
Several features in the different technologies qualify the shredders for different applications. In table 4 the shredding technologies are listed together with advantages, disadvantages and producible output particle sizes.

Table 3: Comparison of the shredding technologies and sieving sizes of investigated technologies

Shredding technology	Advantages	Disadvantages	Sieving sizes [mm]
Cross-flow shredder	- High throughputs possible - Insensitive to massive metal parts - Fast tool change - Short residence time by the continuous discharge of material - Low wear of the acceleration tools	- No production of small particle sizes - Only for pre-shredding	< 150
Rotary shredder	- High throughputs possible - Low power requirements - Automatic adjustment of the residence time by the continuous discharge of material - Easy replace/sharp of blades and cleaning - Handling of metals	- No production of small particle sizes - Only for pre-shredding	< 64
Rotary shear (shredder)	- Low specific energy requirements - Low noise and dust development - Low investment costs - Can shred many different materials	- Heterogeneous particle size distribution - Blades difficult to replace	3 - 300
Hammer mill	- Controllable throughput of the particle size - Simple change of grinding tools - Adjustable rotor speeds - Easy maintenance - Handling of metals by robust designs - Well-known technology	- Can be noisy and dusty - Large amounts of fines - Can have high power requirements - Heterogeneous particle size distribution	8 - 210
Knife mill	- Removable blades for sharping - Easy and safe opening and sieving change	- No crushing of metals - Only suitable for soft materials - Danger of blockade - Low throughput	0 - 25
Granulator	- High throughputs possible - Can produce fine particles - Consistently high cutting quality and liberation of materials	- Higher maintenance costs - No good handling of metals - Can be noisy because of the high speed	2 - 120
Rotary impact mill	- Adjustability of the gap - Easily changing tools - Low operational costs	- Not suitable for large particle sizes - High investment costs - Significant dust development	0 - 15

The cross-flow shredder and the rotary shredder are designed for pre-shredding and for the disintegration of WEEE devices, which can be recognized by the fact that they cannot produce small and homogeneous particle sizes. Both technologies are characterized by the fact that high throughputs are possible due to a continuous discharge of materials as well as fast tool change and handling of massive metals. The cross-flow shredder can produce coarser parts smaller than 150 mm and the rotary shredder smaller than 64 mm.

The rotary shear and the hammer mill are known to be very robust and to crush various materials, including metals. Therefore, they are also suitable for shredding after manual depollution, if a set particle size range is already desired at the first shredder step. It should be noted, however, that a poor particle size distribution is produced. This looks different for the knife mill and the granulator. These shredding technologies cannot break down metals and should therefore only be used after metal removal.

4.1.3 Produced output plastics fractions of pre-processors

The pre-processor produces two plastics fractions, a homogeneous and a heterogeneous plastics fraction. The homogeneous fraction is the kind of plastic which is separated in the pre-sorting while manual dismantling during its purity. This homogeneous fractions are:

- PMMA filters
- Foils
- Screens casings
- Plastics from C&F

PMMA is used in monitors and flat screens and is usually separated due to its high price. The flow of plastics coming from C&F appliances is very homogenous with a PS-share of 75 % to 80 %.
The heterogeneous fractions mainly origin from LHA and SHA. This fraction can also contain flame retardants. The removal of BFR, POP or other hazardous plastics at pre-processing facilities, mainly with sink/float techniques or X-ray detection, depends on the legal requirements or the pre-processors. For example, French companies have the requirements to sort the brominated fraction before recycling, which does not apply to German companies.

Eight out of 18 pre-processors provided information related to shredding technologies and the particle size of the plastics fractions. Results are shown in figure 10. One or two mixed plastics fractions are produced with different size distributions and sold to plastics recyclers. The anonymised pre-processors are labelled *A-H:*

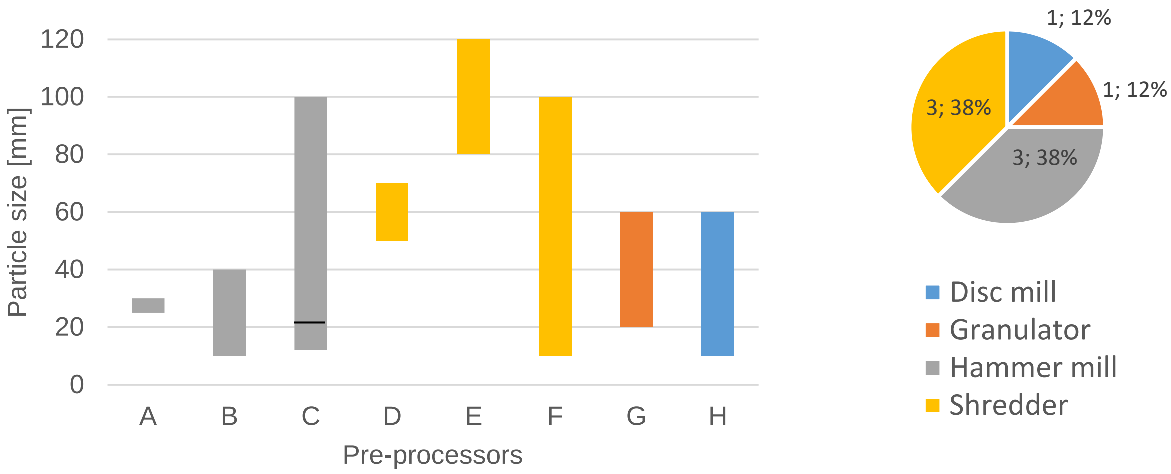


Figure 10: Particle size of the output plastics fractions from sWEEE treatment (left) and related size reduction technologies (right)

The results show that pre-processors take very different decisions, both regarding the selection of a shredding technology for their facility and regarding the ranges of particle sizes of the plastics fractions that they produce. The particle sizes produced by the individual pre-processors are very different, ranging from 10 mm to 120 mm. Some facilities have narrow ranges of particle sizes (e.g. around 20 mm), others produce fractions with particles sizes ranging e.g. from 10-100 mm.

4.1.4 Input particle sizes of sorting technologies

The results of the sorting technologies show significant differences in terms of particle size. In figure 11, the minimum and maximum particle sizes of the individual sorting technologies are plotted separately. This differentiation was chosen, since it can be seen that the minimum particle size range is much smaller than the maximum sorting width upwards. The scattering of the boxplot diagram comes from the fact that several machines of different manufacturers are considered in one sorting technology.

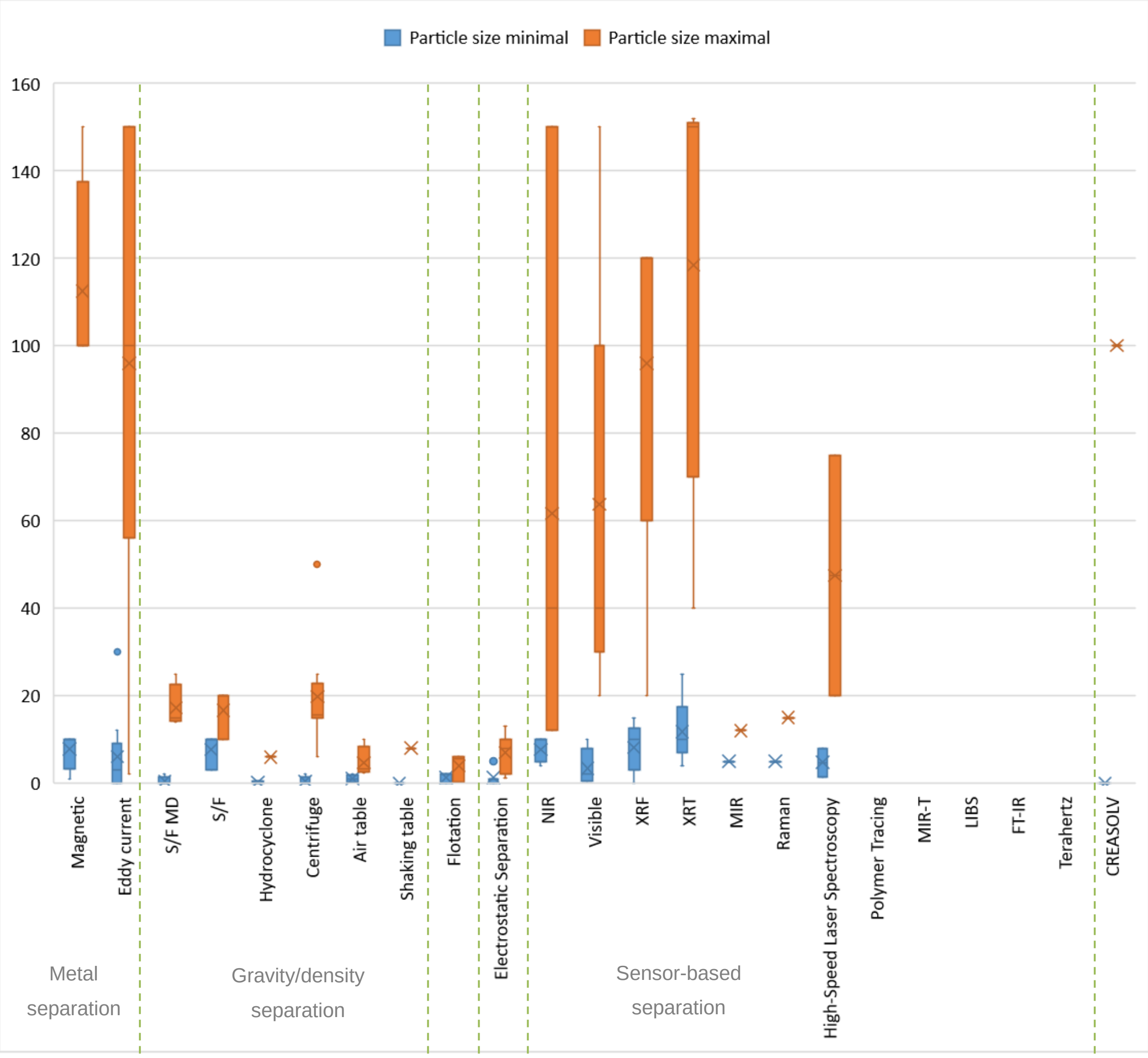


Figure 11: Input particle sizes needed by different sorting technologies

A wide range of 1-150 mm can be set to remove magnetic and non-magnetic particles. Most sensor-based sorting techniques can also sort large particle sizes, such as XRF up to 120 mm and XRT up to 150 mm. The most common technologies NIR and visible sorting can sort particles up to 150 mm. Much smaller particle sizes have to be used for density separation. The maximum for all technologies is 25 mm and minimum can be very small down to 2 mm. For example, sink-float separation needs particles in a range of 10 to 20 mm. Air tables and wet shaking tables need smaller particle sizes in a range of 0.25 mm to 8 mm. For the floatation method, particles with a size range of 2 - 6 mm are needed, triboelectric and electrostatic separation techniques show a maximum of 10 mm. For the sorting technologies polymer tracing, MIR-T, LIBS, FT-IR and Terahertz spectroscopy no required particle sizes could be determined, as these technologies are used only on a laboratory scale and not in industrial applications. Also, development is needed in the industrial use of plastic sorting for the technologies CreaSolv® and Raman spectroscopy.

4.1.5 Quality measurement

Price of the plastics fractions is more a question of bargaining, input description and market situation than of quality measurement. Quality of mixed plastics flakes (i.e. after shredding and before dedicated sorting) is defined on the basis of level of impurities (e.g. glass, metals and wood) and recycling yield of mixed plastics.

Some treatment facilities are working according the WEEELABEX requirements of Annex B.4 and Annex C4.4 (WEEE Forum, 2013):

- Annex B.4: *"End-of-waste plastics shall not contain any Polybrominated Biphenyls (PBB) at levels of more than 50 ppm. Octa- and Penta-Polybrominated Diphenylethers (penta- and octa-BDE) shall not be present in concentrations of more than 1000 ppm each. Representative product samples shall be taken and analysed at least once per quarter and recorded in the compliance documentation of the recycling operator"*
- Annex C 4.4: *"The composition of non-pure fractions (metals, plastics or inorganic material) dedicated to further separation steps or to final recovery operations shall be analysed with batch of the fraction, because the yield is higher than 20 percent in accordance with clause 5.7.5."*

Other treatment facilities make a sampling of each big bag and analyse the polymer distribution with two different analysis technologies after the plastic sorting. Often, the plastic sampling and polymer purity is measured by the sorting facility in order to have a solid base for bargaining the price.

After pre-processing and before compounding, the testing depends on the requirements of the recyclers, in particular on purity and composition. Sampling and analysis is conducted internally and is verified at the lab of the customer. Colour is indirectly a quality criterion, depending on the input flow. No standards, but rather protocols from the compliance schemes are followed. Some compounding companies use differential scanning calorimetry (DSC), IR spectroscopy and density control.

During compounding the melt flow index (MFI) is measured and e.g. MFI, density, flexural modulus, elongation at break, izod impact resistance, fillers content and colours or UL certificate can be listed in the datasheets of the final products.

4.1.6 Technical challenges

Pre-sorting

The pre-sorting depends largely on the collection practices. In theory it would be possible to implement the dedicated treatment, however, if the sorting of the products is not made at the collection level, it will be uneconomic. Therefore it is necessary to have optimized collection conditions for a pre-sorting. At the same time, sorting at the level of the collection is not always possible (but it is under investigation by Task 3.2) considering the large heterogeneity of the products including the following aspects:

- New plastics composition, hazardous potential of additives like flame retardants not investigated before market introduction
- Complex composition of plastics flow. Additives, for instance mineral fillers (not a problem for all)

Polymer composition

Today, one of the main problems related to plastics recycling is the high number of different polymers present in WEEE. Identifying clusters of products is challenging, because each producer uses different materials depending on the country of production and the market where they sell their products. Especially the WEEE stream of small household appliances is problematic for pre-processors, because of the heterogeneous and complex composition (up to 20 or 30 different polymers). This mixed polymer composition is difficult to separate with current sorting technologies. Therefore, the types of plastics used should be better harmonized. The eco-design concepts are in that line, but they have to be implemented by the manufacturers.

It is furthermore expected that the total amount of plastics flows from electronic devices will keep increasing As a result, plastic recycling will become increasingly relevant.

Shredding technologies

The size reduction of WEEE devices during the shredding step is a cost-intensive step in WEEE recycling. Costs arise due to investments, operational and maintenance costs. Therefore, it is recommended to perform as few shredding steps as possible, but as many as necessary to reach optimal economic feasibility. Furthermore, in each shredding step losses of recyclable material in form of dust and fines occur. One important recommendation for optimized shredding:

- Keep the production of fines low by reducing the number of shredding steps and the choice of an adequate shredding technology

Sorting technologies

In SHA and in TVs and screens, there are also many black parts as well, which cannot be detected with NIR spectroscopy. Other sorting technologies, like electrostatic sorting, have to be used, which requires small particle sizes (see section 4.4). In contrast to this, for example, cooling and freezing (C&F) appliances are mainly made of white/grey PS so optic separators can be used.

As the studies have shown (see section 4.2), the different sorting technologies require different sizes in order to achieve an efficient separation performance. If this size is not given, it can come for example in the optical detection to a technical problem that the flake cannot be detected. If the particles are not homogeneous enough, overlaps on the conveyor belt can occur and the particle is also not detected.

4.2 Particle size distributions of sample analysis

In this section the results of the sample analysis are presented. In total, three samples were analysed through a computer vision system and particle size distributions were determined. The samples are provided by the pre-processors *B*, *C*, and *H*. The devices of the input stream of all pre-processors originate from small household appliances.

Figure 12 presents the particle size distribution of the sample analysis of pre-processor *B*. The results show that 55.17 % of the particles have a size ranging between 10 to 40 mm, whereas 17.73 % are larger than 40 mm.

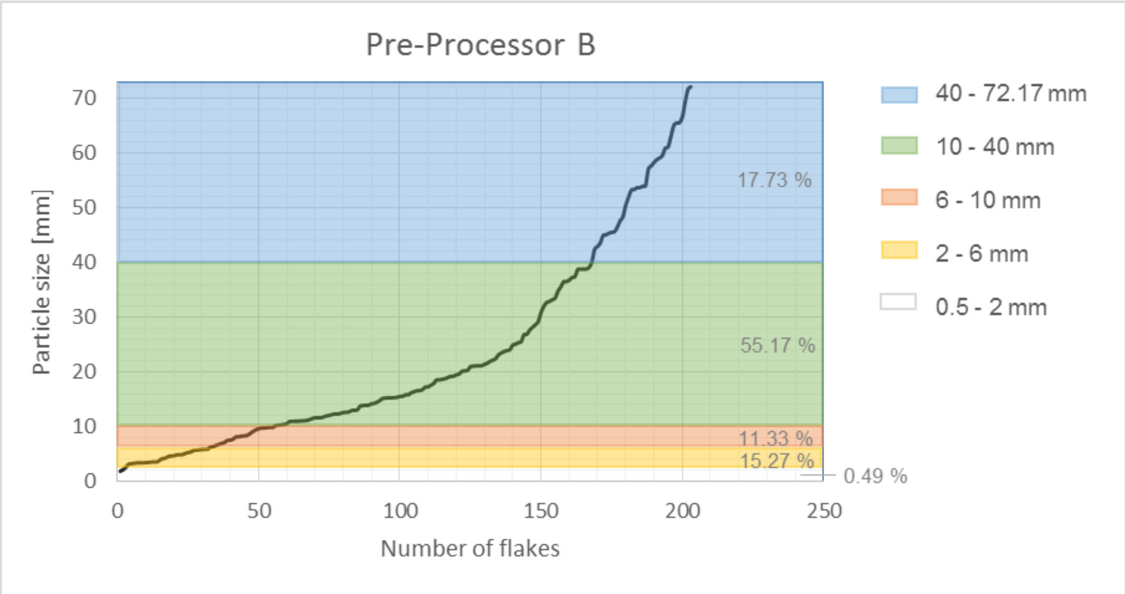


Figure 12: Particle size distribution of pre-processor B

A percentage of 0.49 % of the fraction of particles has a size smaller than 2 mm, and cannot be detected by sorting technologies. A percentage of 27.09 % of the fine particles are smaller than 10 mm and therefore cannot be detected with sensor-based technologies.

The size distribution of the smaller fraction of pre-processor *C* shows as a result that 11.38 % are in the range of 12 to 20 mm, 67.38 % are in the range of 6 to 12 mm and 21.23 % in the range of 0.5 to 6 mm. Larger particles than 50 mm and smaller particles than 0.5 mm are either not produced or not detected by the program. The particle size distribution of the small fraction is shown in figure 13.

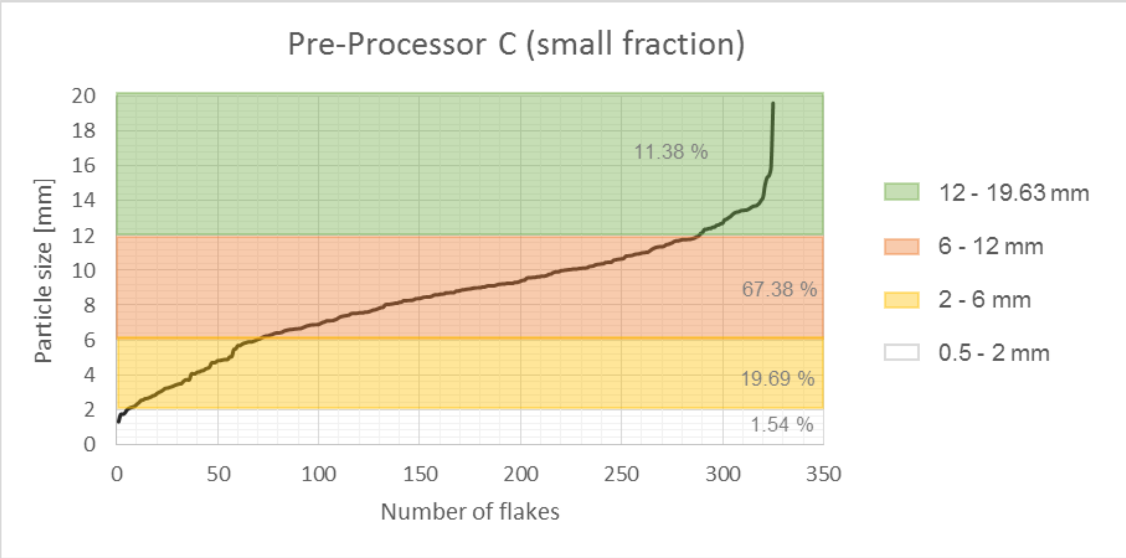


Figure 13: Particle size distribution of small fraction of pre-processor C

Evidently, the finest content of the small sample is much higher than set. The sample should have a size of 12 to 20 mm. The 20 mm are not exceeded, but the sizes below 12 mm are encountered. With a percentage of 88.61 %, the particles smaller than 12 mm frequently occur. Non-detectable particles smaller 2 mm are in a proportion of 1.54 %.

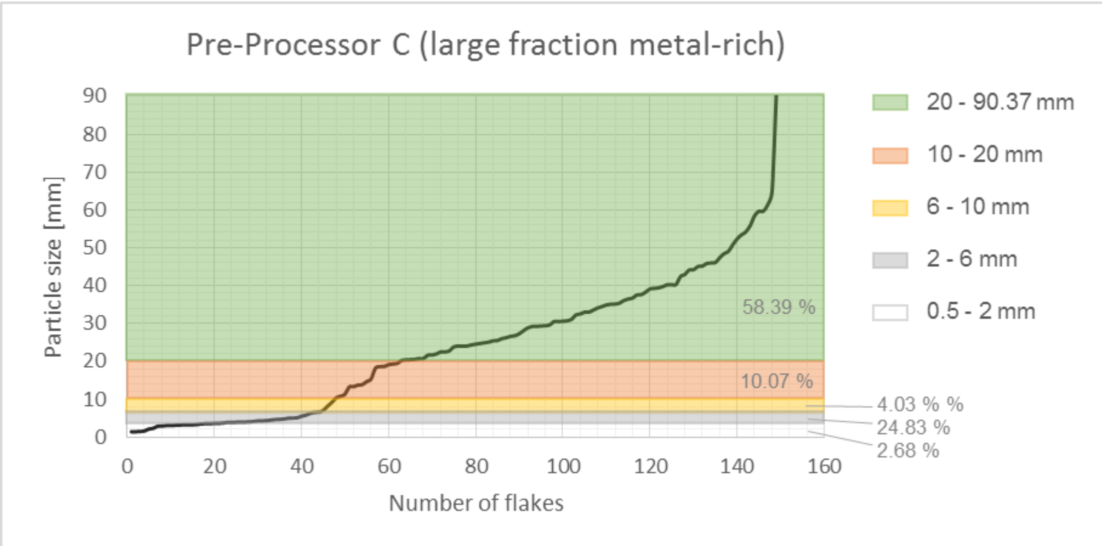


Figure 14: Particle size distribution of large fraction (metal-rich) of pre-processor C

The second sample of the pre-processor is the large and metal-rich fraction which has as only requirement that its size should exceed 20 mm. The particle size distribution is shown in figure 14. The requirement is achieved in 58.39 % of the sample. A percentage of 41.61 % of the samples is below 20 mm. With 24.83 %, the articles with a size between 2 and 6 mm represent a very high proportion. Non-detectable particles have a percentage of 2.68 %.

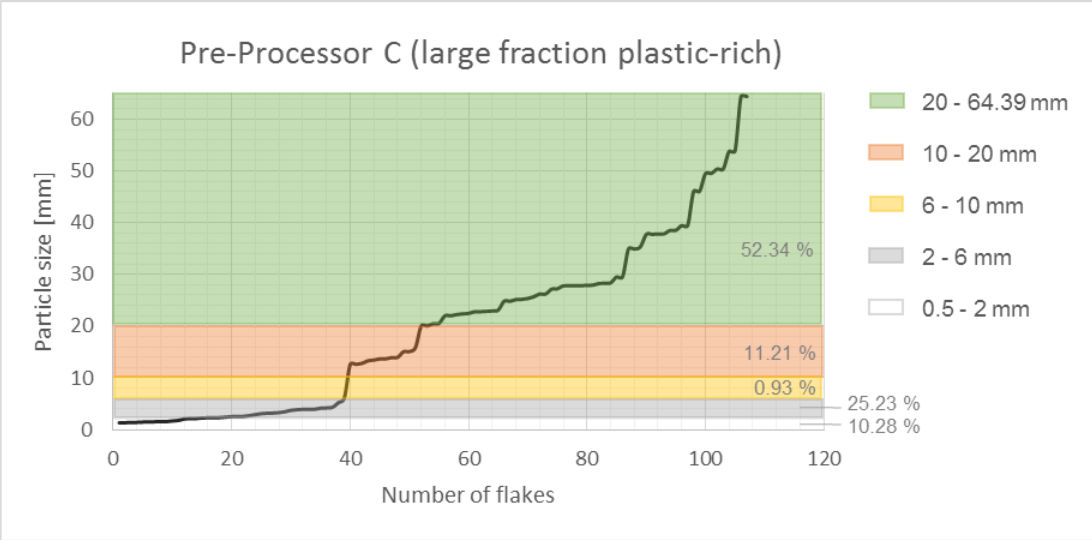


Figure 15: Particle size distribution of large fraction (plastic-rich) of pre-processor C

The particle size distribution of the third sample (large plastic-rich fraction) is shown in figure 15. This is the large and plastic-rich fraction which has the requirement, like the second sample, that the flakes' sizes should exceed 20 mm. Nevertheless, 52.34 % of the flakes have a size greater than 20 mm, which is similar to the second sample of the larger fraction. The percentage of parts smaller than 20 mm is 47.66 %. Fine particles smaller than 2 mm which cannot be detected have a high percentage of 10.28 %. Also similar to the second sample is the high percentage of 25.23 % of particles in a range between 2 and 6 mm.

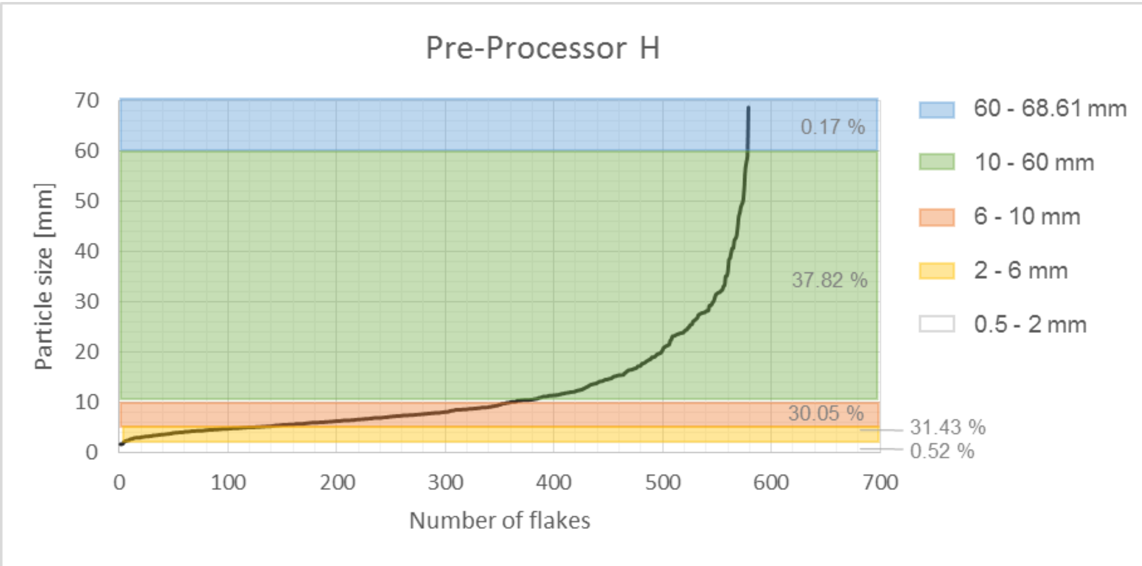


Figure 16: Particle size distribution of pre-processor H

The particle size distribution of pre-processor *H* is given in figure 16. The targeted particle size of this pre-processor is between 10 and 60 mm. This statement is respected to 37.82 %. One particle was found which is larger than 60 mm with a diameter of 68.61 mm, which makes a proportion of 0.17 %. A proportion of 62 % of the particles are smaller than 10 mm, 0.52 % smaller than 2 mm and therefore non-detectable.

4.3 Particle size impacts on PCR plastics

In order to make a statement about the recyclability, the losses of plastics fractions must be identified. The following losses related to particle size are determined:

- Shredding losses
- Landfill/incineration of fractions smaller than 10 mm
- Losses due to composites (large fractions)
- Losses due to wrong input particle size of the sorting technologies

Most losses of fine particles or dust with about 10-20 % occur during the shredding step. Tough plastics produce little losses while brittle plastics produce more losses. In addition to the high energy use, this is a reason why it should be shredded as little as possible. At each shredding step, there are losses into fines or mostly particles smaller than 10 mm, which are incinerated or landfilled. These fine particles and dusts are defined as losses.

With large particle sizes, however, there is the danger that composites will remain, and thus plastic particles are lost in other material streams. For example, during metal separation, plastic parts can attach to the metal and get into the metal fraction. These particles are lost and not transported to the recyclers, which is reducing recyclability.

If a sorting technology cannot separate plastics properly due to the wrong particle size, the target fraction may get into the fraction to be disposed of and thus be lost. If a wrong or undetected particle gets into the target fraction, the quality of the plastic fraction is reduced. If this particle gets into the fraction which is disposed of, the plastic is not recycled.

4.4 Scenarios of plastics output particle size of the pre-processors

4.4.1 Scenario “large particle size”

First scenario created is the shredding to the size 20 to 50 mm at the pre-processors stage. To produce sizes smaller than 50 mm only two shredding steps are necessary. Thereafter, the pre-processor can perform magnetic and eddy current sorting as well as XRF or XRT. Afterwards, the parts in the range of 20 to 50 mm are transported to the recycler. The exemplary scenario 1 is shown in figure 17.

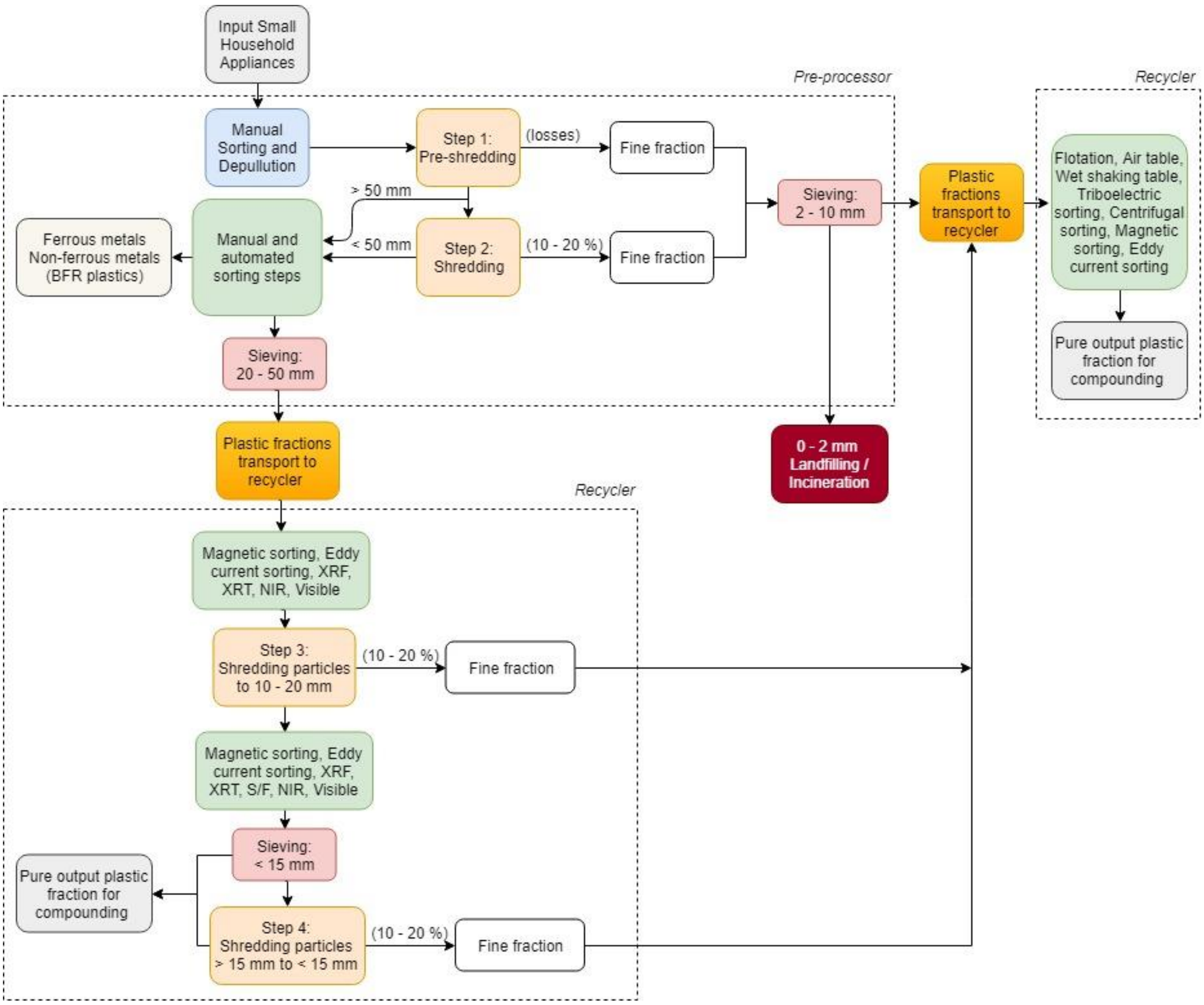


Figure 17: Scenario 1 in a size range from 20 to 50 mm of plastic output fraction of the pre-processor

By the input size of plastic fraction in a range of 20 to 50 mm the recycler can perform the sorting technologies magnetic and eddy current sorting, XRF, XRT, NIR as well as visible sorting, but must introduce another shredding step in order to separate with sink/float technique. Here again, a fine fraction is produced, which can be delivered to a recycler who can separate it, or the recycler can separate it himself with suitable technologies. If these fine fractions must be dispensed, further transport costs arise. As particle sizes smaller than 15 mm are required for the extrusion, the larger plastic parts would have to be shredded again, resulting in fines again.

Advantages:

- less shredding by the pre-processor

Disadvantages:

- Transport costs are the highest
- Danger of composites by the pre-processor during large particles
- High quantities of fine fractions at the recycler for disposal
- 4 shredding steps in total

4.4.2 Scenario “medium particle size”

In the second scenario, exemplary shown in figure 18, the fraction is shredded to 10 to 20 mm at the pre-processing. This requires two shredding steps. Then the fraction can be sieved into this size, and all particles larger than 20 mm are returned to the second shredding step, to comminute them again. This 10 to 20 mm fraction is then transported to the recycler. In contrast to scenario 1, this fraction is twice smaller, which increases the bulk density and reduces transport costs.

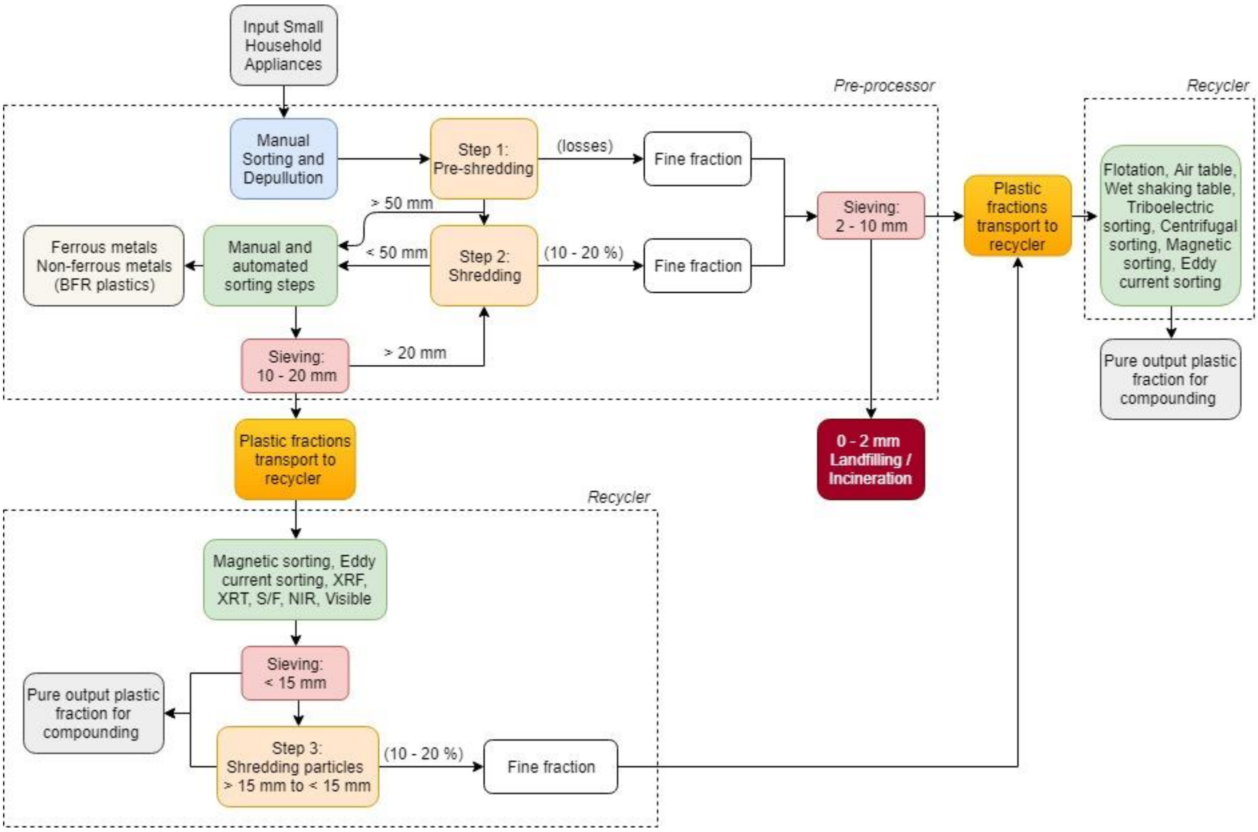


Figure 18: Scenario 2 in a size range from 10 to 20 mm of plastic output fraction of the pre-processor

The recycler then has the possibility to perform the magnetic and eddy current sorting, XRF and XRT, NIR, visible as well as sink/float technique without shredding before. Afterwards, the recycler can screen again for particles larger than 15 mm and crush them for extrusion to a particle size smaller than 15 mm. This means that the recycler needs only one shredding step and the pre-processer only two shredding steps.

Advantages:

- Lower transport costs due to high bulk density
- Prevention of high quantities of fine particles by the recycler
- Avoiding composites
- Wide range of separation technologies possible

4.4.3 Scenario “small particle size”

The scenario 3 now includes shredding the particles to a size range of 6 to 15 mm. This particle size range is deliberately chosen because the particles are then large enough to handle all sorting technologies, but small enough not to be shredded before extrusion. However, shredding particles smaller than 15 mm makes it necessary for the pre-processor to shred in more steps. The fine fraction of the pre-processor increases due to the third shredding step, but this can be added to a suitable recycler to separate again. Figure 19 shows the exemplary chain of the third scenario.

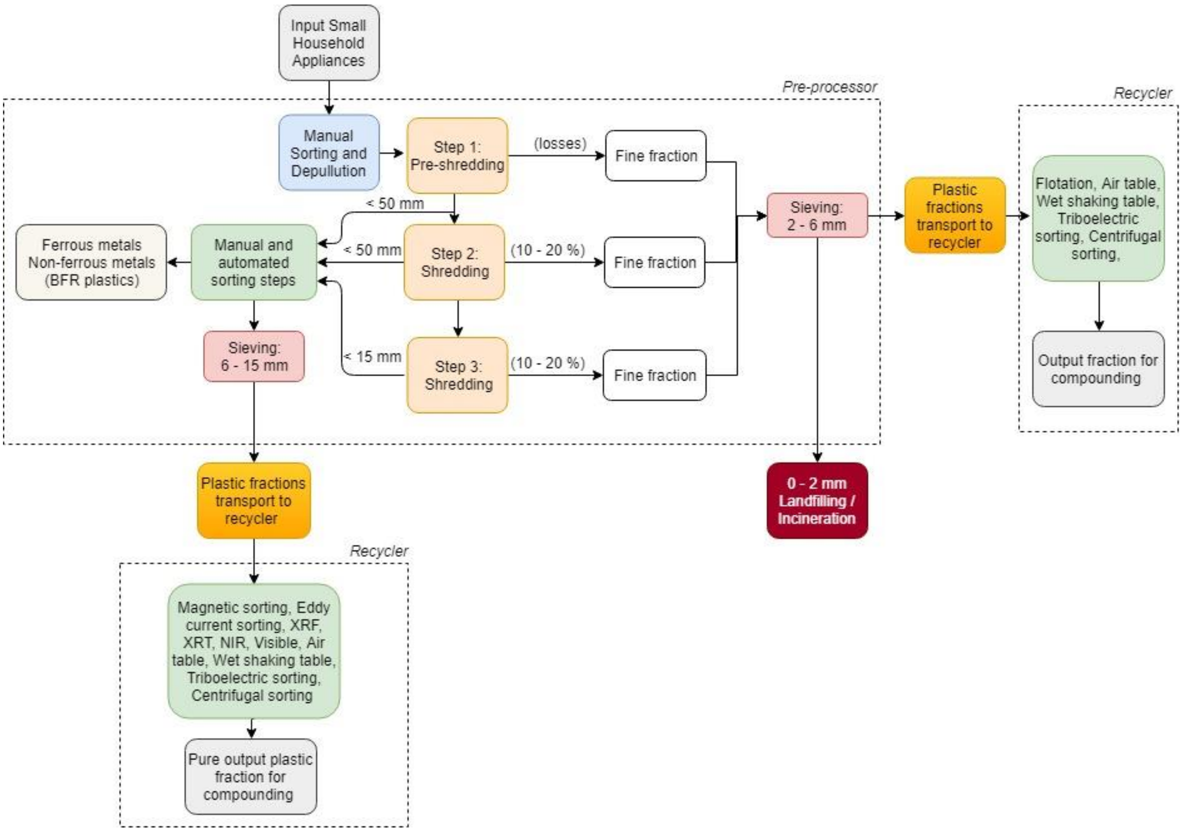


Figure 19: Scenario 3 in a size range from 6 to 15 mm of plastic output fraction of the pre-processor

Advantages:

- Lower transport costs due to high bulk density
- No shredding by the recycler necessary for extrusion
- Wide range of separation technologies possible
- No disposal of fine fraction by recyclers
- Avoiding composites

Disadvantages:

- Particles too small for sensor-based technologies
- Risk of particles smaller 6 mm
- Expensive shredding to small size at the pre-processor (Cost-shifting to the pre-processor)

5 Recommendations for WEEE pre-treatment

Strategies for pre-processors and recyclers to sort and produce high-quality plastics fractions are developed:

1. Improve the communication between pre-processors and recyclers

The interviews showed that the pre-processors hardly seem to know which sorting technologies the recycler operates and what particle size is needed. The pre-processors only get a default of a certain minimum particle size and percentage deviation. For example, a guideline might be that 95 % of the particles should be larger than 5 mm to avoid fine fractions. Thus, the pre-processor has a wide margin upwards in terms of particle size. To fulfil this requirement, much larger particle sizes should be produced by the pre-processor. As a result, too large particle sizes increase transport costs and require a further shredding at the recycling plant. In table 5 advantages and disadvantages of the first recommendations are given.

Table 4: Advantages and Disadvantages of improving the communication between pre-processors and recyclers

For…	Advantage	Disadvantage
…pre-processor	- Decrease of transport costs	- Acquisition costs for additional screenings - Screening for different recyclers necessary
…recyclers	- No further shredding of the particles for sorting technologies necessary	- Risk of disclosure of sensitive information to competitors
…environment	- Reduction of CO_2-emissions through less transport	-

2. Pre-sorting of the mixed plastics fraction in the pre-processing facility (e.g. pure plastic types/BFR/POP/dangerous or not)

Large plastic parts can be removed manually resulting in a more homogenous plastic input for recycler. This early removal is already established e.g. for plastics screen casings. The sooner the material is sorted, the higher the quality in the output fractions. For large appliances in contrast to small household appliances, however, it is much easier to sort large plastic parts before shredding.

As can be seen from the particle sizes of the individual sorting technologies, brominated fractions can be sorted out by XRF or XRT even with large particle sizes. This would reduce or eliminate the proportion of brominated plastics, which makes the output fraction of the pre-processor more valuable and at the same time reduces transport costs. Furthermore, for a better energy balance, shredding should be reduced as much as possible, so it makes sense to sort BFR plastics before the second or third shredding step.

Table 6 listed the advantages and disadvantages of the recommendation to sort the equipment before shredding.

Table 5: Advantages and Disadvantages by pre-sort the equipment before shredding

For…	Advantage	Disadvantage
…pre-processor	- Purer fraction can be sold at a better price - Decrease of transport costs	- High effort and cost of manual sorting - Disposal of the brominated fraction - Acquisition costs for sorting technology
…recyclers	- More homogeneous plastics fractions for recycling - Cost saving due to reduced sorting - Less brominated particles for disposal - Saving on sorting technology	- Rising value of fraction from pre-processor
…environment	- Increasing recyclability due to reduced losses - Reduction of CO_2-emissions through less transport and less shredding	-

3. **Keep the production of fines low by reducing the number of shredding steps and the choice of an adequate shredding technology**

Since the fine fraction smaller than 10 mm, which is produced during the shredding step, is usually disposed of (landfilling or incineration), it is recommended to avoid producing small fractions as much as possible by applying as few shredding steps as possible. This can be achieved by applying recommendations 2 and 3 and using an adequate shredding technology for each fraction with as few losses as possible. The advantages and disadvantages are given in table 7:

Table 6: Advantages and Disadvantages of reducing the shredding steps

For…	Advantage	Disadvantage
…pre-processor	- Decrease of costs during shredding steps - Reduction of the fine fraction and dust	- Investment costs of adequate shredding technology
…recyclers	- Decrease of costs during shredding steps - Reduction of the fine fraction and dust	- Investment costs of adequate shredding technology
…environment	- Reduction of CO_2-emissions through less energy consumption of shredding - Reduction of incineration and landfilling of fines and dust	-

4. **No disposal of the fine fraction. Find suitable recyclers for the fine fraction in order to separate it with appropriate sorting technologies (if it is feasible)**

The investigations have shown that there are different sorting technologies that work efficiently in a size range of 2 to 10 mm. In particular, the sorting technologies air table, wet shaking table, triboelectric sorting, magnetic and eddy current sorting, flotation and centrifugal sorting. For pre-processors and recyclers, following advantages and disadvantages result from separating the fine fraction listed in table 8:

Table 7: Advantages and Disadvantages by separating the fine fraction

For…	Advantage	Disadvantage
…pre-processor	- No disposal of the plastics in the fine fraction	- Search for suitable recyclers - Risk of acceptance of fine fraction by recyclers only against payment
…recyclers	- Metal extraction from the fine fraction - More plastics for end-processing	- Risk of disclosure of sensitive information to competitors - Rising costs due to technologies
…environment	- Less incineration and dumping of the fine fraction - Increasing recyclability	-

5. **Production of plastics mixed fractions that can be easily sorted at downstream facilities (implementation of a standard particle size range)**

The different scenarios show three possibilities of shredding of the particle sizes. These range from 20 to 50 mm, 10 to 20 mm and 6 to 15 mm. If there was a uniform particle size, the pre-processors could minimize their transport costs and the recycler avoid fine particles and shredder steps. It is recommended to implement scenario 2. In this scenario, the particle size is crushed to 10 to 20 mm. In this size range, the separation techniques magnetic and eddy current sorting, XRF, XRT, S/F, NIR as well as visible sorting can take place which allows the recycler a wide range of separation possibilities. Only one shredding step is necessary to perform the technologies air table, wet shaking table, triboelectric sorting, centrifugal sorting as well as extrusion. The advantages and disadvantages for pre-processors and recyclers are given in table 9:

Table 8: Advantages and Disadvantages by implementing a standard particle size

For…	Advantage	Disadvantage
…pre-processor	- Decrease of transport costs	- Rising costs of producing close particle size range
…recyclers	- Wide range of separation possibilities - Only one shredding step before extrusion - No release of sorting technologies	- Disposal of the fine fraction of the shredding step
…environment	- Reduction of CO_2-emissions through less transport	-

6 Conclusion and Outlook

The objective of this deliverable was to evaluate modifiable parameters in the WEEE plastics pre-treatment processes and to provide recommendations aimed at improving the volumes and quality of the plastics materials delivered to post-consumer plastics recycling facilities.
Through interviews with pre-processors, plastics recyclers and machine manufacturers of shredding and sorting technologies valuable information from a variety of stakeholders was collected. Samples of plastic flakes of the pre-processors shredder output fraction were analysed regarding their particle size. Scenarios of different output particle sizes of pre-processors were developed to minimize the losses regarding the pre-processing and recycling step and recommendations for the WEEE pre-treatment were formed.
The results show similarities regarding the plant designs, but differences regarding shredding technologies, particle size and composition of the materials sent to plastics recycling. In conclusion, how pre-treatment and recycling are performed in the different recycling plants depends on the company's know-how and available pre-processing and sorting equipment.
The results of the sorting technologies evaluated show that every sorting technology needs a specific particle size range to provide an efficient separation performance. Likewise, not all sorting technologies that can be used for the separation of plastic fractions are also commercially available.
The results of the particle size distribution of the plastic samples show how difficult it is for the pre-processor to control the produced particle size. The fact that the target sizes of the specified size range were only achieved by about 11 % to 58 % of the samples is due to the fact that it is difficult to set the shredding technology to the correct output size due to the heterogeneous input of the WEEE devices. Each pre-processor uses different technologies which have different properties.
To increase the recyclability of PCR plastics it is essential to strengthen the communication between pre-processors and recyclers when it comes to particle size. Furthermore, it would also be advisable to separate the brominated fraction at the pre-processor in order to reduce further transport costs and thereby reduce CO_2-emissions. The particle sizes required to separate brominated fractions with XRF and XRT lies in a range of 10 to 120 mm, which is feasible for pre-processors. Recommended is also the early sorting of relevant plastic fractions from the WEEE. The sooner the product is sorted, the purer the plastic fractions and the higher recyclability of plastic streams in the end. The third recommendation is not to dispose the fine fraction but to find suitable recyclers able to separate it with adequate sorting technologies. The results show that common sorting technologies already exist, which can most effectively sort in 2 to 6 mm and 6 to 10 mm sizes. This would significantly reduce the fraction for landfilling and incineration and thus increase the recyclability of the plastic fractions and improve the environmental footprint. Last but not least, standardization of plastic sizes is advisable, e.g. uniform size of 10 to 20 mm (scenario 2). Thereby, the losses can be minimized by reducing the shredding steps, optimizing the efficiency of the sorting technologies and therefore avoiding losses, reducing composites of small particle size and reducing CO_2 emissions. This would contribute to an increased recyclability as well as to a higher quality of recycled plastics.

It can be concluded that, if the recommendations for the pre-processor and the recycler are implemented, the plastic losses could be reduced due to shredder losses and misthrows and an efficient sorting according to particle size could take place. Through efficient sorting, the separation into the individual plastic types can take place and thus increase the quality of the plastic fractions for compounding. This would increase recyclability in terms of plastic recycling as there would be less material for landfilling and incinerating.

Further recommendations on how to achieve good plastics quality is to harmonize the requirements for PCR plastics in the legislative framework. An "end-of-waste" clear regulation for WEEE plastics should be put in place. In order to achieve a standardization of the quality of the plastic fractions, harmonisations of the requirements should be proposed.

- Harmonisation of requirements on sorting of brominated plastics, because of international competition on the materials markets (PCR price differences due to costs for sorting of BFR plastics)
- Harmonisation of legislation and its implementation, including regarding monitoring/ control and authorisation of construction and operation of plants
- Control of recyclers, auditors and compliance schemes is necessary to make sure that legal requirements (e.g. sorting of BFR plastics) are enforced
- Bans or restrictions on landfilling or incineration to increase the recycling of the “fine fraction” (Vlugter, 2017)
- Create tax benefits for recycled materials compared with virgin materials to get the manufacturer to buy this fraction instead of the virgin fraction (Vlugter, 2017)
- Technical datasheets of the produced plastics fractions are similar but a bit different, depending of the recycling company.

7 Future works

As a future investigation, it would be necessary to quantify the losses due to shredding. The losses that occur in each shredder in dust or fine particles, are estimated at about 10 to 20 %. However, this may vary depending on the crushing technology. The data is hard to get from pre-processors or plant manufacturers but would be worth investigating to get more accurate data.

Due to the shredding technologies it is important to examine the energy consumption or energy efficiency of the shredding technologies in order to be able to make a quantitative statement about the energy consumption during the shredding process and thus the energy savings through the correct use of the shredder. It should be an investigation to control the minimum particle size during the production of fines by the different technologies and make a systematic comparison.

Another study would be helpful in the field of fine fraction. The fine fraction is a very mixed composition with impurities such as glass or wood. An analysis of the impurities would help to give a meaningful statement regarding the separation of plastic fractions. A quantification can be made as to whether small particles with sizes of 2 to 6 mm or 6 to 10 mm can still be separated, and if this effort is worthwhile. Separating this fraction benefits the environmental footprint as this fraction is currently incinerated or landfilled. With regard to the fine fraction, it is also important to optimize the sorting technologies in this size range and to find suitable recyclers who master these sorting technologies and are thus able to separate the fine fraction.

The transport of plastic flakes represents a cost point in plastic recycling. Minimizing transport costs would be interesting for pre-processor and recycler. However, this only works if the plastic flakes are the right size to have an optimum bulk density. A quantitative study would be advantageous here to underline the cost savings and the economy during particle size of plastics fractions. It could also be a statement about the CO_2-emisison savings to protect the environment.

Furthermore, a feasibility must be considered. The feasibility should be due to economic aspects of the shredder and sorting technologies and the production of a given particle size range. Only if the process is economically feasible, the pre-processors and the recyclers have an incentive to implement the recommendations practically.

8 References

ANDRITZ (2016). Universal Cross-Flow Shredder QZ: Gentle and fast disintegration of composite materials.

Antico, L. & Beerten, C. (2018). Analyzing the shape and colour distribution of shredded recyclates: Master thesis.

Batanic, B., Vaccari M., Savvilotidou V., Kousaiti, A., Gidarakos, E., Marinkovic, T., & Fiore, S. (2018). Applied WEEE pre-treatment methods: Opportunities to maximizing the recovery of critical metals. Global NEST Journal. doi: 10.30955/gnj.002589.

Bennett, M., Edwards, L., Goyos-Ball, L., Hilder, R., Hall, P., & Morrish, L., … myles, n. (2009). Separation of mixed WEEE plastics: A series of demonstration trials on novel techniques for the separation of mixed WEEE plastics.

Bezati, F., Froelich, D., Massardier, V., & Maris, E. (2015). Addition of X-ray fluorescent tracers into polymers, new technology for automatic sorting of plastics: proposal for selecting some relevant tracers.

BHS (2016). Prospekt Rotorprallmühle, Sonthofen.

Biddle, M.B., Dinger, P., & Fischer, M.M. (1999). An Overview of Recycling Plastics from Durable Goods: Challenges and Opportunities.

Biddle, M.B., Dinger, P., & Fisher, M.M. (2003). An Overview of Recycling Plastics from Durable Goods: Challenges and Opportunities.

Bilitewski, B. & Härdtle, G. (2013). Abfallwirtschaft: Handbuch für Praxis und Lehre (4.,aktualisierte und erweiterte Auflage). Springer-Verlag Berlin Heidelberg.

Billitewski, B. & Härdtle, G. (2013). Abfallwirtschaft: Handbuch für Praxis und Lehre (4. aktualisierte und erweiterte Auflage). Springer Verlag.

Buekens, A. & Yang, J. (2014). Recycling of WEEE plastics: A review. Journal of Material Cycles and Waste Management, 16(3), 415–434. doi: 10.1007/s10163-014-0241-2.

Chagnes, A. (2016). WEEE recycling: Research, development, and policies (1st edition). Waltham MA: Elsevier.

Choi, B.-C., Shin, H.-S., Lee, S.-Y., & Hur, T. (2006). Life Cycle Assessment of a Personal Computer and its Effective Recycling Rate (7 pp). The International Journal of Life Cycle Assessment, 11(2), 122–128. doi: 10.1065/lca2004.12.196.

Christine Jeavens (2008). Plastic recycling comes full circle. http://news.bbc.co.uk/2/hi/uk_news/magazine/7470662.stm.

CreaCycle GmbH (2018). Creacycle - Plants: CreaSolv® Pilot plant in Indonesia and in Holland (NL). https://www.creacycle.de/en/creasolv-plants.html (04.12.2018).

Delavelle, C. (2012). État de l'art des technologies d'identification et tri des déchets: State-of-the-art of waste identification and sorting technologies, Angers.

Deloitte (2017). Analyse de la chaîne de valeur du recyclage des plastiques en France – synthèse: Trois grands axes d'actions pour développer la filière.

Dimitrova, G. (2017). Report on proposed Ecodesign Policy Concept and recommendation to strengthen Design for Recycling and the usage of post-consumer recycled plastics in new products: Deliverable D9.3 (intermediate version from November 29, 2017) of research project CloseWEEE, funded from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 641747.

(2011). Directive 2011/65/EC of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment: 2011/65/EC.
Dodbiba, G., Sadaki, J., Okaya, K., Shibayama, A., & Fujita, T. (2005). The use of air tabling and triboelectric separation for separating a mixture of three plastics. Minerals Engineering, 18(15), 1350–1360. doi: 10.1016/j.mineng.2005.02.015.
Drechsel, C. (2006). Mechanical Processes for Recycling Waste Electric and Electronic Equipment with the Rotorshredder and Rotor Impact Mill, Sonthofen.
European Commission (2017). Waste Electrical & Electronic Equipment (WEEE). http://ec.europa.eu/environment/waste/weee/index_en.htm (25.09.2017).
European Food Safety Authority (EFSA) (2008). Guidelines on submission of a dossier for safety evaluation by the EFSA of a recycling process to produce recycled plastics intended to be used for manufacture of materials and articles in contact with food - Opinion of the Scientific Panel on food additives, flavourings, processing aids and materials in contact with food (AFC). EFSA Journal, 6(7), 135. doi: 10.2903/j.efsa.2008.717.
European Union (2012). Directive 2012/19/EU on waste electrical and electronic equipment (WEEE): WEEE-Directive.
Freegard, K., Tan, G., & Morton, R. (2006). Develop a Process to Separate Brominated Flame Retardants from WEEE Polymers – Final report. Waste & Resources Action Programme (WRAP), 335.
Frerejean, V., Mani, S., Littner, A., Coiffier, F., Tilleux, G., & Geurts, W. (2015a). REMIX Interim Reports 1-2.
Frerejean, V., Mani, S., Littner, A., Coiffier, F., Tilleux, G., & Geurts, W. (2015b). REMIX Interim Reports 1-2.
Haarman, A. & Gasser, M. (2016). Managing hazardous additives in WEEE plastic from the Indian informal sector: A study on applicable identification & separation methods.
Hobohm, J. (2017). Ressourcenoptimierte Erfassung von Elektro- und Elektronikaltgeräten am Beispiel des Ballungsgebietes Hamburg, Hamburg.
Hu, B. (2014). Magnetic Density Separation of Polyolefin Wastes.
Hyks, J., Cimpan, C., Oberender, A., Hjelmar, O., Hu, G., & Cramer, J. (2014). Shredder residues: Problematic sub-stances in relation to resource recovery, Kopenhagen, Denmark.
Kistenmacher, A. (2003), *Plastics Recycling – State of the Art*. Proceedings of RECCON 03. Bilbao, Spain, Bilbao, Spain.
Koehnlechner, R. (2016), *Erzeugung wertvoller Kunststoff-Fraktionen aus Elektronikschrott-Abfällen*. Großschirma, Großschirma.
Kranert, M. (2017). Einführung in die Kreislaufwirtschaft. Wiesbaden: Springer Fachmedien Wiesbaden.
Liang, R. & Gupta, R.K. (2001). The effect of residual impurities on the rheological and mechanical properties of engineering polymers separated from mixed plastics.
Maris, E., Aoussat, A., Naffrechoux, E., & Froelich, D. (2015). Polymer tracer detection systems with UV fluorescence spectrometry to improve product reyclability.

Maris, E., Botané, P., Wavrer, P., & Froelich, D. (2015a). Characterizing plastics originating from WEEE: A case study in France. Minerals Engineering, 76, 28–37. doi: 10.1016/j.mineng.2014.12.034.
Maris, E., Botané, P., Wavrer, P., & Froelich, D. (2015b). Characterizing plastics originating from WEEE: A case study in France. Minerals Engineering, 76, 28–37. doi: 10.1016/j.mineng.2014.12.034.
Martens, H. & Goldmann, D. (2016). Recyclingtechnik: Fachbuch für Lehre und Praxis (2. Auflage). Wiesbaden: Springer Vieweg.
Martinho, G., Pires, A., Saraiva, L., & Ribeiro, R. (2012). Composition of plastics from waste electrical and electronic equipment (WEEE) by direct sampling. Waste management (New York, N.Y.), 32(6), 1213–1217. doi: 10.1016/j.wasman.2012.02.010.
Martinho, G., Pires, A., Saraiva, L., & Riberio, R. (2012). Composition of plastics from waste electrical and electronic equipment (WEEE) by direct sampling. Waste Management, 32, 1213–1217.
Meyer, J. (2017), *Laser-Spectroscopy for Polymer Sorting. The Revolution in Sorting*. Amsterdam, Netherlands, Amsterdam, Netherlands.
Nowakowski, P. (2016). A proposal to improve e-waste collection efficiency in urban mining: Container loading and vehicle routing problems - A case study of Poland.
Peeters, J.R., Vanegas, P., Tange, L., van Houwelingen, J., & Duflou, J.R. (2014). Closed loop recycling of plastics containing Flame Retardants. Resources, Conservation and Recycling, 84, 35–43. doi: 10.1016/j.resconrec.2013.12.006.
Saimu Corporation (2018). Raman Plastic Sorter, Japan.
(2016). Sammlung, Logistik und Behandlung von Elektro- und Elektronik-Altgeräten (WEEE) – Teil 3-1: Spezifikation der Schadstoffentfrachtung.
Schlummer, M., Gruber, L., Mäurer, A., Wolz, G., & van Eldik, R. (2007). Characterisation of polymer fractions from waste electrical and electronic equipment (WEEE) and implications for waste management. Chemosphere, 67(9), 1866–1876. doi: 10.1016/j.chemosphere.2006.05.077.
Schlummer, M., Wolff, F., & Maurer, A. (2016). Recovery of PC/ABS from WEEE plastic shred by the CreaSolv ® process In (Eds.)M. Schlummer *et al., Recovery of PC/ABS from WEEE plastic shred by the CreaSolv®process* (pp. 1–6). IEEE.
Stenvall, E., Tostar, S., Boldizar, A., Foreman, M.R.S., & Möller, K. (2013). An analysis of the composition and metal contamination of plastics from waste electrical and electronic equipment (WEEE). Waste management (New York, N.Y.), 33(4), 915–922. doi: 10.1016/j.wasman.2012.12.022.
Tang, S., Daryoosh, S., & Iniewski, K. (2017). Advances in imaging and sensing. Devices, circuits, and systems. Boca Raton, London, New York: CRC Press Taylor & Francis Group.
Taurino, R., Pozzi, P., & Zanasi, T. (2010). Facile characterization of polymer fractions from waste electrical and electronic equipment (WEEE) for mechanical recycling. Waste management (New York, N.Y.), 30(12), 2601–2607. doi: 10.1016/j.wasman.2010.07.014.
Ueberschaar, M., Geiping, J., Zamzow, M., Flamme, S., & Rotter, V.S. (2017). Assessment of element-specific recycling efficiency in WEEE pre-processing. Resources, Conservation and Recycling, 124, 25–41. doi: 10.1016/j.resconrec.2017.04.006.

Vegliό, F. & Birloaga, I. (2018a). Waste Electrical and Electronic Equipment Recycling: Aqueous Recovery Methods. United Kingdom: Elsevier.
Vegliό, F. & Birloaga, I. (2018b). Waste Electrical and Electronical Equipment Recycling: Aqueous Recovery Methods. United Kingdom: Elsevier.
Veit, H.M. & Bernardes, A.M. (2015). Electronic Waste: Recycling Technologies. Springer Verlag.
Vlugter, J. (2017). Scaling Recycled Plastics across Industries.
WEEE Forum (2013). WEEELABEX normative document on Treatment V10.0.
Weiss, M. (2012). XRF-New Applications in Sensor-Based-Sorting Using X-ray Fluorescence.
Widmer, R., Oswald-Krapf, H., Sinha-Khetriwal, D., Schnellmann, M., & Böni, H. (2005). Global perspectives on e-waste. Environmental Impact Assessment Review, 25(5), 436–458. doi: 10.1016/j.eiar.2005.04.001.
Woldt, D. (2004). Zerkleinerung nicht-spröder Stoffe in Rotorscheren und -reißern.

9 Appendices

Annex A: Check-list for the collection of information from the WEEE treatment facilities

(The questions only asked if the interviewee has enough knowledge and trust are in *italic*.; the questions arising from Task 3.2 led by ECODOM are in green)

1. Input

- Which collection categories (or product groups) do you treat?
- Do you treat the collection categories or other mixes separately? Do you pre-sort the input before treatment? [See sheet “Current plastic material flows” of the ECODOM questionnaire]
- Do you have information on the polymers contained in the input streams? What are the shares of the polymers?
- *Does this influence the sorting?*

- ECODOM: Did you identify some correlation between brands of products and the plastics they use? If yes, please specify.

2. Technologies used

- What is the basic layout of the treatment plant (types and order of technologies)?
- To what degree is manual sorting employed? Do you sort plastics manually? Why/why not?
- Which particle size is chosen for grinding/ shredding?
- Which metal types are removed and how?
- Which fractions are sorted with positive sorting? Which ones with negative sorting? Why?
- Which optical sorting technologies do you use? Why?
- Do you operated a float-vs-sink sorting process? What solution density is used during float-vs-sink sorting?
- Which materials are aimed to be separated during float-vs-sink sorting?

3. Plastics fractions

- How many plastic fractions are produced?

Plastics fraction	Origin (process step, input)	Description of the quality (high purity, mixed?)

- Which output streams achieve high purity and which are mixed material fractions?
- If you sort the BFR plastics? What is the percentage of marketable plastics? (Ratio BFR/non-BFR)
- Do you test or analyse the plastics fractions? Which parameters are measured? With which measurement methods? (e.g. WEEELABEX, ISO standards) Which analysis results are available to you? [see sheet "Plastic quality test" of the ECODOM questionnaire"]
- Which markets are the plastics sold to?
- Which output streams are difficult to market?

- ECODOM: Does the value of the output plastic streams vary depending on the plastic purity or quality? If yes, please specify how the value is influenced.
- *What is the revenue per tonne for the different plastic fractions?*

4. Challenges

- Which are the biggest problems you face? (E.g. PS, always 10% ABS --> today quality not good enough for the following process)

- ECODOM: Is there a plastic stream that is seen as problematic? If yes, please specify.
- ECODOM: Do you believe technological improvements will substantially increase the recycling efficiency of plastics from WEEE in the coming 5 and 10 years? If yes, please explain.
- ECODOM: Do you personally believe that compared to today more plastic types will be recycled in the coming 5 and 10 years? If yes, please explain.
- ECODOM: For some products, the separated plastics might be easily kept separated from those of other products, whereas today your plastics are mixed in your organization. Does this occur? If yes, please explain.

5. Interests

- Would you be interested in technical specifications linking input, technologies and quality of plastics fractions?
- Are interested in getting informed of the progress of the PolyCE research and of further contributing?
- Which market are you specifically interested in for the sales of your output streams?

Annex B: Check-list for the collection of information from machine manufacturer

Question	Answer
Company (Shredder)	
Which shredders do you own for old electrical appliances?	
Which shredders do you own for plastics from WEEE?	
Type of shredder	
Number of rotors [piece]	
Rotation speed [m / s]	
Drive power [kW]	
Rotor width [mm]	
Rotor diameter [mm]	
Throughput [t/h]	
Grain Size Fraction [mm] (Minimal/Maximal)	
How is the particle size adjusted?	
With what accuracy is the particle size produced? (If acceptable)	
Investment costs [€]	
Lifetime [a]	
Specific to the maintenance (Easy, medium, hard?)	
Advantages / Special Features	
Disadvantages	

Annex C: Shredding technologies of different manufacturer

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
Donasonic (UK)	Double-shaft (Pre-shredder)	Thunderstorm X165	1650	750	2 x 90	60	10-50	-
		Thunderstorm X225	2250	750	2 x 110/132	60	10-50	-
		Thunderstorm X295	2950	750	2 x 110/132/160	60	10-50	-
		Thunderstorm X325	3250	750	2 x 160/200	60	10-50	-
	Single-shaft (shredder)	Micro X60	600	600	55	-	< 15	5-80
		Micro X120	1200	600	75/90/110/160	-	< 15	5-80
		Micro X170	1700	600	110/132/160/200	-	< 15	5-80
		Micro X200	2000	600	250/315	-	< 15	5-80
	Single-shaft (shredder)	Macro X90	900	-	75/90	-	< 3	3-10
		Macro X120	1200	-	90/110	-	< 3	3-10
	Cross-flow shredder	Crossflow X95	-	-	75	-	< 15	-
		Crossflow X125	-	-	75/90	-	< 15	-
		Crossflow X165	-	-	132/160	-	< 15	-
Eggersmann Anlagenbau GmbH (DE)	Single-shaft (shredder)	Teuton Z55	3000	1050	405	40	-	80-250
	Double-shaft (shredder)	Forus FLX85-200	2000	-	354	8-33	-	-
		Forus FLX85-250	2500	-	405	8-33	-	-
		Forus FLX85-300	3000	-	455	8-33	-	-
SatrindTech (I)	Single-shaft (shredder)	1K28	600-1300	280	15-45	-	0,2-1	12-50
		1K46	1490-1790	460	110	-	0,8-3	20-50
		1K65	2100-3000	650	160-315	-	4-16	20-80
	Double-shaft (shredder)	K25	-	-	18,5	-	0,6-1,5	30-300
		K30	-	-	22	-	0,6-2	30-300
		K50	-	-	37	-	0,8-3	30-300
		2R50-100/ER	1008	-	37	-	1,5-3	30-300
		2R100-150/SD	1510	-	75/110	-	4-7	30-300
	Three-shaft (shredder)	3K30	488/728	-	22	-	0,3-0,4	30-50
		3K60	750/1000/1250	-	44	-	1-1,5	30-50
		3K80	750/1000/1250	-	59	-	1,5-3	30-50
		3R75/ER	1008/1258	-	55,5	-	1,5-2	30-50

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
		3R125	758/1008/1258	-	93	-	1,5-2	30-50
WIPA (DE)	Granulator	G35/30-60	-	-	5,5/11	-	0,1-0,3	-
		G45/30-120	-	-	7,5/30	-	0,1-0,7	-
		G50/30-55	-	-	30/55	-	0,3-1	-
		G60/80-150	-	-	75/132	-	0,5-1,5	-
		G80/120-200	-	-	160/250	-	1-2	-
		G100/250	-	-	320	-	< 5	-
THM recycling solutions (DE)	Granulator AG	AG 1608	-	785	250	-	< 20	10-100
		AG 2008	-	785	315	-	< 20	10-100
		AG 2808	-	785	500	-	< 20	10-100
	Granulator Universal	XG2400	-	785	220	-	-	20-100
	Granulator klein	ZM300	300	200	7,5	-	-	10-30
	Granulator ZM	ZM600	-	590	55	-	< 10	10-100
		ZM1020	-	480	90	-	< 10	10-100
		ZM1620	-	480	110	-	< 10	10-100
		ZM1008	-	785	160	-	< 10	10-100
	Granulator ZMK	ZMK 1607	-	785	250	-	< 15	10-100
		ZMK 2007	-	785	315	-	< 15	10-100
	Knife mill	CM100	-	495	90	-	-	< 4
	Shredder	KPS 500	500	320	30	-	-	10-40
		RSP2000	2000	750	132	-	-	10-60
	Rotary impact mill	RM900	-	-	75	-	-	< 10
	Rotary shear	TSM1500	1500	550	134	-	-	80
	Cross flow shredder	TQZ 900	-	-	75	-	< 17	< 150
		TQZ 1200	-	-	90	-	< 17	< 150
		TQZ 1600	-	-	160	-	< 17	< 150
		TQZ 2000	-	-	250	-	< 17	< 150
		TQZ 2500	-	-	315	-	< 17	< 150
Lindner Recyclingtech GmbH (AU)	Single-shaft (shredder)	Micromat 2000 Getriebe	2025	-	110	79	-	15-100
		Micromat 2000 Riemen	2025	-	132	265	-	15-100
		Micromat 2500 Getriebe	2525	-	132	79	-	15-100

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
		Micromat 2500 Riemen	2525	-	160	265	-	15-100
	Single-shaft (shredder)	Antares 1000	950	-	45	99	-	10-80
		Antares 1300	1258	-	55	99	-	10-80
		Antares 1600	1567	-	75	99	-	10-80
		Antares 1900	1875	-	90	99	-	10-80
	Single-shaft (shredder)	Apollo 700	650	-	15-30	60-110	-	10-80
		Apollo 1000	1000	-	30-45	50-110	-	10-80
		Apollo 1600	1600	-	55-75	60-110	-	10-80
UNTHA shredding technology (AU)	Single-shaft (shredder)	QR800	800	450	-	-	-	15-100
		QR1000	1000	450	-	-	-	15-100
		QR1200	1200	450	-	-	-	15-100
		QR1400	1400	450	-	-	-	15-100
		QR1700	1700	560	-	-	-	15-100
		QR2100	2100	560	-	-	-	15-100
	Four-shaft (shredder)	RS30	450	-	11/15/22	23-34	-	15-40
		RS40	750	-	30/37/44	24-32	-	15-40
	Four-shaft (shredder)	RS50	750	-	44/50/60	21-43	-	15-40
		RS60	960	-	60/74	17-25	-	15-100
		RS100	1200	-	100/110/150	17-28	-	30-100
Neue Herbold (DE)	One-shaft (shredder)	HZR 800	800	400	-	-	-	-
		HZR 1300	1300	400	-	-	-	-
		HZR 1600	1600	600	-	-	-	-
	Two-shaft (shredder)	Typ ZRM 1100/2	-	-	-	-	-	-
	Four-shaft (shredder)	Typ ZRM 1100/4	-	-	-	-	-	-
	Knife mill	SX	-	-	-	-	-	-
	Knife mill	SMV	-	-	-	-	-	-
	Knife mill	SM	-	-	-	-	-	-
	Knife mill	LM	-	-	-	-	-	-
BHS Sonthofen (DE)	Shredder Universal	NGU0513	1305	495	55-90	80-240		10-120
		NGU0518	1795	495	90-132	80-240		10-120
	Granulator	NGV1020	1850	950	400	320	< 12	12-80

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
		NGV1028	2590	950	500	320	< 15	12-80
	Rotary shredder	RS2018	-	-	110-400	-	-	-
		RS3218	-	-	110-400	-	-	-
	Rotary impact mill	RPMV0813	-	-	75	-	-	0-15
		RPMV1113	-	-	132	-	-	0-15
		RPMV1513	-	-	200	-	-	0-15
		RPMV1116	-	-	315	-	-	0-15
		RPMV1516	-	-	315	-	-	0-15
Erdwich Zerkleinerungs-systeme (DE)	Hammer mill	HA800/1-1000	1000	800	45-90	-	-	8-100
Andritz MeWa GmbH (AU)	Cross-flow shredder	QZ 900	-	-	75	-	1	-
		QZ 1200	-	-	90	-	2	-
		QZ 1600	-	-	160	-	3-5	-
		QZ 2000	-	-	250	-	8-12	-
		QZ 2500	-	-	315	-	12-15	-
	Granulator Universal	UG 600	-	-	55	-	< 5	8-120
		UG 1000	-	-	90-160	-	< 5	8-120
		UG 1600	-	-	110-250	-	< 5	8-120
		UG 2000	-	-	315	-	< 5	8-120
	Rotary shear (Pre-shredding)	UC 850	850	-	30	-	< 15	-
		UC 1050	1050	-	44	-	< 15	-
		UC 1200	1200	-	44-55	-	< 15	-
		UC 1300	1300	-	110-150	-	< 15	-
		UC 1500	1500	-	110-180	-	< 15	-
		UC 2000	2000	-	110-180	-	< 15	-
amis Recycling Technology (DE)	Single-shaft (shredder)	ZBS Kompakt 600	600	310	11	61	-	> 16
		ZBS Kompakt 850	850	310	18,5	61	-	> 16
	Universal Shredder	ZSS Universal 850	850	387	37	80	-	20-100
		ZSS Universal 1200	1200	457	55	80	-	20-100
		ZSS Universal 1500	1500	457	75	80	-	20-100

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
		ZSS Universal 2000	2000	457	2x55	80	-	20-100
	Single-shaft (shredder)	ZIS 1200	1200	457	55	74	-	20-100
		ZIS 1500	1500	457	75	74	-	20-100
		ZIS 2000	2000	457	2x55	74	-	20-100
	Single-shaft (shredder)	ZXS 1500	1500	750	2x75	45	-	20-100
		ZXS 2000	2000	750	2x75/2x90	45	-	20-100
		ZXS 3000	3000	750	2x110	45	-	20-100
	Knife mill	GSE 300/300	300	300	7,5-11	-	-	> 6
		GSE 300/600	600	300	11-18,5	-	-	> 6
		GSE 300/1000	1000	300	18,5-22	-	-	> 6
		GSE 300/1400	1400	300	22-37	-	-	> 6
	Knife mill	GSE 500/500	500	500	22-37	-	-	> 6
		GSE 500/700	700	500	30-45	-	-	> 6
		GSE 500/1000	1000	500	37-55	-	-	> 6
		GSE 500/1400	1400	500	45-55	-	-	> 6
	Knife mill	GSE 700/700	700	700	45-55	-	-	> 6
		GSE 700/1000	1000	700	45-75	-	-	> 6
		GSE 700/1400	1400	700	55-75	-	-	> 6
	Knife mill	GSH 350/500	500	350	22	-	-	> 6
		GSH 500/600	600	500	45-55	-	-	> 6
		GSH 500/1000	1000	500	75-90	-	-	> 6
	Knife mill	GSH 600/800	800	600	75-90	-	-	> 6
		GSH 700/1000	1000	700	90-110	-	-	> 6
	Knife mill	GSH 800/1200	1200	800	110-160	-	-	> 8
		GSH 800/1600	1600	800	132-200	-	-	> 8
		GSH 800/2000	2000	800	2x160	-	-	> 8
	Knife mill	GSH 1100/1200	1200	1100	200	-	-	> 8
		GSH 1100/2400	2400	1100	2x200	-	-	> 8
Bomatic (DE)	Granulator	U1200	1200	500	75/90	280	1-2	10-100
		U1700	1700	600	132/160	240	5-9	10-100
		U2100	2100	800	250	240	7-8	10-100

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
	Cross-flow shredder	R750	-	-	30-45	1200	1-4	-
		R1200	-	-	75-90	1000	1-12	-
		R1600	-	-	160-200	900	1-20	-
	Rotary shear (Pre-shredding)	B1350 S	1355	-	55-75	-	3-4	-
		B1350 DD	1355	-	2x55	-	5-6	-
		B1700 S	1700	-	55-75	-	3-4	-
		B1600	1600	-	2x75	-	7-8	-
		B2000	2000	-	2x110	-	ca. 10	-
For Rec Recycling Systems (IT)	Four-shaft (shredder)	TQ 1300	1320	-	2x22+2x30	10-12	-	30-120
		TQ 1800	1760	-	2x37+2x55	10-12	-	30-120
	Granulator	FMS	-	800	90/110/200	-	1-2,5	<8
		FML	-	450	30/37/45	-	0,3-0,8	<6
	Hammer mill	Z 15	1018	900	200/250	-	-	-
	Double-shaft (Pre-shredder)	TB700	720	-	2x11/2x15	10-12	-	-
		TB1000	1020	-	2x11/2x15	10-12	-	-
		TB1300	1260	-	2x22/2x30/2x37	10-12	-	-
		TB1500	1460	-	2x37/2x55/2x75	10-12	-	-
		TB1800	1760	-	2x37/2x55/2x75	10-12	-	-
		TB2000	1960	-	2x55/2x75/2x90	10-12	-	-
Herbold-Meckesheim (DE)	Hammer mill	HM 100/100 PR	1000	1000	75-200	-	0,8-5	-
		HM 100/150 PR	1500	1000	90-250	-	1,2-8	-
	Knife mill	SML-LS 35/42	400	320	7,5	150	-	-
		SML-LS 35/62	600	320	7,5-11	150	-	-
		SML-LS 35/82	800	320	7,5-18,5	150	-	-
	Granulator	HGM 60/100	1050	175	75	200	-	-
		HGM 60/145	1420	175	90	200	-	-
		HGM 80/160	1600	175	132	200	-	-
		HGM 100/210	2100	175	200	200	-	-
	Single-shaft (shredder)	EWS 45/120	1300	450	45-90	-	-	-
		EWS 45/160	1500	450	55-132	-	-	-
ATM	Single-shaft	SS 400	380	115	11	11-72	-	5-50

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
Recyclingsystems GmbH (AU)	(shredder)	SS 600	765	200	11	11-72	-	5-50
	Single-shaft (shredder)	SSE 700	700	450	30-132	60-140	-	20-50
		SSE 1400	1400	450	30-132	60-140	-	20-50
		SSE 2100	2100	450	30-132	60-140	-	20-50
	Double-shaft (Pre-shredder)	DS (360-950)	380-1700	115-480	110/2x90	11-72	-	5-50
	Four-shaft (shredder)	QS (320-800)	380-1200	175-340	2x55/2x45	11-72	-	5-50
Sicon GmbH (DE)	Hammer mill	Sicon PTS 500	500	-	-	-	-	15-90
		Sicon PTS 1000	1000	-	-	-	-	75-132
		Sicon PTS 1500	1500	-	-	-	-	90-210
	Granulator	SIC-G600	600	260	15	580	-	<12
		SIC-G600T	600	320	22	580	-	<12
		SIC-G800	800	320	30	580	-	<12
		SIC-G800T	800	420	37	580	-	<12
		SIC-G1000	1000	420	45	580	-	<12
	Single-shaft (shredder)	SI K1500	1500	480	110+110	80	-	40-100
		SI K1700	1650	480	132+132	80	-	40-100
		SI K2000	2000	650	110+110	80	-	40-100
		SI K2200	2200	650	164+164	80	-	40-100
Eldan Recycling (DK)	Granulator	Fine	1200-2000	-	-	475	up to 4,5	4-100
	Granulator	Heavy	475-1425	-	-	400	up to 8	8-100
Gross Zerkleinerer (DE)	Single-shaft (shredder)	GAZ 82	-	252	15/18,5/22	60-100	-	8-50
		GAZ 82S	-	368	18,5 - 37	60-120	-	8-50
		GAZ 102	-	252	18,5 - 22	60-100	-	8-50
		GAZ 102S	-	368	22 - 45	60-120	-	8-50
		GAZ 132S	-	368	22 - 45	60-120	-	8-50
		GAZ 152S	-	368	30 - 75	60-120	-	8-50
		GAZ 182S	-	368	45 - 90	60-120	-	8-50
		GAZ 202S	-	368	55/75/90	60-120	-	8-50
	Single-shaft (shredder)	GAZ 62 / GAZ 62 E	600	252	11/ 15 / 18,5	60-100	-	10-40
		GAZ 62 S	600	368	15 / 18,5 / 22	60-100	-	10-40

Company	Shredder	Type	Rotor length [mm]	Rotor diameter [mm]	Drive power [kW]	Rotor speed [rpm]	Throughput [t/h]	Size range [mm]
	Four-shaft (shredder)	GZ30	1250	-	2x5,5;2x7,5;2x11	-	-	20-40
		GZ30S	1400	-	2x11;2x15;2x18,5	-	-	20-40
		GZ40	1400	-	2x11;2x15;2x18,5	-	-	20-40
		GZ50	1400	-	2x11;2x15;2x18,5	-	-	20-40
	Granulator	-	-	-	-	-	0,1-2,5	4-10
Hazemag (DE)	Hammer mill	HNM 0703	250	650	-	-	-	-
		HNM 0705	500	650	-	-	-	-
		HNM 0708	750	650	-	-	-	-
		HNM 1008	750	1000	-	-	-	-
		HNM 1013	1250	1000	-	-	-	-
		HNM 1020	2000	1000	-	-	-	-
		HNM 1313	1250	1300	-	-	-	-
		HNM 1325	2000	1300	-	-	-	-
Rapid Granulator (SWE)	Single-shaft (shredder)	Raptor 800	800	280	11-45	-	-	16-72
		Raptor 1350	1350	280	11-45	-	-	16-72
	Knife mill	Rapid 600-90	900	600	75	-	-	8-25
		Rapid 600-120	1200	600	90	-	-	8-25
		Rapid 600-150	1500	600	90	-	-	8-25

Annex D: Sorting technologies of different manufacturer

Sorting technique	Minimal input particle size [mm]	Maximal input particle size [mm]	Through-put [t/h]	Reference	Comments
MDS	2	14	-	Bin Hu	Emailkontakt mit Bin Hu
MDS	0.2	15	-	Peter Rem, TU Delft	Emailkontakt mit Peter Rem, TU Delft
MDS	0	15	-	Liquisort	http://liquisort.com/
MDS	0.1	25	-	Emerald-energy	http://www.emerald-energy.net.au/mds-magnet-density-separation/mds-plastics/
CREASOLV	0.1	100	-	Andreas Mäurer	Emailkontakt mit Andreas Mäurer von Fraunhofer IVV
Hydrocyclone	0	6	-	Ruj 2015	Paper "Sorting of plastic waste for effective recycling"
Hydrocyclone	0,5	6	-	Gent 2009	Paper: Recycling of plastic waste by density separation: prospects for optimization
Air table	2	10	-	Freegard 2007	Bericht "WEEE Plastics Separation Technologies"
Air table	0,25	3,2	-	Electronic Waste Management	Buch Electronic Waste Management; Kapitel Recycling and Recovery (Ratio 1:2,8)
Air table	1,59	2,38	-	WEEE Handbook	Buch WEEE Handbook; Kapitel Mechanical methods of recycling
Air table	0,25	3,2	-	WEEE Recycling Arda	Buch Arda
Shaking table	0	8	1-2,5	Holman Wilfley	Emailkontakt mit David Goldburn von Holman-Wilfey
Flotation	0,02	0,3	-	Martens	Buch Recyclingtechnik Martens (Für sehr kleine Teilchen)
Flotation	2	6	-	Wang 2016	Paper Flotation separation of waste plastics for recycling—A review
Flotation	2	5,6	-	Pita 2016	Paper Separation of plastics by froth flotation. The role of size, shape and density of the particles
Electrostatic Separation	0	10	-	Hamos Advanced Separation Technologies	Purities: PS>98,5, ABS >98,5, no limitation swith black particles
Electrostatic Separation	5	8	-	Freegard 2007	Bericht "WEEE Plastics Separation Technologies"
Electrostatic Separation	1	10	-	WEEE Recycling	Buch WEEE Recycling
Electrostatic Separation	0,6	1,2	-	WEEE Recycling Arda	Buch Arda; Corona Electrostatic separation
Electrostatic	0,1	5	-	Electronic Waste	Buch Electronic Waste Recycling Technologies (Optimal aber

Sorting technique	Minimal input particle size [mm]	Maximal input particle size [mm]	Through-put [t/h]	Reference	Comments
Separation				Recycling Technologies	zwischen 0,6 und 1,2)
Triboelectric	1	2	-	Remix Interim Report	Remix Interim Report
Triboelectric	1	13	-	Wu 2012	Paper Triboelectrostatic separation for granular plastic waste recycling: A review
Centrifuge	2	16	-	Flottweg Separation Technology	Datasheet of "Sorticanter", Density sorting in heavy fraction and light fraction, zuerst Schmutzbefreiung, Lösung in Suspension
Centrifuge	0	15	ACZ 4-3: 0,5 ACZ 6-3: 1 ACZ 9-3: 2	Andritz Separation	Datasheet of "Censor", Density sorting in heavy fraction and light fraction, zuerst Schmutzbefreiung, Lösung in Suspension,
Centrifuge	2	16	-	Remix Interim Report	Information of "Sorticanter", Density sorting in heavy fraction and light fraction, zuerst Schmutzbefreiung, Lösung in Suspension
Centrifuge	0	6	-	Parnaby Cyclones	Brochure of Hydrocyclone Separators
Centrifuge	0	15	-	Parnaby Cyclones	Brochure of Hydrocyclone Separators
Centrifuge	0	25	-	Parnaby Cyclones	Brochure of Hydrocyclone Separators
Centrifuge	0	50	-	Parnaby Cyclones	Brochure of Hydrocyclone Separators
Centrifuge	0	15	-	Einführung in die Kreislaufwirtschaft	Buch Einführung in die Kreislaufwirtschaft (Beispiel SENSOR ANDRITZ)
Raman	5	15	0,1-0,4	Saimu Corporation	Raman Plastic Sorter
High-Speed Laser Spectroscopy	1,5	20	-	Powersort	Laser-Spectroscopy for polymer sorting; Powersort 200
High-Speed Laser Spectroscopy	8	75	-	Powersort	Laser-Spectroscopy for polymer sorting, Powersort 350
Magnetic	10	100	-	Remix Interim Report	Remix Interim Report
Magnetic	10	100	-	Billitewski und Härdtle	Buch Abfallwirtschaft
Magnetic	10	150	-	Einführung in die	Buch Einführung in die Kreislaufwirtschaft

Sorting technique	Minimal input particle size [mm]	Maximal input particle size [mm]	Through-put [t/h]	Reference	Comments
				Kreislaufwirtschaft	
Magnetic	1	100	-	Martens	Buch Recyclingtechnik Martens (Optimal 1 bis 10)
Eddy current	0.5	2	-	Steinert	Datasheet "Steinert EddyC" Sorting of NE-metals
Eddy current	30	100	-	Sicon Technology	https://sicontechnology.com/en/eddypro-inp/
Eddy current	12	100	-	Sicon Technology	https://sicontechnology.com/en/eddypro-inp/
Eddy current	0.2	12	-	Sicon Technology	https://sicontechnology.com/en/eddypro-inp/
Eddy current	0	100	-	Sense2Sort	https://toratecnica.com/machines/eddy-current-separator/
Eddy current	3	150	-	Electronic Waste Management	Buch Electronic Waste Management; Kapitel Recycling and Recovery
Eddy current	3	150	-	WEEE Recycling Arda	Buch Arda
Eddy current	1	150	-	Einführung in die Kreislaufwirtschaft	Buch Einführung in die Kreislaufwirtschaft (Info Ratio 1:3 optimal)
Eddy current	6	100	-	Martens	Buch Recyclingtechnik Martens (Möglich aber auch bis 0,5 oder 2 mm (Exner))
S/F	10	20	1	Neue Herbold	Emailkontakt mit Abraham Peter von "Neue Herbold"
S/F	10	20	-	Sicon Technology	https://sicontechnology.com/wp-content/uploads/sicon_polyfloat.pdf
S/F	3	10	-	Remix Interim Report	Remix Interim Report
NIR	5	30	0,4-2	Steinert	Datasheet "UniSort Flake"
NIR	10	40	-	Steinert	Datasheet "UniSort BlackEye"
NIR	10	150	bis 250	Steinert	Datasheet "Steinert NIS"
NIR	10	50	ca. 2,3	Redwave	NIR SSI320 V320
NIR	5	12	2,5-3	Tomra	Emailkontakt mit Andre Lehmann von Tomra; Autosort
NIR	5	12	2,5-3	Tomra	Emailkontakt mit Andre Lehmann von Tomra; Autosort Flake
NIR	4	18	1-2	Meyer Rock 120Li NIR	http://www.shmeyer.com/products/rock-120li-nir-sorter-for-pet-pvc-flake-separation/
NIR	10	150	-	WEEE Handbook	Buch WEEE Handbook; Kapitel Mechanical methods of recycling
Visible	10	50	bis 1,5	Redwave	Redwave C

Sorting technique	Minimal input particle size [mm]	Maximal input particle size [mm]	Through-put [t/h]	Reference	Comments
Visible	0,5	100	-	Sense2Sort	https://toratecnica.com/machines/s2s-qolor-beltsense/
Visible	0,5	100	-	Sense2Sort	https://toratecnica.com/machines/s2s-qolor-slidesense/
Visible	0,5	20	-	Sense2Sort	https://toratecnica.com/machines/s2s-qolor-twinsense/
Visible	2	30	1-3	Meyer Rock 180F	http://www.shmeyer.com/products/rock-f-pet-flake-color-sorter/
Visible	2	30	2-5	Meyer Rock 300F	http://www.shmeyer.com/products/rock-f-pet-flake-color-sorter/
Visible	2	30	3-8	Meyer Rock 420F	http://www.shmeyer.com/products/rock-f-pet-flake-color-sorter/
Visible	10	150	-	WEEE Handbook	Buch WEEE Handbook; Kapitel Mechanical methods of recycling
XRF	10	120	0,5-150	Steinert	Datasheet "Steinert KSS LXF"
XRF	15	120	bis 30	Redwave	http://www.redwave.com/produkte/redwave-xrf/
XRF	12.7	100	-	nrt In-flight sorting	Datasheet of "TruSort with XRF"
XRF	10	120	-	Sense2Sort	https://toratecnica.com/machines/s2s-xrfsense/
XRF	6	20	1-1,5	Meyer Rock X90	http://www.shmeyer.com/products/rock-x90-x-ray-pet-pvc-separator/
XRT	4	100	bis 180	Steinert	Datasheet "Steinert XTS"
XRT	10	200	-	Steinert	Datasheet "Steinert XSS T"
XRT	25	152	2 bis 3	Sicon Technology	https://sicontechnology.com/en/sicon-libs-sorter/
XRT	10	40	-	Freegard 2007	Bericht "WEEE Plastics Separation Technologies" Scan and Sort, Hamburg Germany, Separation accuracy >99,5%
XRT	10	150	2,5-3	Tomra	Emailkontakt mit Andre Lehmann von Tomra; X-Tract
Terahertz	-	-	-	-	-
Polymer Tracing	-	-	-	-	-
MIR	-	-	-	-	-
MIR-T	-	-	-	-	-
LIBS	-	-	-	-	-
FT-IR	-	-	-	-	-

Annex E: Form to be filled from the pre-processors (blank)

(To be anonymized)		
Company		(name)
Full address of the plant		(address)
E-mail address contact person		(e-mail)
Phone number contact person		(phone number)
(Used confidentially)		
Product categories:		
Small household appliances		(yes/no)
Large household appliances		(yes/no)
Television screens		(yes/no)
Monitors		(yes/no)
Cooling and freezing equipment		(yes/no)
Washing machines and dryers		(yes/no)
Other, please specify		(description)
Manual sorting		
Components manually removed pre-shredder		(component(s) description)
Components manually removed post-shredder		(component(s) description)
Size reduction processes:		
Knife shredder		(yes/no)
Hammer mill		(yes/no)
Granulator		(yes/no)
Crusher		(yes/no)
Other, please specify		(description)
Sieving:		
Sieving size(s)		(max mech size in mm)
Metal sorting technology:		
Float/sink method		(yes/no)
Magnetic roller		(yes/no)
Eddy currents		(yes/no)
Other, please specify:		(description)
Plastic sorting technology:		
Float/sink method		(yes/no)
(Hydro)cyclone/centrifugal sorting		(yes/no)
Wet jig (shaking table)		(yes/no)
Dry jig (shaking table)		(yes/no)
Other density-based method (please specify)		(description)
(Froth) Flotation		(yes/no)
X-ray sorting		(yes/no)
Polarized UV-light sorting		(yes/no)
Other optical method		(description)
Dispersive Fourier Transform		(yes/no)
Diffraction grating Fourier Transform		(yes/no)
Laser-induced breakdown spectroscopy (LIBS)		(yes/no)
Laser-induced plasma spectroscopy (LIPS)		(yes/no)
Thermal infrared spectroscopy (TIR)		(yes/no)
Mid-infrared spectroscopy (MIR)		(yes/no)
Near-infrared spectroscopy (NIR)		(yes/no)
Other spectrographic method (please specify)		(description)
Electrostatic sorting		(yes/no)