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Feedstock mapping

Deliverable 1.6 of NONTOX project

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Abstract

This report addresses the treatment of End of Life Vehicles (ELV), Waste Electrical and Electronic Equipment (WEEE) and Construction and Demolition Waste (CDW) in EU with a special focus on plastics contained in these streams. The purpose of the study was to find out how the treatment of these target waste streams is performed in EU today, where the plastics in these streams are directed to, and what would be the possible potential for the NONTOX concept for increased recycling of plastics containing hazardous additives from these wastes. The overall objective of the NONTOX project is to increase the recycling rates of plastics waste containing hazardous substances, most notably brominated flame retardants (BFRs) by developing and optimising recycling processes to produce safe and high quality secondary plastic materials and by optimising the overall process economics by integration.

Based on public data and interviews with recyclers, the study arrived at rough estimates of 1.1, 0.7 and 1.7 Mt/a of plastics in ELV, WEEE and CDW streams in EU, respectively. Part of the target waste streams are today treated mixed with each other but also with other metal containing wastes, such as mixed metal scrap from industries and municipalities. The resulting plastics containing fractions from primary shredder metal recovery processes are often times very heterogeneous in nature, challenging plastic recycling from the shredder residues. Other challenges include the wide variety of polymers included in all of the waste streams, let alone a mixture of these.

The main route for plastics in the target waste streams today in EU is incineration or even landfill. Most plastics recycling is applied for WEEE, partly because of the polymer types used and partly because many WEEE streams are treated as mono streams for metal recovery purposes making the resulting non-metallic fractions less complex in nature.

As results from this study, the maximum potential feed for the NONTOX concept could be even around two million tonnes on a yearly basis based on waste amount collected today, but requiring however significant improvements in management and treatment chains of the target waste streams. Improved collection rate of WEEE in EU could quite obviously increase the chances of acquiring more feed materials into the NONTOX concept.

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Abbreviations

ABS	Acrylonitrile butadiene styrene
BDE	Decabromodiphenyl ether
BFR	Brominated flame retardant
CDW	Construction and demolition waste
EEE	Electrical and electronic equipment
ELV	End-of-life vehicles
EPS	Expanded polystyrene
CRT	Cathode Ray Tube
CRT-TVs	Cathode Ray Tube televisions
HIPS	High impact polystyrene
HBCDD	Hexabromocyclododecane
LDA	Large domestic appliances
LCDs	Liquid Crystal Display
PBDEs	Polybrominated diphenyl ethers, a regulated class of BFRs
PC	Polycarbonate
PCB	Printed circuit board
PE	Polyethylene
PFR	Phosphorus based flame retardant
POP	Persistent Organic Pollutant
PP	Polypropylene
PS	Polystyrene
PST	Post shredder treatment
PUR	Polyurethane
PVC	Polyvinyl chloride
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SDA	Small domestic appliances
SHF	Shredder heavy fraction
SLF	Shredder light fraction
TBBPA	Tetrabromobisphenol A
WEEE	Waste electrical and electronic equipment
XRF	X-ray fluorescence (spectroscopy)

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1. Introduction

This report is an output of NONTOX EU-project from Work Package 1, Sub-task 1.1.1 "Identification of main feed streams". The task will screen and identify the main waste streams in Europe relevant for NONTOX concept based on the existing literature, previous EU studies and European statistics and through contacts with the industrial partners handling ELV, CDW and WEEE. Focus is on three specific waste streams, namely construction and demolition waste (CDW), end-of-life vehicles (ELV) and waste electronic and electrical equipment (WEEE). The identified waste streams will be evaluated for preliminary estimate of the potential European feedstock for the NONTOX concept. An overview of current plastic recycling treatment methods and process chains are further explained in the deliverable D1.1 of the NONTOX project.

The overall objective of the NONTOX project is to increase the recycling rates of plastics waste containing hazardous substances by developing and optimising recycling processes to produce safe and high quality secondary plastic materials and by optimising the overall process economics by integration. Increasing recycling rates is crucial for the implementation of a circular economy as clearly stated in the EU Plastic Strategy. According to recent statistics, plastic recycling rates are still too low, especially for the ELV and WEEE in comparison to the targets set by EU in the EU Directives for 2020. With an average plastics content of about 30% in the WEEE, the recycling and recovery of this material is a key issue in achieving recycling rates from 50% to 75% and recovery rates from 70% to 80% of WEEE as stated in the Directive (Plastics Composition of WEEE and Implications for Recovery-European Commission report).

NONTOX focuses on the removal of hazardous and undesired substances, with a focus on especially brominated flame retardants, from plastic waste taking into account the whole value chain: sorting and pre-treatment techniques, recycling technologies but also post-treatment techniques. Valorisation of by-products and removed substances is also considered to enhance potential applications. NONTOX will target material recovery of plastics originating from WEEE, ELV and C&DW streams. Main secondary plastic outputs will include for example, ABS, EPS, PS, HIPS, PE, and PP. On the other hand, PVC is not included in NONTOX target polymers (although mixed plastic streams with PVC as a minor contaminant may however be considered in NONTOX). The market for these polymers is massive as together they represent about half of the EU demand for plastics and yet a significant portion of these valuable plastics is landfilled or incinerated. In NONTOX, innovative sorting and pretreatment techniques, recycling technologies, valorisation of by-products and safe disposal of removed substances are developed (Figure 1). NONTOX will further develop two different technologies (Extruclean and CreaSolv®) to remove hazardous substances allowing for increased recycling rates. Thermochemical conversion of non-target plastics and side streams from the main recycling processes will be investigated to increase system efficiency by integration and widen the range of final products and applications. NONTOX is comprised of a multidisciplinary consortium including internationally renowned RTOs, universities, key industrial partners and recyclers as well as product design experts.

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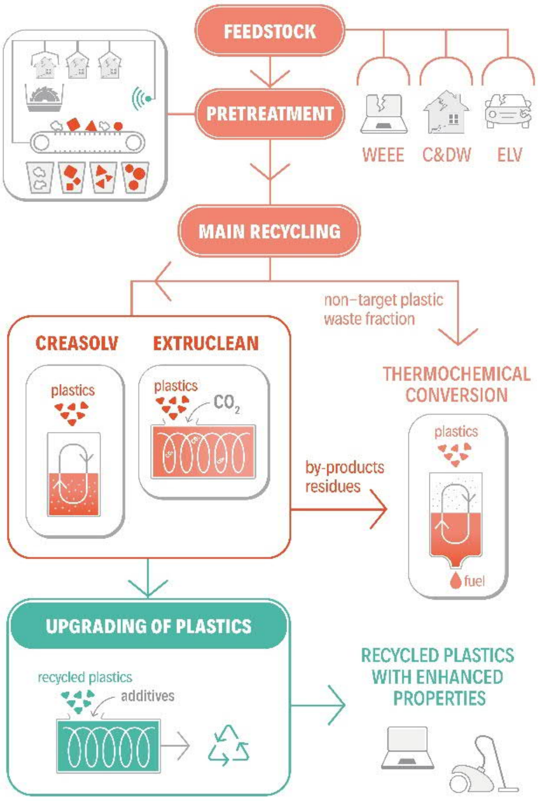

Figure 1. Process scheme of NONTOX project concept

This report addresses the current volumes and treatment of Waste Electrical and Electronic Equipment (WEEE), End of Life Vehicles (ELV) and Construction and Demolition Waste (CDW) in Europe with the focus on the plastics contained in these waste streams. Some plastics in these waste streams are of high value and are attractive for mechanical recycling processes. On the other hand, many plastics in these waste streams are worn out, consist of mixtures of hardly separable different types of plastics, and/or contain also harmful contaminants, such as brominated flame retardants restricted and also prohibited by POP (EC 2019/1021), and by REACH (EC 1907/2006) regulations. According to the EU POP regulation, materials containing regulated compounds, or which contain restricted substances in amounts that exceed the given limit values, must be removed from circulation and safely disposed of.

The aim of this study was to find out which of the current plastic containing fractions in the above mentioned waste streams could be attractive for the proposed NONTOX concept. Therefore, this study is limited to the perspective of these waste streams in Europe as well as the NONTOX recycling concept. Potential target waste streams could include plastic containing fractions that are today sent to e.g. incineration to dispose the POPs, or even landfilled. On the other hand, the goal was also to look for plastic containing streams that are today recycled, but for which the current routes might not be as viable or attractive due to for example negative price, i.e. recycling company has to pay to get rid of the material.

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This report also takes into account the overall objective of NONTOX project, which is to increase the recycling rate of hazardous plastic waste from these target waste streams and upgrade them to be used in primarily high-value applications. Therefore, most focus is put on the hazardous plastics containing fractions arising from these waste streams.

Many of the WEEE streams in Europe today are treated as separate streams without mixing into other waste streams. That is not the case for the other waste streams, which are merely treated as mixed with other waste streams. This is mentioned to highlight the complexity of the treatment scheme, meaning that also the plastics arising from the target waste streams are often times - to a large extent - mixed in the treatment process into plastics and other light materials coming from other waste streams. Figure 2 is a rough illustration of the treatment of at least some of the target waste streams today based on authors' understanding and e.g. interviews with recycling companies. For CDW this illustration is only applicable for the metal containing fractions, which are directed to a shredder process.

Especially ELV- and WEEE-streams contain metals which are their most abundant and valuable "ingredients". The primary processes for treatment of these target waste streams are developed for metal recovery and not for plastic recovery.

Mixed metal containing wastes from industries and municipalities (Figure 2), that often times contain CDW as part of the stream in recyclers' documentation, can constitute even 70-80 % of the mass of the feed to a shredder plant (interviews with recyclers). The shredder plants are often operated with mixed feed, and therefore e.g. plastic fractions from ELVs cannot be separated as such using current pre-treatment technologies, or this is not economically feasible.

The treatment operations of target waste streams are geographically scattered in Europe. To the best of our knowledge, up to date (2020) information was not found on the current situation. According to Mehlhart et al. (2018) in 2014 there were 354 "automotive shredders" in Europe, which ELVs but also large appliances and mixed metal scrap from municipalities and industries. Therefore, it was challenging to form a current overall view of the European treatment operations of these waste streams.

In addition, most studies investigated for this report to evaluate the plastic containing fractions from ELV waste streams were carried out so that the ELV was the only feed to the shredder process (e.g. Vermeulen et al. 2011). Yet, the reality is that ELVs are typically fed in to the shredder as mixed waste streams together with e.g. large household appliances and mixed metal scrap from municipalities and industries, not as monostreams. Also, information available for plastics in CDW is largely case-dependent and as concluded in several studies (Wahlström, et al. 2019; Iacoboaea, et al., 2019; EEA, 2020) the waste stream is underutilized and there is a lack of available data.

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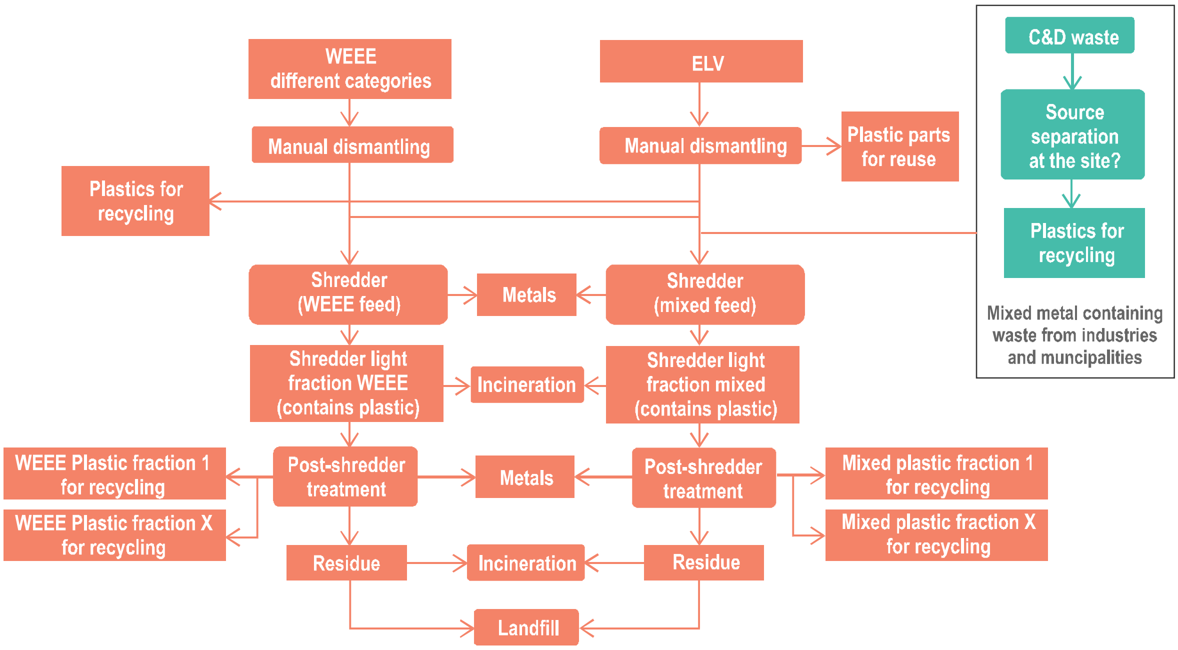

Figure 2. Visualisation of typical treatment of target waste streams in Europe (based on e.g. communication with recyclers).

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2. Objectives and methods

The specific objectives of this task and report were to (1) evaluate the volumes and current treatment routes of WEEE, ELV and CDW plastics in Europe, (2) assess the attractiveness of the current recycling routes and, most importantly, (3) identify the plastic waste streams currently not recycled or otherwise potential for the NONTOX concept.

To evaluate the current volumes and routes of WEEE-, ELV-, and CDW plastics in Europe, existing literature, previous EU studies (EU projects, other research) and European statistics were analyzed. Also interviews were carried out with industrial partners handling especially the WEEE waste fractions. Specific goal was to identify the volumes and current routes regarding the targeted waste streams from the following perspectives:

- reuse
- recycling (sorts of plastics, means of recycling)
- energy recovery
- landfill disposal

The attractiveness, or rough feasibility, of the current plastic recycling routes of the targeted waste streams was studied to assess what kind of boundary conditions and opportunities could exist for the NONTOX concept. For the identification of boundary conditions, evaluation of the current situation in regards to the quality and e.g. polymer types was carried out. To evaluate the opportunities for the NONTOX concept, it was important to formulate an overview of what kind of polymers and qualities currently are not recycled or utilised well and assess whether they could be potential waste streams, e.g. volume wise, for the NONTOX concept. Especially tapping into the potential in non-recycled plastics through analysing their material flows in Europe is crucial to further contribute to the implementation of EU-wide circular economy strategies and especially the set plastics recycling targets. Yet, it is important to acknowledge the potential opportunities as well as boundaries or bottlenecks the non-recycled plastics may create or have in regards to the concept.

The study was conducted by using publicly available data regarding the volumes (e.g. Eurostat) and compositions of the target waste streams from previous studies. Regarding the current treatment schemes, both publically available data and specified data gathered from project partners, that is the recycling companies in this case, were used. Also, information available within the NONTOX project, e.g. compositional analyses made on waste samples, were used to assess the potential of the target streams for the NONTOX concept. The main goals and methods for data gathering are summarised in Table 1.

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Table 1. *Goals and methods for data gathering in mapping of NONTOX feedstock.*

Goal	Used methods
Identify the target waste streams for NONTOX. Find out the volumes and more specifically plastic volumes and compositions of target waste streams.	Eurostat, previous studies
Find out where plastics in target waste streams are directed today in Europe.	Previous studies, data acquired from recycling companies
Investigate by what criteria are the decisions in treatment of plastics containing fractions being made, e.g.: Given property like density Previous knowledge on material composition Regular measurements on e.g. Br-content	Previous studies, data acquired from recycling companies
The attractiveness of the current recycling routes for plastic containing fractions Positive or negative cash flow in relation to given plastic containing fraction	Data acquired from recycling companies

A data gathering template was used to acquire first hand information from recyclers, the recyclers were also interviewed for further information and analyses. The data filled into the templates by recyclers are confidential and are not publicly available. The data gathered are used to draw conclusions related to the potential feed materials to the NONTOX concept in the future. Principle of the data gathering from recycling companies is shown in Figure 3.

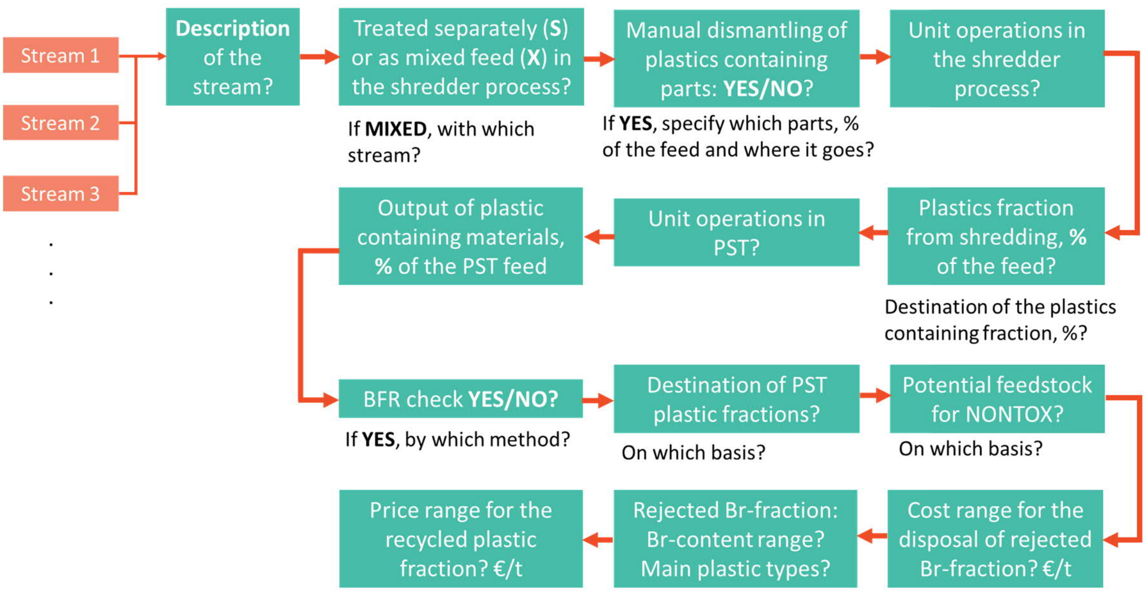

Figure 3. Principles of the data gathering from recycling companies.

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3. Volumes and treatment of target waste streams in Europe today

Plastics is the term commonly used to describe a wide range of synthetic or semi-synthetic materials that are used in a huge and growing range of applications. Plastics are not just one material, but are instead a whole family of hundreds of different materials, designed to meet the needs of each single application in the most efficient way possible. The plastics are split in two main categories: thermoplastics and thermosets (Figure 4).

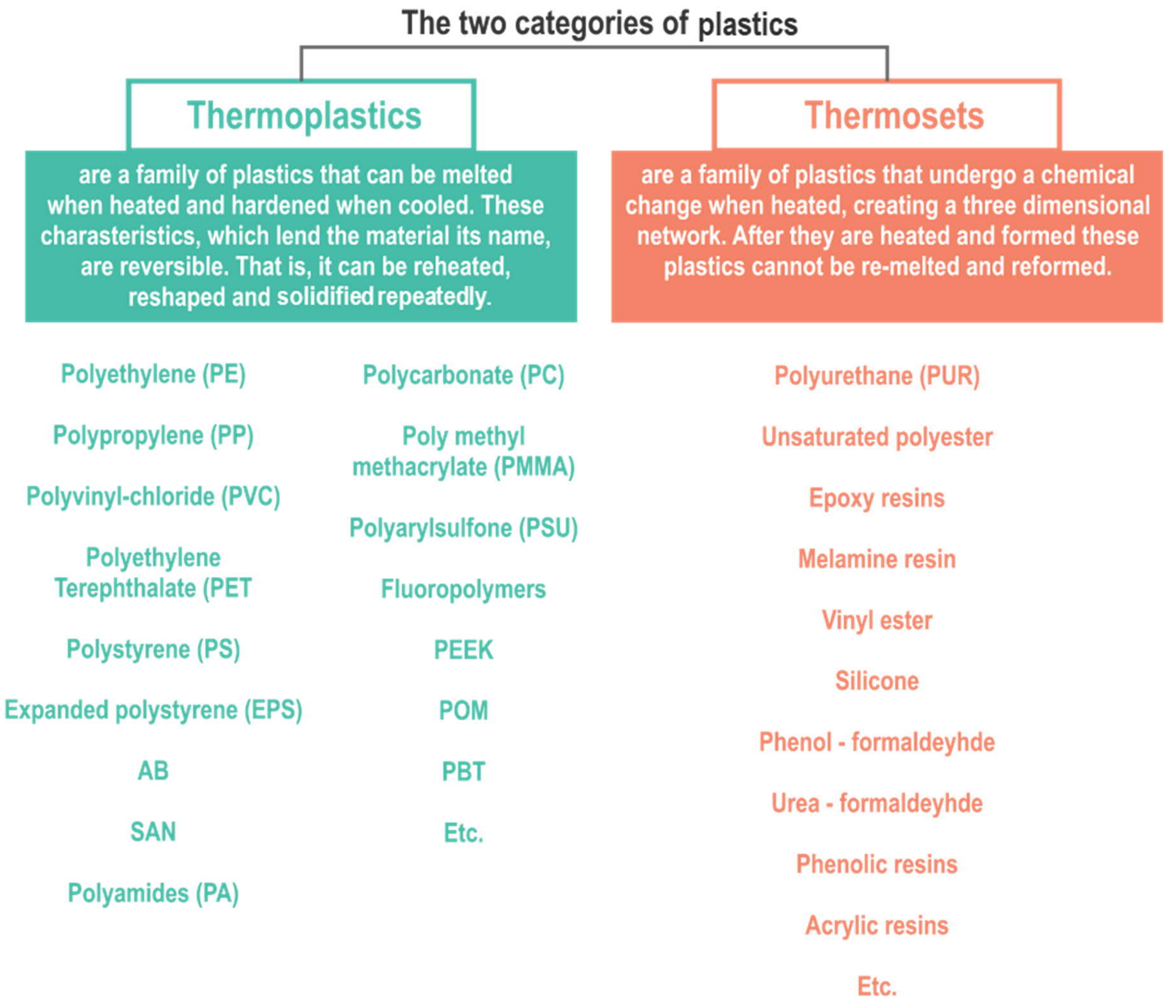

Figure 4. Thermoplastics vs Thermosets (based on Plastics Europe 2018)

Cars, electronics and electrical equipment and products in the construction sector use considerable amounts of plastics. The advantage of using plastics instead of e.g. metals, reduce the weight of applications and also the thermoformability allows for construction of products in different shapes and sizes that would not otherwise be possible. The annual plastic demand in Europe is 51.2 million tonnes, of which plastics used in electrical and electronic products count for 6.2% (e.g. about 3.2

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million tonnes). Combined with the automotive industry, these two sectors use nearly 16.1% of plastics, which equals 8.2 million tonnes per year (Plastics Europe 2019). Packaging and Building & Construction represents by far the largest end-use market, the third biggest end-use market is the Automotive Industry Figure 5).

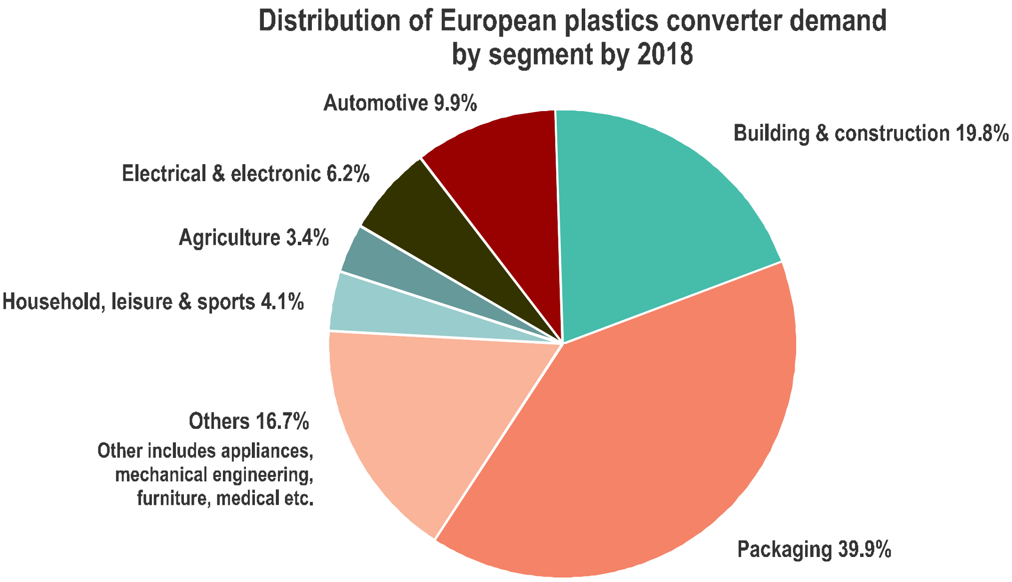

Figure 5. Distribution of European plastics converter demand by segment in 2018. Based on data from Plastics Europe (2019).

Recycling of plastics from the target streams is crucial in order to increase recycling rates and realize the circular plastics economy. The target material streams; ELV, WEEE, CDW, contain high amounts of legacy chemicals that can be hazardous, especially chemical additives like brominated flame retardants. However, chemical additives are critical as they are used to improve processing, functionality, safe use and longer lifetime. For example, the brominated flame retardants contain bromine, which effectively hinders the spread of flames. Typically, 10-30 weight-% of BFR is added to plastics where the risk of fire is high, e.g. heated appliances, circuit boards, insulation, cables, and so on. (Andersson et al., 2019) According to the Danish EPA, there have been more than 70 brominated flame retardant substances in the markets over the years; however, only about 30 are in commercial use after regulations and banning of several substances. The use of hazardous substances is regulated in both materials and products, e.g. via limits, to ensure safe use of plastics by making sure that the hazardous substances are not recycled and transferred into new products in a new life cycle. A more thorough analyses of the relevant regulations (e.g. RoHS directive, POPs regulation, REACH regulation, ELV directive) is carried out in Work Package 5 of the NONTOX project. Nevertheless, to comply with the regulations is to remove these substances during recycling process, if the set limit values are not met, the material needs to be disposed via incineration. It needs to be noted that the regulations for plastic waste is different outside Europe, which means that imported plastic products and materials could have higher quantities of regulated

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hazardous substances. Also, tightening the limit values seem to be a trend for regulating these substances in the EU. (Andersson et al., 2019)

Examples of the hazardous brominated flame retardants—the removal of which from the target waste plastic streams is among the specific objectives of NONTOX—include hexabromocyclododecane (HBCDD) and polybrominated diphenyl ethers (PBDEs), namely tetra-, penta-, hexa-, hepta-, octa-, and decaBDEs, which are all chemicals restricted by the Stockholm Convention on persistent organic pollutants (POPs). The legislative framework related to the field of recycling of plastic waste containing hazardous substances are however not in the scope of this report, since these topics are discussed in detail in Deliverable D5.1 of the project.

In the following subsections the ELV, WEEE and CDW target waste streams, their composition and volumes, relation to brominated flame retardants and also further treatments (also sorting) are separately described based on the available information. However, it is emphasized that there are limitations in the amount and comprehensiveness of the available data and research regarding the waste streams and their material flow analyses. It has been acknowledged in several studies, (Wahlström, et al., 2019; Andersson, et al., 2019; ProSUM, 2018), that there is absence of studies and available data on the current situation of legacy chemicals in recycled plastics from ELV, WEEE and CDW waste streams.

3.1. End of Life Vehicles

In the EU, the end of life management for automotive products like motor vehicles such as cars, vans, buses and trucks, is addressed by the End of Life Vehicles Directive. The amount of passenger cars and car ownerships has increased considerably, e.g. in EU-28 between the years 2000-2017, the growth has been on average 1.5 % per year and just in 2017-2018, the increase was over 2 % (ACEA, 2019). According to Eurostat, 5.3 million passenger cars and light goods vehicles were scrapped in 2017 (Eurostat, 2020). Furthermore, according to Eurostat, in EU-28 about 7.3 million tonnes of ELV was generated as waste in 2017. Average age of an End of Life Vehicle varies across Europe. As examples, France reported an average age of ELV in 2015 of 17.5 years and Germany in 2014 of 14 to 15 years (Mehlhart et al. 2018). For the purposes of this mapping study, an average age of 15 years is used for an ELV.

3.1.1. ELV composition and plastics volumes in ELVs

ELV composition varies depending on vehicle age, but also to a large extent by make and model. Table 2 presents examples of ELV compositions from some manufacturers (Bacher et al. 2017, data from Tian et al. 2016).

Table 2. Compositions of ELVs from some manufacturers (Bachér et al. 2017, derived from Tian et al. 2016)

Material, %	Daimler	Volkswagen	Ford	Fiat-Chrysler	Nissan
Ferrous metals	47	59	76	63	59
Non-ferrous metals	24	12	n.a.	10	14
Plastics	21	20	18	13	13
Fluids	n.a.	4.7	0.8	5	n.a.
Electronics	0.2	0.2	0.2	n.a.	n.a.
Other	7.5	4.4	5	9	14

Based on the example provided in majority of the materials in ELVs is ferrous metals (ranging from 47 to 76 %). Depending on the manufacturer, the share of non ferrous metals in this example range from 10 to 24 %. Also, the share of plastics in ELVs varies across manufacturers and in this case from 13 to 21 %.

According to Schönmayer (2017), the share of plastics in new cars was 14 % by mass on average in 2000 and 16 % by mass in 2010. Therefore, for the analyses in this report, it is justified to use a share of 15 % by mass for plastics for an ELV that was a new car in 2005 and reaches its end of life in 2020. Based on these estimations, it is our evaluation that 1.1 million tonnes of ELV plastics is generated in 2020 in EU-28 countries. Elsewhere, Slijkhuis (2015) presented similar figures with an estimate of 1.2 Mt/a ELV plastics generated.

Schönmayr (2017) shows an estimation of a plastic content of a 2015 ELV (Table 3). In addition, the same publication lists the components and parts in which these plastics are used in a typical car (Table 4).

Table 3. Estimation of plastic content in a 2015 ELV (Schönmayr 2017) and in total in the EU in 2017 (calculation based on Eurostat's estimation of 5.3 million passenger cars and light goods vehicles in 2017 (Eurostat, 2020)).

Plastic type	Share of specific polymer (%)	Amount of specific polymer in one car (kg)	Estimated amount of specific polymer in 5.3 million cars and light goods vehicles (million kgs)
PP	42	45	238.5
PU	11	12	10.6
PA/PC	8	8.5	45.1
ABS	7	7.4	39.2
PVC	7	7.4	39.2
Other	12	14	74.2
Total	100	106	561.8

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Table 4. Plastics used in a typical car (Schönmayr 2017)

Component	Main types of plastics	Weight in average car (kg)
Interior trim	PP, ABS, PET, POM, PVC	20
Seating	PUR, PP, PVC, ABS, PA	13
Bumpers	PP, ABS, PC/PBT	10
Under-bonnet components	PA, PP, PBT	9
Upholstery	PVC, PUR, PP, PE	8
Dashboard	PP, ABS, SMA, PPE, PC	7
Electrical components	PP, PE, PBT, PA, PVC	7
Fuel systems	HDPE, POM, PA, PP, PBT	6
Body (including panels)	PP, PPE, UP	6
Lighting	PC, PBT, ABS, PMMA, UP	5
Exterior trim	ABS, PA, PBT, POM, ASA, PP	4
Liquid reservoirs	PP, PE, PA	1
Total		105

Furthermore, the plastics distribution in cars by location is presented in Figure 6 (Plastics Europe, 2013).In the context of plastics recycling, the location is crucial as it has to do with how easy it is to dismantle plastics containing parts from ELVs. The ones located in the exterior of the vehicles, such as bumpers and gasoline tanks, are easier to dismantle in comparison to interior parts, even by using machinery.

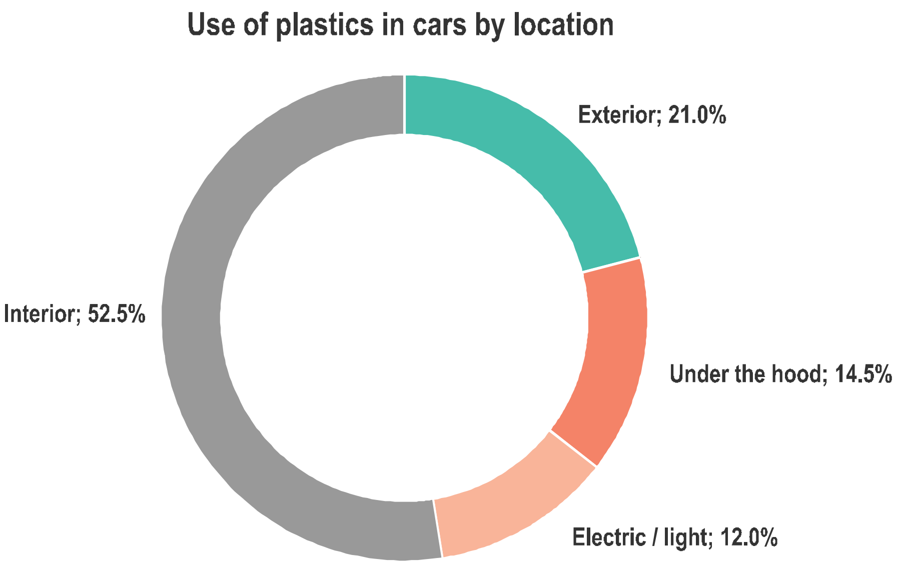

Figure 6. Use of plastics in cars by location (Plastics Europe 2013).

3.1.2. Treatment scheme for ELVs in Europe

Directive 2000/53/EC, the "ELV Directive" on end-of life vehicles lays down quantified targets for reuse, recycling and recovery of the ELVs and their components.

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- 85 % of the weight of vehicle shall be reused and recycled
- 95 % of the weight of vehicle shall be reused and recovered

Annex I (3) of the ELV-directive sets requirements for the "depollution" of an ELV, this is:

- removal of batteries and liquefied gas tanks,
- removal or neutralisation of potential explosive components, (e.g. air bags),
- removal and separate collection and storage of fuel, motor oil, transmission oil, gearbox, oil, hydraulic oil, cooling liquids, antifreeze, brake fluids, air-conditioning system fluids and any other fluid contained in the end-of-life vehicle, unless they are necessary for the re-use of the parts concerned,
- removal, as far as feasible, of all components identified as containing mercury.

In addition to this regulatory pre-treatment, part of the authorised treatment facilities remove parts from the ELVs based on their (anticipated) market for reuse.

The main driver in the treatment and recycling of metal-rich complex waste streams, such as ELVs has been the extraction of metals. As a consequence, the pre-treatment operations are often optimized for this purpose. However, changes in regulatory framework, such as the tightening requirements for the reuse and recycling rates for ELV (directive Se 2000/53/EC) in the European legislation, as well as the generation of markets for recycled plastics, have created interest towards the extraction of plastics from ELV waste streams.

According to Mehlhart et al. (2018) in 2014 there were 354 "automotive shredders" in Europe. Typical mass-share of ELVs in the mixed feed to a shredder process varies significantly, and no public data is available on European level on the shares of ELVs in the shredders' feeds. According to Buekens and Zhou (2014), ELVs represent only 20–30 % of the input and other feed materials are composed differently. Even lower shares of ELVs in the mixed shredder feed, between 10 and 20 % are also reported (reference: interviews with recycling companies).

After pre-treatment also referred to as de-pollution, and manual dismantling of parts and components to be reused or recycled, an ELV hulk enters a shredder process and is mixed with other metal containing waste streams at the latest upon feeding into the process. A typical shredder plant (Figure 7) consist as a minimum of a hammer mill followed by a cyclone that separates the shredded material into a shredder "light" fraction (SLF), which is sometimes referred to as "fluff", and a shredder "heavy" fraction (SHF). SLF is typically composed of light metal, paper, cardboard, various types of plastic, foam, textile, wires, wood and such, whereas SHF contains scrap iron, various non-magnetic metals, wires, high density plastic, and glass. Ferromagnetic metals are removed from both fractions by magnetic separators, while eddy-current separators are used to remove the non-magnetic metals. At some plants, a system for separation of different types of plastics may be installed. Typically, tanks containing liquid of different densities are used for density separation of plastics by polymer types. Alternatively, sensor-based sorting systems may be applied. Shredder residue is basically a mix of all rejected materials. As such, the composition of

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shredder residue is highly dependent on the recovery process and thus may vary significantly between the different plants. (Hyks et al. 2014).

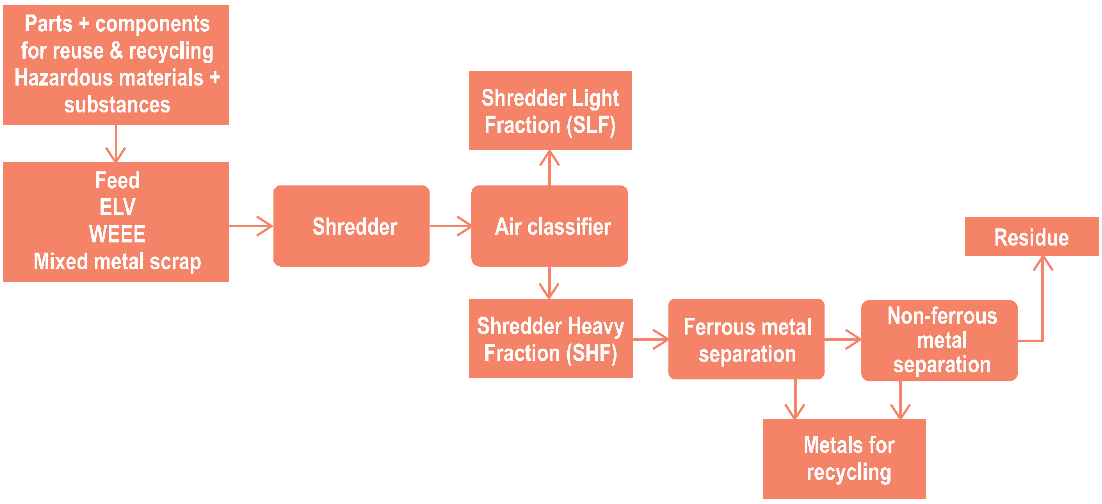

Figure 7. Visualisation of a typical primary shredder process for ELVs and other metal containing wastes.

As a "best practise" example of a real ELV treatment chain, the mass flow of plastics in ELV treatment from Auto Recycling Nederland (ARN) is shown in Figure 8. Almost 75 % of the plastics entering the shredder does not end in Post Shredder Plant (PST) plant but in incineration. The rest is fed to PST plant (post shredder technology is described further in 3.1.3) from which roughly 20 % is separated to recycling, while the rest is incinerated. Overall, roughly 8 % of all plastics is recycled and 18 % reused, while 74 % is incinerated in the entire system, taking into account also the amount outside the ARN system. Based on ABS, PUR and PS concentration assumptions (Leslie et al. 2013) in different streams, 16 % of ABS ends up in reuse fraction while 16 % and 68 % end in recycling and incineration, respectively. For the PUR distribution, the shares are 25 % reuse, 9 % recycling, 66 % incineration. As for PS: 18 % reuse, 8 % recycling and 74 % incineration. The figures should be looked at with critical mindset as they describe only one case that is most likely quite an ideal one with reference to general European level.

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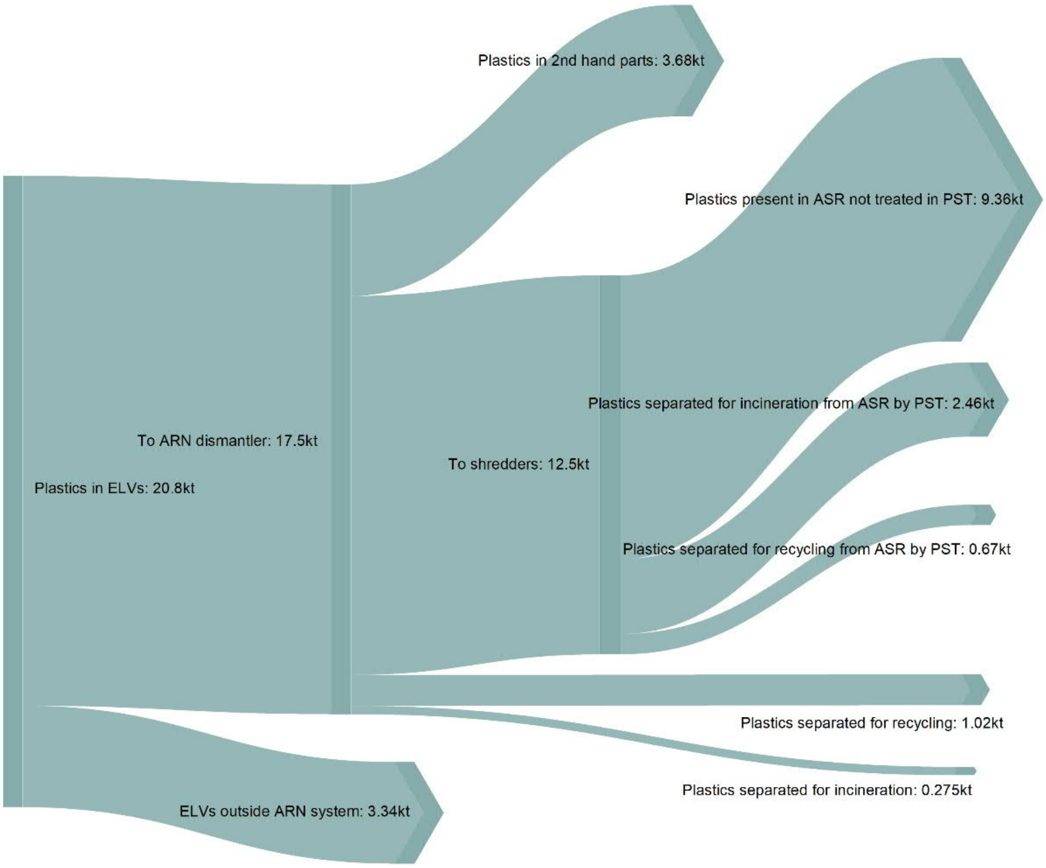

Figure 8. Plastics mass flows in ARN ELV treatment chain (Leslie et al. 2013).

Generally in EU, in 2011, the proportion of plastics from ELVs being recycled was low (European Commission DG ENV et al. 2011 ref Schönmayr 2017). The low rates imply that treatments other than recycling are predominant in the end-of-life process of automotive plastics. Possibly a best practise example can be found from the Netherlands where according to data by Leslie et al. (2013), around 8.1 % of ELV plastics were recycled, of which 4.9 % resulted from manual dismantling of plastics parts and 3.2 % from plastics recycling from PST.

In the context of the ELV Directive, several countries report voluntarily on the volume of dismantled large plastic parts as displayed in Table 5 (Mehlhart et al. 2018). According to the data, most of the volume dismantled is directed to recycling and less volume is directed to reuse. The total volumes of shredder light fraction generated are also displayed in Table 5. In addition, the percentage of dismantled large plastic parts of total shredder light fraction (+large plastic parts) is displayed. The percentage of dismantled large plastic parts by country differs between less than 1% and more than 40% of the sum of shredder light fraction plus dismantled large parts from dismantling.

Table 5. Large plastic parts dismantled from ELVs compared to shredder light fraction, in tonnes (Eurostat, ref Mehlhart et al. 2018).

	Disposal	**Energy recovery**	**Recycling**	**Reuse**	**Disposal**	**Energy recovery**	**Recycling**	**Dismantled**
	Large plastic parts from dismantling				**Shredder light fraction**			**%**
BE	0	0	218	1	1 469	3 323	5 259	2.1%
CZ (2104)			612		14 327	0	0	4.1%
DE	26	0	1 285	45	15 265	30 141	45 892	1.5%
EE	47	69	87	45	891	0	0	21.8%
EL	0	0	197	106	0	2 730	3 025	5.0%
ES	0	0	904	0	35 542	50 288	12 572	0.9%
FR		35	4 727		33 688	42 645	34 363	4.1%
HR			249		60	1 002	5 447	3.7%
CY			55		474	0	0	10.4%
LV	3	0	28	24	0	0	245	18.3%
HU	10	0	61	47	148	0	0	44.4%
AT	2		382	0	1 159	2 876	849	7.3%
PT	0	0	475	40	3 179	6 379	0	5.1%
SI (2014)	194	7	62	10	218	236	115	32.4%
SK	17	34	442	32	171	0	821	34.6%
IS	15	0	0	28	0	0	341	11.2%

3.1.3. Post-shredder treatment for Shredder Light Fraction (SLF)

Post-shredder technology (PST) is the further reprocessing of shredder residues. Some shredders have integrated PST or separate PST on site; other shredders send residues of the shredding process to offsite PST plants. Typical operations of PST are displayed in

Figure 9 below. PST is considered as a necessary operation to fulfil the recycling quotas defined by the ELV Directive (Mehlhart et al. 2018).

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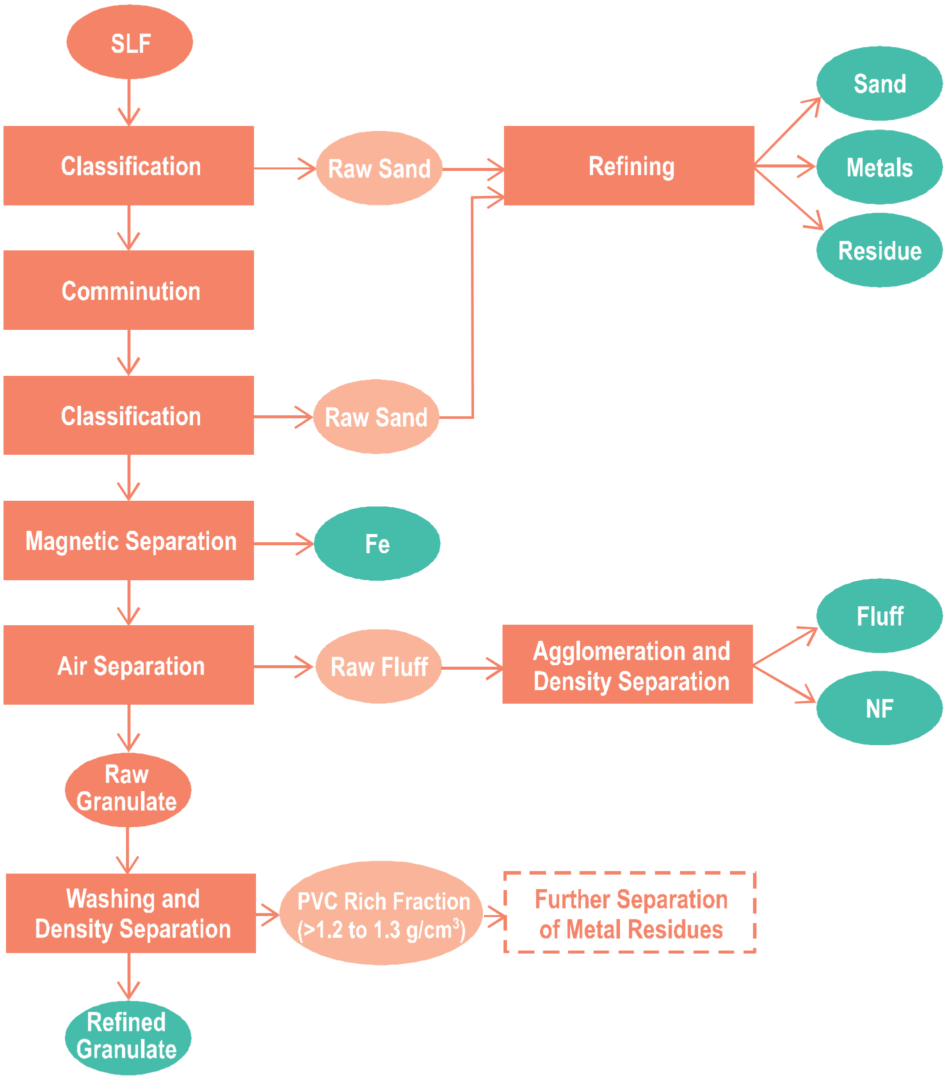

Figure 9. Visualisation of typical PST installation for the treatment of shredder light fraction (based on Mehlhart et al. 2018).

In general, according to Mehlhart et al. (2018), and as detailed in the NONTOX Deliverable D1.1, the most common PST are:

- Classification (size separation)
- Metals separation: Magnetic separation of ferrous metals, Eddy current separation of nonferrous
- metals, All-metal separators (for negative sorting of e.g. plastics)
- Density separation: air classification, ballistic separation, sink-float devices, air tables
- Sensor-based sorting for separation of different metals and alloys

3.1.4. Brominated flame retardants in ELV plastics

A number of different BFRs are commonly used in plastic vehicle components such as dashboards, including also in textiles. The purpose of adding BFRs to polymers is to both inhibit material ignition and slow the rate of possible combustion.

Extensive research has been made regarding the occurrence of restricted brominated flame retardants in ELV plastics (e.g. Mehlhart et al. 2018 & Leslie et al. 2013). In these studies, bromine content measured by XRF analysis has been used as an indicator for occurrence of brominated flame retardants. The results from measurements of PST plant output fractions have shown, that:

- Bromine content (detected with XRF) in shredder granulate < 1.1 g/cm^3 was on average low (202 mg/kg) and with very few outliers (2 samples out of 48, Figure 10). Separation technology to separate bromine-containing parts is in principle available, thus material recycling might be an option.

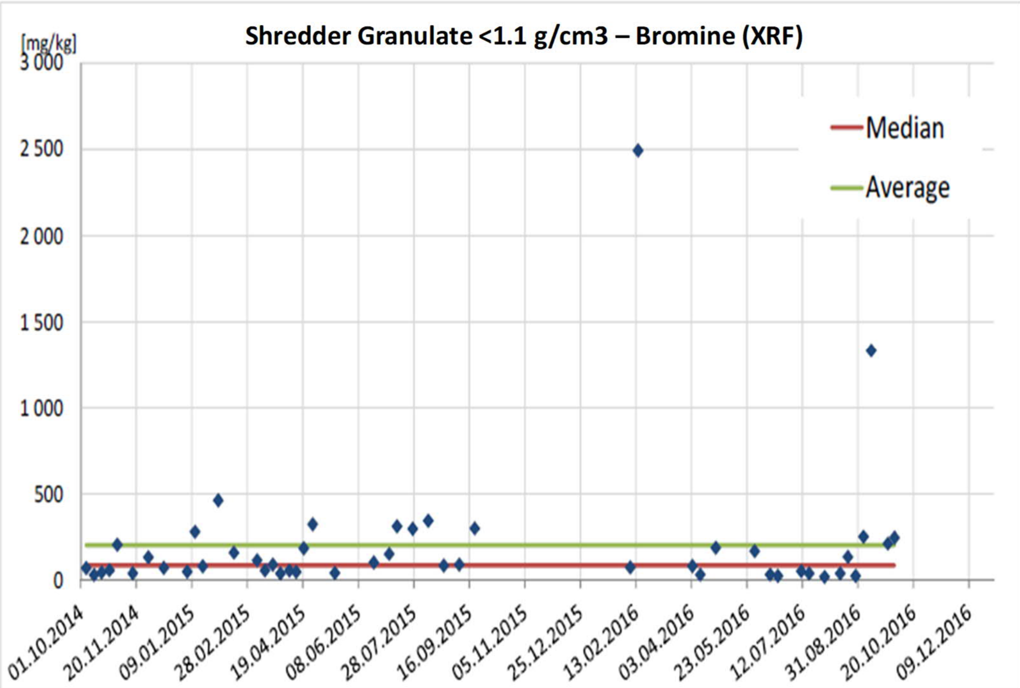

Figure 10. Bromine content measured by XRF in plastics granulate fraction <1.1 g/cm^3 from ELV PST plant. Reprinted with permission from Mehlhart et al. (2018).

- Bromine content in shredder granulate (detected with XRF) of > 1.1 g/cm^3 and < 1.3 g/cm^3 was comparatively high, as illustrated in Figure 11. As a consequence, the use as a secondary raw material for new products (material recycling) is not favourable. Moreover, the mixture of different sorts of plastics in this fraction would not allow material recycling without material specific separation. However, it can be used as a reducing agent in a blast furnace (feedstock recycling).

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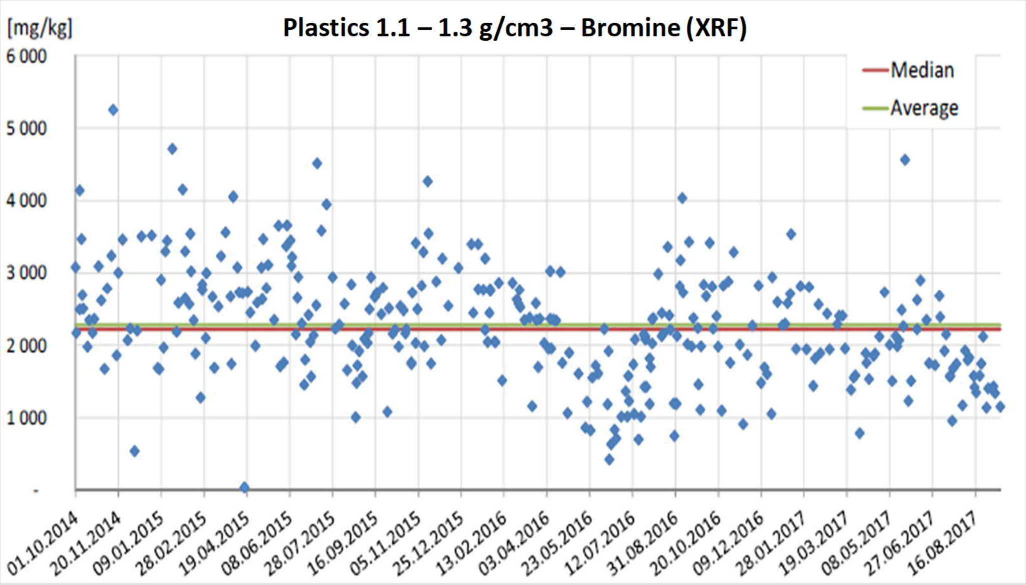

Figure 11. Bromine content by XRF in plastics 1.1-1.3 g/cm^3 from ELV PST plant. Reprinted with permission from Mehlhart et al. (2018).

- Bromine content (detected with XRF) in shredder granulate sized > 1.3 g/cm^3 was, as expected, on average fairly high and it is known to contain halogenated mixed plastics (e.g. PVCs), see Figure 12. Due to its high chlorine content, which would result in corrosion in the furnace, this fraction is normally not accepted for the use as a reducing agent in metallurgical processes. It can either be sent to waste incineration (energy recovery or thermal disposal) or (after further treatment) could be introduced into chemical recycling.

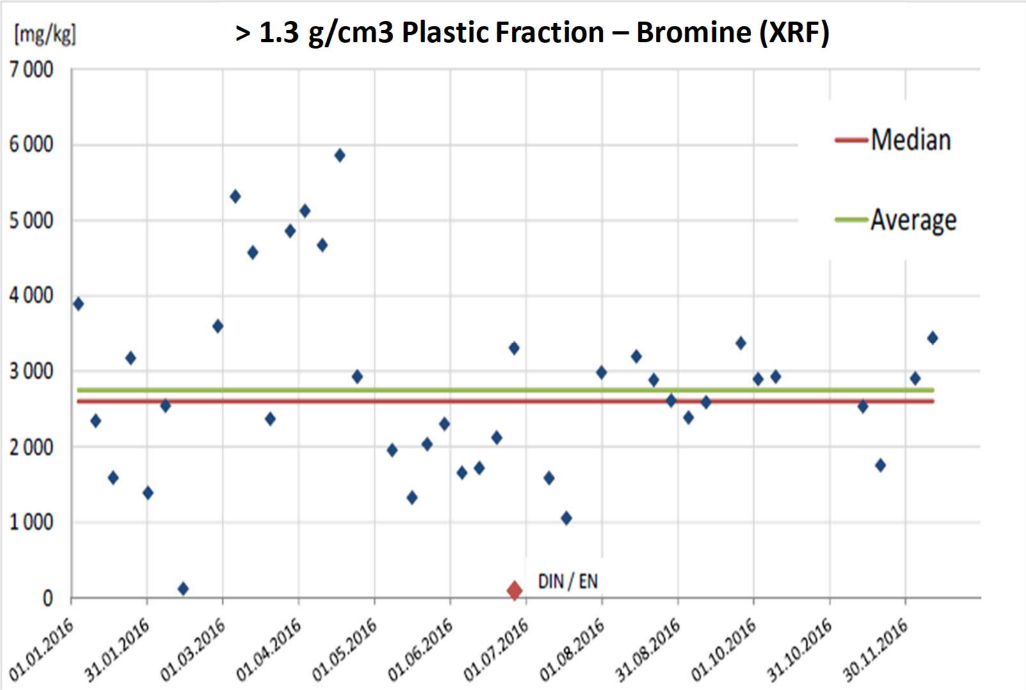

Figure 12. Bromine content measured by XRF in plastics >1.3 g/cm3 from ELV PST plant. Reprinted with permission from Mehlhart at al. (2018).

It needs to be noted, however, that the studies presented above present a quite advanced case, where input material for the PST-installation originates mainly from the automotive sector including some WEEE flows (Leslie et al 2013).

3.2. Waste Electronics and Electrical Equipment (WEEE)

WEEE is a complex mixture of materials and components that — because of their hazardous content— can cause major environmental and health problems if not properly managed. To address problems related to the damages caused by an improper management of WEEE, the European Commission has published, in 2002, the Directive on waste electrical and electronic equipment (WEEE Directive 2002/96/CE). The first WEEE Directive (Directive 2002/96/EC) entered into force in February 2003. According to the Directive, producers have the responsibility of managing the end-of-life of electronic products.

Directive 2002/96/EC, repealed on 15 February 2014, was replaced, in 2012, by the new WEEE Directive 2012/19/EU to tackle the fast growth of this stream. The recast Directive 2012/19/EU has introduced a stepped increase in collection targets for years 2016 and 2019. Furthermore, from reference year 2018 onwards, the scope of the Directive has been extended to all categories of EEE. Based on the scope, EEE have been categorized in six streams according to Annex III of the document:

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1. temperature exchange equipment;
2. screens, monitors, and equipment containing screens having a surface greater than 100 cm^2;
3. lamps;
4. large equipment (any external dimension more than 50 cm) including, but not limited to: Household appliances; IT and telecommunication equipment; consumer equipment; luminaires; equipment reproducing sound or images, musical equipment; electrical and electronic tools; toys, leisure and sports equipment; medical devices; monitoring and control instruments; automatic dispensers; equipment for the generation of electric currents.;
5. small equipment (no external dimension more than 50 cm) including, but not limited to: Household appliances; consumer equipment; luminaires; equipment reproducing sound or images, musical equipment; electrical and electronic tools; toys, leisure and sports equipment; medical devices; monitoring and control instruments; automatic dispensers; equipment for the generation of electric currents.
6. small IT and telecommunication equipment (no external dimension more than 50 cm).

According to recyclers, the collection of WEEE is often times organized slightly differing from the official according to the following streams:

1. Cooling appliances
2. TV and Monitors
3. Lamps
4. Large household appliances, including e-bikes and solar panels
5. Big IT appliances
6. Small IT appliances

3.2.1. WEEE volumes and composition

Waste of electrical and electronic equipment (WEEE) is one the fastest growing waste streams in the EU, with some 12.3 million tonnes generated in 2016 (and 44.7 million tonnes worldwide), and expected to grow to more than 52.2 Mt in 2021 worldwide (Global e-waste monitor 2017).

According to Eurostat (2020), in 2017 some 3.7 million tonnes of WEEE was collected in Europe. Figure 13 shows trends in the amount of electrical and electronic equipment (EEE) placed on the market and WEEE collected and treated in the EU in the years from 2010 to 2017. During 2016 and 2017, the volumes collected and treated in EU are close to equal. From 2016 to 2017, the amount of EEE put on the market in the EU increased by 6.5% from 8.4 million tonnes to 8.9 million tonnes.

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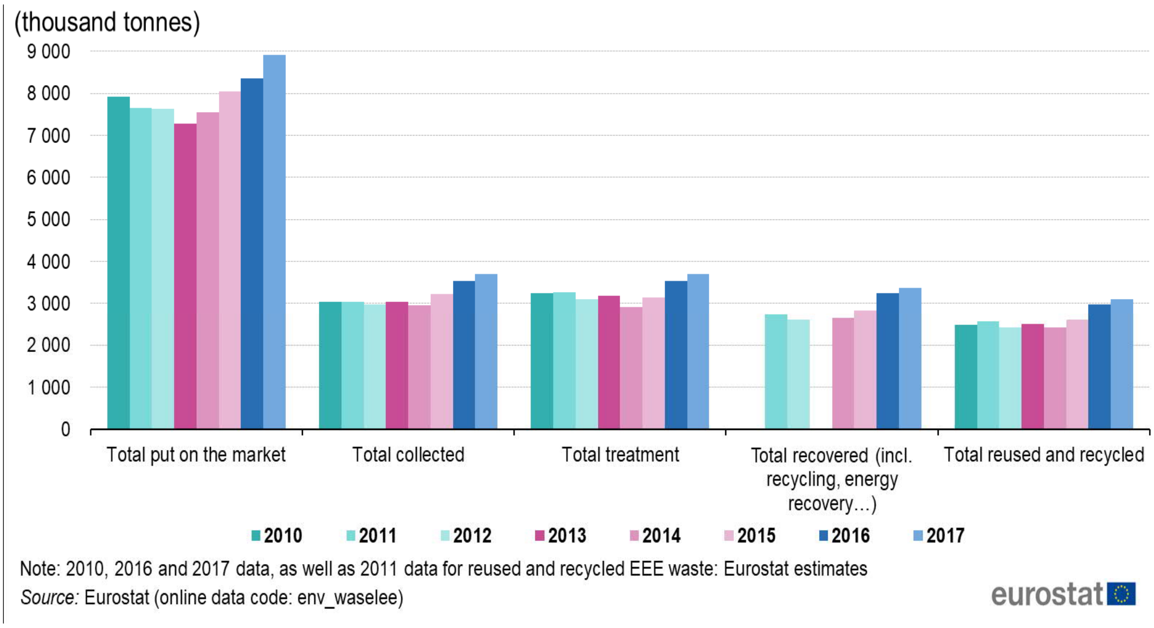

Figure 13 Electrical and Electronic Equipment (EEE) put on the market & WEEE collected and treated in EU, 2010-2017 (thousand tonnes, Eurostat 2020)

Figure 14 shows the distribution of EEE placed on the market in Europe per country and category. Large household appliances (category 1) is the dominant product category in Europe. In 2017, the proportion of total EEE put on the market ranged from 40.9 % in Germany to 72.4 % in Bulgaria, at EU level, large household appliances accounted for 52.4 %. IT and telecommunication equipment (category 3) were the second largest product category in most countries, accounting for between 5.0 % in Bulgaria and 16.2 % in Austria, with an average share of 11 % at EU level. At EU level, Small household appliances (category 2) ranked third with a 9.8 % share and Consumer equipment (category 4) fourth with an 8.0 % share (Eurostat 2020).

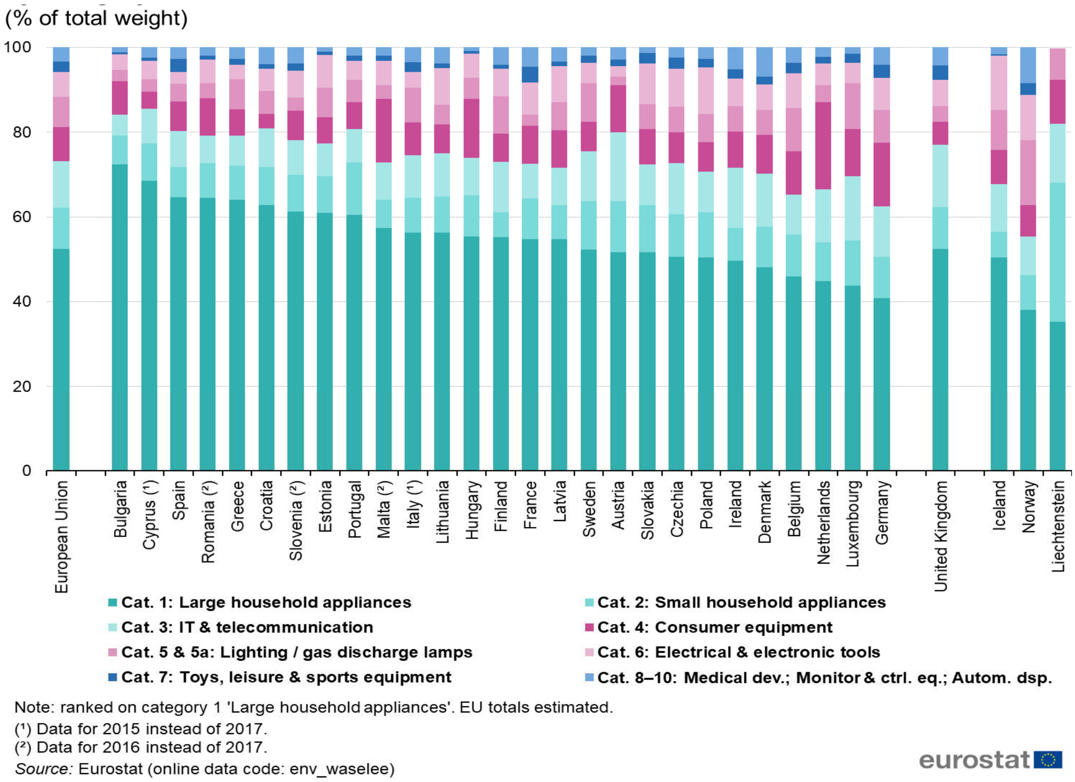

Figure 14. EEE put on the market, by category, 2017 (% of total weight, Eurostat 2020)

In 2017, the collected WEEE varied across the EU Member States, from 2.4 kg per inhabitant in Romania to 14.1 kg per inhabitant in Sweden. Figure 15 shows the shares of WEEE collected in percentages of EEE put on the market (in three preceding years). On average, the collection rate was about 46 %.

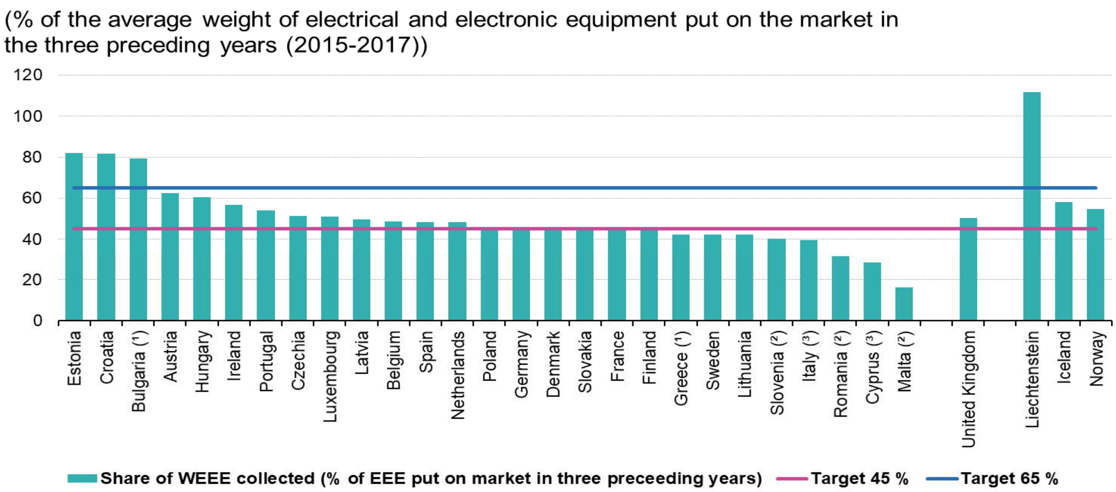

Figure 15. WEEE collected in 2017 across the European Union (EU) and EFTA countries (Eurostat 2020).

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The composition of WEEE, due to the vast range of different equipment and appliances, is truly heterogeneous with significant variations. Therefore, a detailed material composition analysis of the entire waste stream is difficult to do (Bacher et al. 2017). As reference, material composition of WEEE based on a study commissioned by European Commission (Seyring et al. 2015) is shown (Table 6) combining data on material composition of EEE and WEEE from several studies and annual reports from producer compliance schemes. The ranges shown in Table 6 are for five of the six WEEE categories (lamps excluded).

Table 6. Average WEEE composition ranges based on Seyring et al. (2015).

	Ferrous metals, %	Non ferrous metals, %	Plastics, %	Glass, %	Other, %
Share	20 - 45	6 - 16	10 - 51	0 - 27	21 - 29

Examples of plastic contents in some WEEE categories are shown in Table 7 (Slijkhuis 2015). Plastic content in these categories varies between 20 and 30% (Slijkhuis 2015). The plastics composition varies a lot, but an example of the breakdown from WEEE from a slightly older study is shown in Figure 16 (Freegard 2006).

Table 7. Plastic Content in WEEE per category (Slijkhuis 2015).

WEEE Category	Plastic content %
SDA	30%
LDA	15%
ICT	20%
Tools	10%
Temp Control Equipm.	25%
Screens	20%

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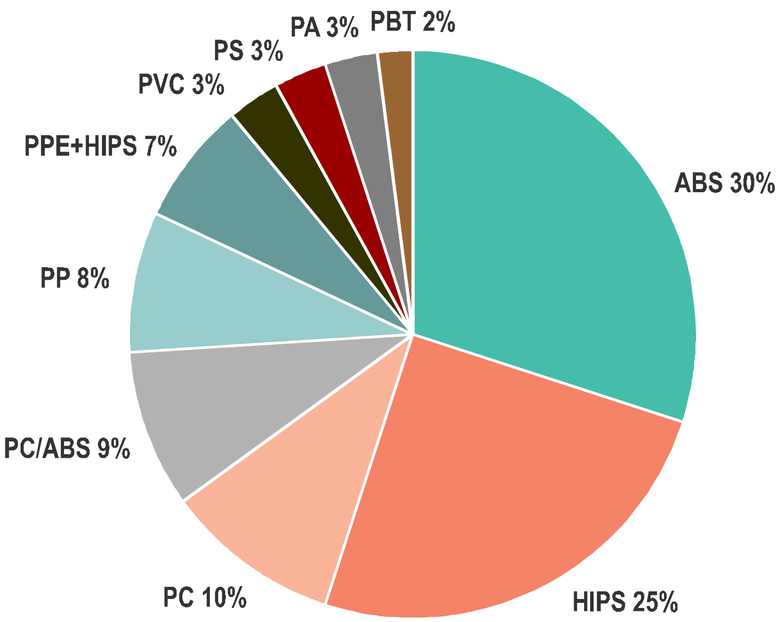

Figure 16. Typical Plastics Composition in WEEE (based on Freegard et al. 2006)

A more detailed composition investigation made by Wäger et al. (2010) on the plastic polymeric matrix of WEEE by category is presented in the Figure 17. In conclusion, the most common plastic polymers in WEEE are HIPS, ABS, PP and PC-ABS.

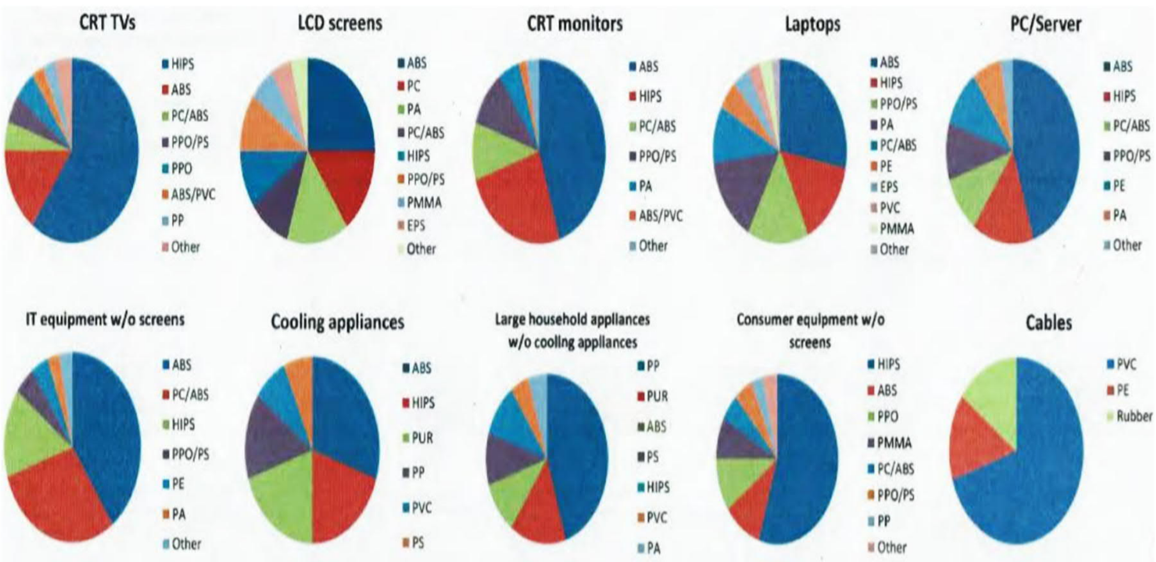

Figure 17. Plastics composition by polymer and by WEEE Category (Wäger et al. 2010)

The average composition of WEEE has been estimated from the data elaborated by NONTOX partner Ecodom based on data from WEEE Forum, Reptool 2018+ software and Prosum-project database and on the results of the analysis made by NONTOX partner Fraunhofer on WEEE samples collected by several partners (Figure 18). It should be noted that the WEEE plastics composition

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presented is based on separate studies conducted and might not represent the general EU level WEEE plastics composition schematics.

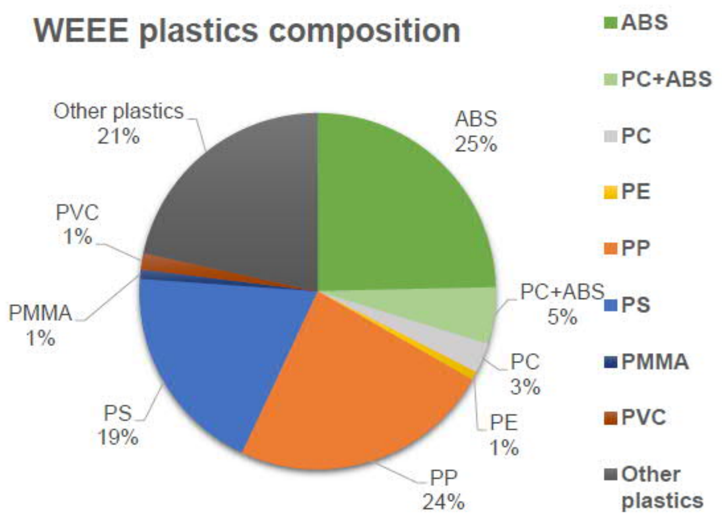

Figure 18. Plastics Composition in WEEE as found out in NONTOX project. Partly based on data from (Key Figures - WEEE Forum, 2019), (Reptool 2018+ software) and (ProSUM EU project, 2018). Data refined based on input from NONTOX recyclers.

The WEEE plastics waste stream and further the plastics composition is aggressively changing. The product lifetimes are much shorter compered to e.g. ELVs and CDW. There are continuous changes in product design and additionally, totally new products can be found frequently. Tablet computers or smart watches can be considered as recent examples of new electronic devices, let alone new emerging products such as smart textiles which are currently being actively developed. Consequently, the WEEE streams have changed over the last 8-10 years – especially, the average amount of High-Impact PS has reduced considerably and an important reason is the disappearing CRT fraction as well as the replacement of HIPS by PC and PC/ABS in particularly Flat Panel Displays and the Set-Up boxes and modems. Also, the content of PP in Household Appliances has increased. (Based on interviews with NONTOX recyclers).

Table 8 shows the quantities of WEEE collected in Europe in 2017 and the estimated amount of mixed plastics. The data were elaborated starting from data provided by NONTOX partner Ecodom and information available in technical annual reports and specific Reptool database (WEEE Forum).

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Table 8. Estimates of amounts of WEEE collected and mixed plastics obtained from collected WEEE for each category in Europe in 2017. Estimates are derived by NONTOX partners.

	Temperature exchange equipment	Large equipment	Screens and monitors	Small equipment	Lamps
WEEE collected from EU Collective Schemes (t/year)	693 000	1 230 000	452 000	1 082 000	35 000
Mixed plastics (t/year)	99 800	172 000	80 500	379 000	1 640

Finally, considering the data available in the document "The Global E-waste Monitor 2017" it is possible to estimate the amount of WEEE generated in Europe in 2016. According to the data available from that report, more than 9 million tonnes of WEEE have been generated in 2016. The WEEE generated per category can be calculated using the data provided by the "Urban Mine Platform" developed by the EU funded project ProSUM (www.prosumproject.eu). Even in this case the amount of mixed plastics containing in the e-waste generated has been estimated, all data are available in Table 9.

Table 9. Amount of WEEE generated and estimation of mixed plastics obtained from generated WEEE for each category, in Europe in 2016. Estimates are derived by NONTOX partners.

	Temperature exchange equipment	Large equipment	Screens and monitors	Small equipment	Lamps
WEEE generated in Europe (t/year)	2 100 000	3 100 000	951 000	2 920 000	57 700
Mixed plastics (t/year)	276 000	396 000	155 000	934 000	2 480

On the other hand, slightly different figures of collected plastic waste from EEE sources in the EU is estimated to be around 1.2 million tonnes per year (EERA 2017). According to the data, reuse of post-consumer recycled (PCR) plastics in EEE is estimated below 1% (RDC Environment, 2017). The lack of harmonisation across the member states in the reporting of volumes of collected WEEE in particular also for the split of total WEEE volume to individual collection categories can lead to discrepancies between the quantity of waste generated and the quantity collected (ProSUM, 2018).

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3.2.2. Treatment schemes for WEEE in Europe

The main driver in the treatment and recycling of metal-rich complex waste streams, such as WEEE has been the extraction of metals. As a consequence, the pre-treatment operations are often optimized for this purpose. However, changes in regulatory framework, such as the tightening requirements for the reuse and recycling rates for WEEE (directive 2012/19/EU) in the European legislation, as well as the generation of markets for recycled plastics, have created interest towards the extraction of plastics from ELV waste streams.

Typical WEEE treatment, as shown in the Figure 19 below, includes the following steps:

1. Manual sorting of the entering WEEE stream in categories. Manual Dismantling is divided into depollution to recover hazardous components (mercury in the batteries, CFC in the Refrigerators) and non-valuable materials to be eliminated by a careful disposal, and the removal and recovery of the valuable components (e.g. PCBs).
2. Shredding of WEEE to reduce big pieces into small particles in order to liberate metals from plastics and wood.
3. Low-intensity Magnetic Separation to recover ferrous metals (e.g iron scraps).
4. Eddy current to recover non-ferrous metals and inert (mixed material mainly shredded plastics)
5. Optical sorting to recover PCBs or to the separation of brominated from non-brominated plastics.
6. Other separation technique: air table, screening, image processing, X-Ray sorting, electrostatic sorting, dry density separation etc. to optimize the separation of the plastics for the other impurities (within inert).

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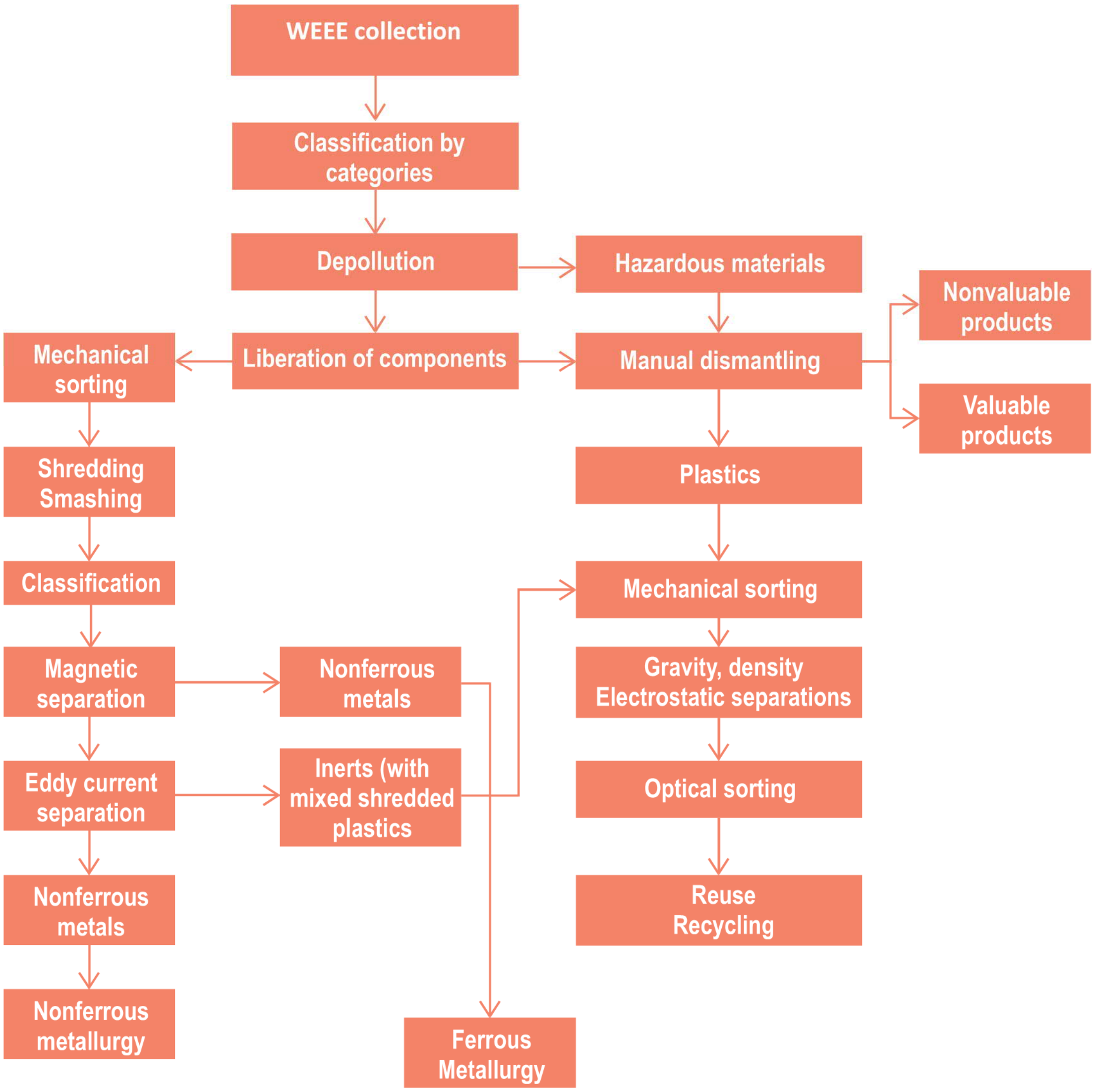

Figure 19 - General flow-chart of Mechanical and Manual Sorting of WEEE (based on NONTOX partners).

In addition, wet separation technologies can be used including e.g. sink-float to recover different plastics and metals, flotation to separate different types/polymers of plastics and heavy medium hydro-cyclones, jigging and shaking table to separate metals from plastics.

Once separated, these concentrates are directly treated or purified using other treatment operations before their recycling. Metal remaining after magnetic and eddy-current separation can be separated from plastics by vibration systems or by electrostatic separation. Plastics identification is often performed by density separation, infrared radiation sorting, x-ray transmission sorting or triboelectric separation.

WEEE types like cathode ray tubes, fluorescent lamps, refrigerators and freezers, require special treatment facilities and are also sorted out initially if they are mixed with other WEEE.

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General process flow-charts of Small Domestic Appliances Treatment, CRT TVs and Monitors treatment are presented in details in Appendix 1.

3.2.3. Plastic sorting for WEEE

Further sorting for the plastic rich fraction has to be performed to split the plastics in polymer categories such as PP/PE, PS and ABS etc. Several techniques combining dry and wet technologies can be used.

Multiple sorting steps are usually required to obtain homogeneous single plastic fractions with a relatively low level of contamination. The identification and separation of different plastics is however complicated by the many different plastic types used in EEE, the small property differences between the plastic polymers and the huge number of grades and additives causing a wide range of properties even in plastics based on the same type. This results in an expensive, time-consuming and complicated WEEE plastics separation process leaving relatively large residual fractions. The complicated recycling process is also indicated by the fact that only a minor fraction (less than 25 wt-%) of the WEEE plastic fraction is recycled globally (Swedish Environmental Protection Agency, 2011).

Wet technology comprises merely of a series of density baths to separate polymers with different densities. The density of the baths is set according to the density of the polymer to be extracted, in this way, one polymer type can float and the other one sinks. One drawback of this method is that there is some overlap between the densities of some polymers, for example the polyolefins.

An electrostatic separator can be used to increase the purity of separated fractions. The process is based on polymer charge transfer, which means the transfer of electron from one plastic to another also known as the surface charge transfer phenomenon. When two polymers are in contact and rubbed, they will transfer electrons and their charges will be different from one and the other (positive, negative or neutral). The separation happens then based on the charge difference. This is called the triboelectric effect (and the polymer charge is based on the triboelectric series, specific for each polymers). A high voltage is creating an electromagnetic field in the chamber. Two electrodes are then present to stir the material from the positive or the negative one based on the polymer charged. The positively charged polymer is attracted to the minus electrode, and the other way around.

Another dry technology is color separator. This method can be used to obtain a monocoloured material. In general, the dry technologies are used to reach higher quality of recycled material or materials destined to technical applications and markets.

Figure 2020 shows a typical process of a WEEE plastics separation.

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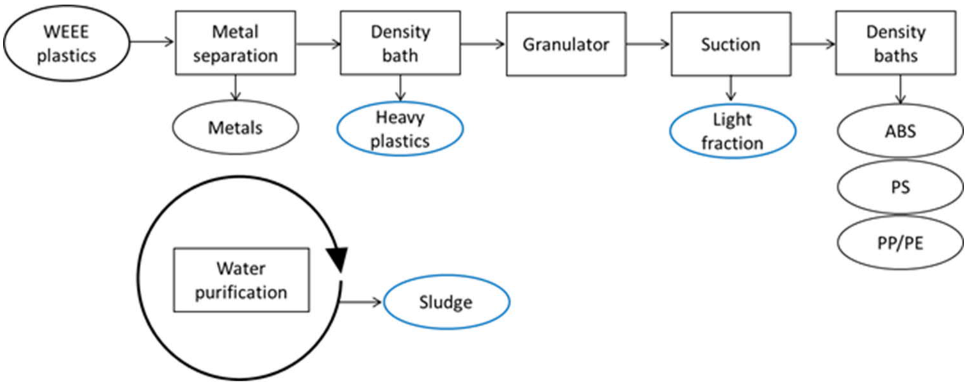

Figure 20. Typical process from a WEEE separation plastics plant (source: Coolrec)

There are two main recycling routes for WEEE plastics, either mechanical recycling (recycling by re-melting and re-processing the plastic material, without influencing the polymer length substantially) or chemical recycling (recycling by depolymerization or thermochemical recycling (gasification or pyrolysis), where plastic is broken into monomers or other small-sized molecules).

- Mechanical recycling involves component recovery, pre-treatment, size reduction, separation and the reprocessing of waste, which can be performed in many different ways depending on the specific recycler.
- Physical / solvent-based dissolution: as mechanical recycling, this method does not affect the polymeric chain length. This technique aims at treating the plastics containing restrictive additive, as the additive can be filtered out of the polymer matrix.
- Chemical recycling by thermochemical recycling or depolymerization involves the scission of polymers into low molecular weight products that can be reused in fuels or as raw materials (monomers) in the generation of new polymers.

3.2.4. Brominated flame retardants in WEEE plastics

The European Waste Electrical and Electronic Equipment (WEEE) Directive 2002/96/EC requires separate treatment of electronic waste containing polybrominated diphenyl ethers (PBDEs). While it is possible to screen for brominated flame retardants (BFRs) in WEEE plastics using X-ray fluorescence (XRF), the separation of plastics with and without BFRs is currently often based on differences in their densities. A rough distinction is made between plastics containing BFRs, assumed to have densities ca. 1.20 tonnes/m^3 or more, and plastics with densities of maximum 1.05 tonnes/m^3 which are considered unlikely to contain BFRs. The high density fraction containing BFRs is often incinerated. However, these relatively simple detection and separation techniques do not distinguish between POP-BDEs and other BDEs or BFRs. (Leslie et al. 2013)

Leslie et al. (2013) reviewed existing literature on POP-BDEs in WEEE plastics as well as conducted experimental research on Dutch WEEE streams. The conclusion of their literature review was that It was really challenging to summarize or generalize the data on POP-BDEs in waste streams. An important aspect that differed between studies was the types of samples studied, from the analysis of single products to shredded WEEE products and specific plastic fractions from WEEE streams,

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sampled per batch or over several months. Concentration data were sometimes expressed as total BDE concentrations, sometimes as c-PentaBDE or c-OctaBDE, and sometimes per specific BDE congener. These aspects contributed to the variations in concentration data reported. Many of the reviewed studies reported the then POP-BDE concentrations to be generally lower than decaBDE (later added as a POP substance) and TBBPA levels. In samples from shredder material (the average of many individual products) POP-BDE levels were generally found up to several 100 mg/kg. In samples from single products, the concentration ranges were naturally bigger, with levels occasionally above 10 000, but also often below limit of detection. Total amounts as well as concentrations of POP-BDEs were generally higher in WEEE than in automotive samples.

Experimental research by Leslie et al. (2013) led to conclusions that both in the case of an ELV shredder residue and in the case of mixed ELV+WEEE shredder residue the density separation of plastics successfully results in a lower density fraction with lower BDE concentrations and a higher density fraction in which BDE concentrations are higher.

3.3. Construction and demolition waste (CDW)

Construction and demolition waste comes from construction, renovation and demolition of buildings and infrastructure. This waste stream consists of various materials in addition to plastics such as concrete, bricks, gypsum, wood, glass, metals, solvents, excavated soils, and so on. According to Wahlström et al., 2019, the recycling and reuse potential of CDW is underexploited.

3.3.1. CDW Volumes and composition

According to Eurostat data, in 2016, the EU generated around 374 million tonnes of CDW. The amount of CDW generated is calculated as the sum of following waste categories;

- W061 ferrous metal wastes,
- W062 non-ferrous metal wastes,
- W063 mixed ferrous and non-ferrous metal-wastes,
- W071 glass wastes,
- W074 plastic wastes,
- W075 wood wastes, and
- total of waste category W121 mineral waste from construction and demolition

The mineral fraction forms the majority of CDW streams (Wahlström et al. 2020). In some sources, e.g. in Monier et al. (2011), soil has also been included in the volumes of CDW increasing the overall volume substantially. The CDW consists of various materials including concrete, bricks, gypsum, wood, glass, metals, plastic, solvents, hazardous substances (asbestos, PCBs, etc.) and excavated soil, many of which can be recycled. CDW originates from activities such as the construction of buildings and civil infrastructure, total or partial demolition of buildings and civil infrastructure, road construction and maintenance. (BIO Intelligence Service 2011).

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Construction waste and demolition waste are considered as one waste stream. Data does not allow distinction of these two categories. However, they have quite different characteristics, both in terms of quantities, composition and potential for recovery. Construction waste (originating from new constructions) is usually less mixed, less contaminated, and its recovery potential is higher than that of demolition waste because of these characteristics. Its share in the total quantities of CDW is generally low (e.g. 16 % in Finland). On the other hand, demolition waste, which represents the highest amounts of CDW, tends to be more contaminated and mixed, and therefore is more difficult to recover. (BIO Intelligence Sevice 2011)

Generally, around one fifth of all plastics are used in construction. The most typical end-uses of plastics include insulation materials, moisture and damp proofing materials, floor coverings and window frames. Plastics are commonly used also as different kinds of profiles and items related to electrical systems, plumbing, and heating, ventilation, and air conditioning (HVAC) systems. Furthermore, most paints, glues, boards, roof coverings, mineral-material based insulations, and laminated surfaces include plastics as raw materials or resins. Plastics can help to achieve many essential technical and functional properties that are vital for modern buildings. (Häkkinen et al. 2019)

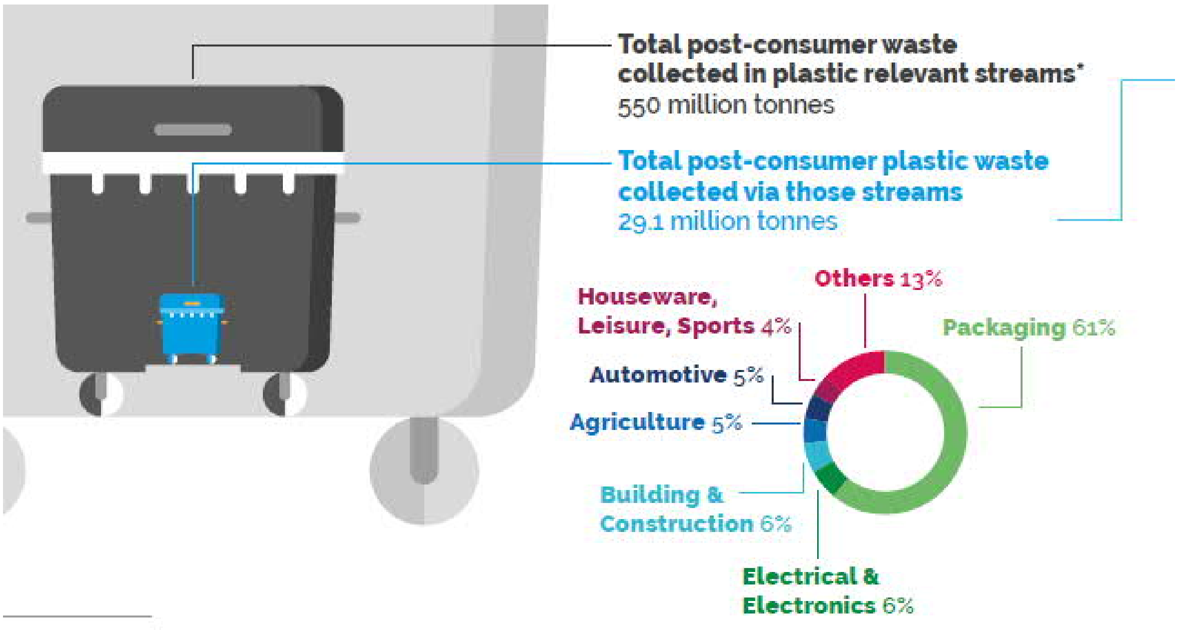

Figure 21. Plastics containing waste streams in EU28+2 in 2018 (Plastics Europe 2019).

Based on Figure 21, a rough estimate on plastics contained in construction and demolition waste is around 1.7 Mt/a in EU. To the best of our knowledge and carried out research, no good quality general data on the composition of plastics from CDW is available. The plastic material in CDW contains a wide range of polymer types, and its composition within CDW is generally seen as unclear (e.g. Lahtela et al. 2019). As an example, the estimated shares of different polymers in building and demolition waste in Finland in 2017 were as follows (Häkkinen et al. 2019).

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- PVC 50– 55%,
- PS 14–19%,
- PU 3–8%,and
- PE-HD 4–9%.

Older data by Hendriks et al. (2000) reports composition of CDW plastic waste in the Netherlands to be:

- PVC 40 %,
- PE&PP 30 %,
- PS 10 %,
- PUR 10 %, and
- others 10 %.

3.3.2. Treatment of CDW in Europe

Systems for collecting plastic waste are currently not envisaged during the design of construction or demolition sites, and the management of this waste stream for plastics is still at an early stage (Häkkinen et al. 2019). However, changes are likely to happen in the near future. According to the Waste Framework Directive (WFD), "Member States shall take measures to promote selective demolition in order to enable removal and safe handling of hazardous substances and facilitate reuse and high-quality recycling by selective removal of materials, and to ensure the establishment of sorting systems for C&DW at least for wood, mineral fractions (concrete, bricks, tiles and ceramics, stones), metal, glass, plastic and plaster" (Wahlström et al. 2020). Furthermore, it is suggested that, by 31 December 2024, the Commission should consider setting preparing-for-reuse and recycling targets for C&DW and its material-specific fractions.

According to AEA and BIO (2011), 35% of all construction and demolition plastic waste in Europe (EU-27, Norway and Switzerland) went to energy recovery, 16% to mechanical recycling, and the rest (49%) was sent for disposal. In another study, the share of mechanically recycled plastics waste was reported to be 20 % (Villanueva and Eder 2014).

Collection of CDW waste at building and demolition sites varies within countries as well as between countries in EU. The Waste Framework Directive is planned to bring harmony also to the source separation of different materials fractions arising from these sites. At the moment it is not possible to get a general picture of CDW collection and management practices across Europe. Some country-specific practices of managing CDW have been presented by DG Environment (2011), but the description of Flanders below is the only one including some sort of description of material sorting starting from construction or demolition site.

3.3.3. Case example: Flanders, Belgium

In Flanders, the total amount of CDW amounted to 8.5 Mt/a in 2007. Due to mixing of other waste streams into plastics in statistics, the data does not allow for finding out the amount of plastics in particular in CDW. Common practices include in minimum sorting of CDW at the site in a hazardous

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and a non-hazardous component. Non-hazardous waste is usually further sorted in stony waste, glass, metals and a residual mixed fraction. The mixed fraction (less than 10 %) of CDW is destined to permitted sorting installation. The majority of the mixed waste going to sorting installations is masonry / brickwork rubble from small works and households. Sorting processes in the different companies in the Flemish region follow a similar pattern. Storage of the input waste requires dry conditions to increase the sorting performance of the installation. Large pieces of waste (wood, large bricks) are pre-sorted before the waste is fed to the installation. The installation first sieves the finest sand particles. In a next step, the ferrous metals are removed by means of a magnet. Wind-sifting further separates the lightest fractions of the waste (paper, foils, polystyrene…). The remainder of the waste stream is manually sorted on one or several belt conveyors (particle size). In this final step, wood, plastics, gypsum and non-ferrous metals are further separated. Sorting installations target to obtain "uncontaminated" new fractions of stony inert material, plastics, metals, wood, etc. that are further treated in specified recycling facilities. No description of plastic waste's further treatment is available in the report.

3.3.4. Finnish case study on CDW composition

In a recent (2019) study by Liikanen et al., CDW streams in the South Karelia region of Finland were investigated. The objectives of the study were to quantify regional CDW streams, to estimate the composition of CDW based on the reported waste streams and to assess the composition of mixed CDW based on manually sorted CDW samples from the South Karelia region. In 2016, the South Karelia region reported the generation of approximately 165,000 tonnes of construction and demolition waste. This reflects approximately 14% of the total waste generated in the region. The CDW generated consisted of mineral waste (34%), metals (32%) and soil (23%). Additionally, the share of mixed CDW (6%) as well as wood, glass and plastic (4% combined) was notable. The manually analysed mixed CDW samples indicated significant material recovery potential as minerals, wood and plastic made up approximately 70% of the samples, with the plastic fraction being 18% of the mixed CDW waste by average.

3.3.5. Brominated flame retardants in CDW plastics

Flame retardants are added to construction products to lengthen escape time, reduce the heat production, decrease the combustion of a material and reduce the production of toxic gases. Flame retardants containing bromine or chlorine can be found in plastics, furniture and carpeting. The main concern of brominated flame retardants in CDW relates to the presence of HBCDD (Hexabromocyclododecane, Wahlström et al. 2019). HBCDD is classified as a POP substance and banned since 2015 in EU.

The main part (90 %) of HBCDD is used as flame retardant in polystyrene (PS). Expanded polystyrene (EPS) is extensively used from 1975 to 2015 in building industry because of its durability and insulation properties. EPS insulation is used for example for roofs, facades, ground floor structures, foundations, frost insulation and for civil engineering applications. Extruded polystyrene (XPS) is used in roofs, parking levels, ground floor, foundations and frost. HBCD is used as a flame retardant in XPS products. (Wahlström et al. 2019).Duan et al. (2016) found high contents of HBCD (up to 7000 µg/kg) and PBDEs (up to 80 000 µg/kg) in typical CDW components, particularly polyurethane foam materials.

Although some observations from literature could be made regarding brominated flame retardants in CDW plastics, general picture of their occurrence cannot be made.

3.4. Summary of plastics containing fractions main destinations

3.4.1. ELV

Based on current treatment schemes for end of life vehicles in Europe, it can be estimated that most of the plastics contained in a typical 15 years old ELV end up in the shredder light fraction. The amount of shredder light fraction resulting from only ELV treatment is around 20 % by mass of an ELV, and therefore the volume of shredder light fraction in Europe resulting from ELVs only would be around 1.5 million tonnes. However, as mentioned earlier, SLF does not constitute from ELVs only. It has been estimated that around 30 % of SLF would arise from ELVs in a case where the share of ELVs in a mixed shredder feed is between 15 and 20 % by mass (interviews with recyclers).

An interesting yet quite natural finding based on data from Mehlhart et al. (2018, Table 5) seems to be that in EU countries with lower price for man hours, the manual dismantling of plastic containing bigger parts from ELVs comprises a significantly higher share of total SLF generated.

In modern PST treatment of ELV-generated SLF, the plastics containing fractions are often separated into three fractions with differing densities. Experimental research presented by e.g. Leslie et al. (2013) and Mehlhart et al. (2018 have led to conclusions that PST for shredder residue originating from treatment of ELV (+other waste streams) can successfully result in a lower density fraction with lower BDE concentrations and a higher density fraction in which BDE concentrations are higher. The lower density fraction has potential for mechanical recycling but the higher density fractions can be seen as potential for the NONTOX concept.

Table 10 summarizes the possible routes today for the plastics in ELV in EU. The data is calculated based on routes for Dutch ELV plastics (Leslie et al. 2013) and it represents “a best case scenario” with today’s technologies. In reality, a greater share of ELV plastics ends up in incineration or even to landfill today.

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Table 10. Summary of the estimates on ELV-plastics possible destinations in EU based on "best case scenario" with today's technologies.

Plastics from ELV	Estimate on volume, Mt/a	Sources
Plastics in ELVs	1.1	Based on ELV statistics (Eurostat 2020) and plastics content of ELV (Schönmayr 2017)
Plastic parts manually dismantled for reuse	0.19	Based on Leslie et al. 2013
Plastics manually dismantled for recycling	0.05	Based on Leslie et al. 2013
Plastics separated in PST for recycling	0.04	Based on Leslie et al. 2013
Incinerated (+landfilled)	0.82	Based on Leslie et al. 2013

3.4.2. WEEE

Based on estimates prepared by NONTOX project partners, officially collected WEEE in EU contains 0.73 Mt/a plastics. Estimations on destinations of these plastics (Table 11) is based on following assumptions:

- Large equipment plastics (0.17 Mt/a) are treated with ELV plastics with similar distribution with the exception of non-existent reuse (=recycling).
- Specialized treatment for temperature exchange equipment (0.10 Mt/a plastics).
- The rest (0.46 Mt/a) with similar distribution to as described by Leslie et al. (2013) in a case study for The Netherlands.

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Table 11. Summary of the estimates on WEEE-plastics possible destinations in EU based on “best case scenario” with today’s technologies.

Plastics in collected WEEE	**Estimate on volume, Mt/a**	**Sources / remarks**
Plastics in WEEE	0.73	NONTOX data synthesis
Large equipment Recycled Incinerated (+landfilled)	0.17 0.04 0.13	Leslie et al. 2013
Temperature exchange equipment Recycled Incinerated(+landfilled)	0.10 0.05 0.05	Estimate based on 50 % split between recycled and incineration/landfill. Proven technology exists for plastics recycling.
Small equipment* Recycled Incinerated (heavy plastics from WEE plastic sorting + WEEE collected with MSW) Other (export+not documented)	0.46 0.15 0.16 0.15	Leslie et al. 2013

* small equipment, small IT and telecommunication equipment

3.4.3. CDW

Based on estimates presented by Plastics Europe (2019) and AEA & BIO (2011), Table 12 comprises an estimate of CDW plastics routes in EU today.

Table 12. Estimates of CDW plastics destinations today in the EU.

Plastics from CDW	**Estimate on volume, Mt/a**	**Sources**
Plastics in CDW	1.7	Plastics Europe 2019
Plastics recycled	0.27	AEA and BIO (2011)
Plastics incinerated	0.60	AEA and BIO (2011)
Plastics landfilled	0.83	AEA and BIO (2011)

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4. Analysis of current situation in ELV, WEEE and CDW plastics treatment and the potential streams for NONTOX concept

It is important to recognize that in general, ELV, WEEE and CDW treatment schemes and processes are designed to optimize metal recovery from these waste streams and have not been initially designed from the point of view of optimum plastic recovery. The environmental, safety and processing related challenges the BFR substances pose to the recycling sector have directed the more challenging high BFR-content plastic streams to disposal. The untapped potential of recycling plastics which are currently non-recyclable, as well as plastics which are currently recycled but consist of rather high bromine-content, are potential waste streams for NONTOX concept where the aim is to safely remove or decrease the amount of bromine. One integral innovation pathway in NONTOX is the development of smart sensor-based sorting to identify the bromine content of the plastic streams. Developing two key technological approaches – the removal of bromine and identification and sorting based on bromine content – can open new possibilities to begin recycling non-recyclable plastic streams. The potential as well as the possible bottlenecks of the different target waste streams are analysed from the concept's point-of-view below.

ELV, large WEEE (large household appliances LHA excluding cooling devices, waste streams that are mostly treated as mixed shredder feed)

- Very little plastics separation is done in manual dismantling stage of ELV or/and WEEE treatment except for ELV to some extent, which is carried out mostly in countries with lower cost for work. This results in highly mixed plastic waste streams for further processing. This heterogeneous waste could be a potential stream for NONTOX, especially upon further development of detection and sorting technology in NONTOX
- Most of the plastics in these streams (ELV plastics approx. 1 MT/a, LHA plastics approx. 0.17 Mt/a), end up in shredder light fraction (SLF) which is a very heterogeneous waste stream composed of light metal, paper, cardboard, various types of plastic, foam, textile, wires, wood and such. The recovery of these plastics is challenging from the mixed SLF waste stream and the lost potential in these plastic streams is high. The mixed SLF waste stream from ELV and large WEEE is seen as a potential stream for NONTOX, especially upon further development of detection and sorting technology.
- Modern Post Shredder Treatment (PST) separates plastics in SLF into basically three categories based on density (e.g. <1.1, 1.1-1.3 and >1.3 g/cm^3). The bromine analysis show that plastic fraction with density below 1.1 g/cm^3 have rather low bromine content, which is desirable as it is currently sent for recycling. For the other two density fractions, the bromine content is much higher. In the density fraction 1.1–1.3 g/cm^3 there is in general a large variation in the bromine content, which does not favour current recycling. In addition, this fraction contains a significant variety of different polymers, which also hinders recycling with current recycling systems. These high-bromine content fractions can be seen as

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potential streams for NONTOX concept, where both reduction and removal of bromine and innovative sensor-based sorting technology are developed.

Other WEEE streams

The treatment schemes vary a lot across Europe and recycling operators. Some recyclers treat all WEEE except for the large appliances as a single stream. As an example, modern PST for this type of mixed WEEE feed might produce plastics containing fractions of three different densities, e.g. <1.1 g/cm^3, 1.1 - 1.3 g/cm^3 (typically high bromine content) and above 1.3 g/cm^3 (typically high chlorine content). Lighter fractions are today products with positive cash flow, but the heavier fractions create costs for the operator. These high-bromine content fractions can be seen as potential streams for NONTOX concept, where the both reduction and removal of bromine and innovative sensor-based sorting technology are developed. Furthermore, there might be potential in further decreasing the bromine level within recyclates that meet the limit values.

CDW

Management of CDW in EU varies significantly across building and demolition sites in different countries and regions. The most abundant polymer in CDW plastics is PVC, which is not in the scope of NONTOX, and accounts roughly for 50 % of the plastics in CDW. Other polymers in CDW, such as PE&PP, PS and PU can be seen as potential streams for NONTOX concept, although significant improvements are needed in source separation and processing of plastic containing CDW fractions.

Table 13 is a compilation of estimates of plastics content in target waste stream as well as estimates of the total potential in these waste streams for the NONTOX concept. It needs to be noted, however, that the realization of the estimated potential calls for significant improvements in the management systems for these waste streams starting from source separation and collection systems. On the other hand, improvements in collection rates for especially WEEE could increase the potential feed materials for the NONTOX concept.

Table 13. Summary of estimates of plastics in target waste streams and potential for the NONTOX concept.

Waste stream	ELV	WEEE	CDW
Volume, Mt/a collected	7.3	3.7	374
Plastics, Mt/a	1.1	0.73	1.7
Main polymers	PP, PU, PA/PC, ABS, PVC	HIPS, ABS, PP, PC-ABS	PVC, PE&PP, PS, PU
Potential for NONTOX, Mt/a	0.82 [1)]	0.51 [2)]	0.85 [3)]

1) Non-recycled plastics from ELVs today
2) Includes incinerated/landfilled + exported WEEE plastics

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3) Non-PVC part of the CDW plastics

As a result of this study, we estimate that all together within the target waste streams approximately 2.18 million tons per year of mixed polymer feeds are potential for the NONTOX concept. The main polymers within these stream are PP, PU, PA/PC, ABS, HIPS, PC/ABS, PE&PP and PS.

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5. Summary

Work presented in this report addresses the current volumes and treatment of Waste Electrical and Electronic Equipment (WEEE), End of Life Vehicles (ELV) and Construction and Demolition Waste (CDW) in Europe with the focus on the plastics contained in these waste streams. Estimates formed show volumes of 1.1 Mt/a for ELV plastics, 0.73 Mt/a for WEEE plastics and 1.7 Mt/a for CDW plastics today in the official collection systems.

All of the target waste streams are heterogeneous in nature. Available literature on their composition includes significant variations depending on the scope of the study, i.e. whether it was products or e.g. shredded plastics containing fractions were characterized, and what were the feed materials to the processes. In addition, different analytical tools have often been used.

Directive 2012/19/EU on WEEE and Directive 2000/53/EC on ELVs regulate the treatment of the respective waste streams in the European Union, whereas the treatment of CDW is regulated by the Waste Framework Directive 2008/98/EC. Mineral materials are one of the target materials for recovery in CDW treatment, as they represent a major share of that waste stream. However, changes in regulatory framework, such as the tightening requirements for the reuse and recycling rates for WEEE, ELV and CDW in the European legislation, tightening limit values, as well as the generation of markets for recycled plastics, have created interest towards the extraction of plastics from the complex waste streams. At the same time, regulations require hazardous substances such as brominated flame retardants to be removed from material cycles.

The main driver in the pre-treatment and recycling of metal-rich complex waste streams, such as ELVs and WEEE, has been the extraction of metals. As a consequence, the pre-treatment operations are often optimized for this purpose. Mineral materials are one of the target materials for recovery in CDW treatment, as they represent a major share of that waste stream.

ELVs are today treated at shredders that are designed for metal recovery. Also large household appliances often times are treated at the same facilities as mixed feed with ELVs and mixed metal scrap from industry and municipalities. Some part of CDW plastics is also treated as mixed feed with the same shredder facilities. The mixing of different feeds creates challenges for plastics recycling from these waste streams, since the non-metallic contents of the feeds creates a very heterogeneous residue fraction at the shredders, where also most of the plastics end up. Small share of ELV plastics is recycled in EU today, and mostly the plastics in ELVs and large household appliances end up in incineration or even at landfills. This study estimated a potential of even 1 Mt/a for further plastics recycling from ELVs and large household appliances provided that impurities in the plastics containing fractions can be tackled with better pre-treatment.

Most of the WEEE categories are treated in dedicated WEEE treatment plants because of the valuable metallic contents in these streams. The dedicated treatment has also allowed for better development of plastics recycling from these streams. Today recyclers are able to sell some of the plastics fractions in WEEE streams, but heavier plastics fractions from WEEE treatment are still a challenge for the recyclers because of e.g. brominated flame retardants and chlorine contents. This study estimated a potential of even 0.5 Mt/a for further plastics recycling from WEEE in EU, and even more with increased WEEE collection rates.

In this work it was challenging to form a clear picture of CDW treatment in Europe due to the widely acknowledged lack of comprehensive data published. Thus the routes of plastics containing CDW fractions still remain largely unknown at this point. Nevertheless, in this study it was estimated that CDW could include a potential of around 0.85 Mt/a (non-PVC plastics in CDW) for increased plastic recycling.

The overall objective of the NONTOX project is to increase the recycling rates of plastics waste containing hazardous substances by developing and optimising recycling processes as well as sensor technology for bromine detection to produce safe and high quality secondary plastic materials. Based on the study conducted and boundaries of NONTOX concept, we estimate that the potential mixed polymer feed from the target streams (ELV, WEEE, CDW) is approximately over 2 million tonnes per year. These streams can be generally characterized as very heterogeneous mixtures as well as high in bromine content. However, it needs to be noted that the realization of the estimated potential calls for significant improvements in the management systems for these waste streams starting from source separation and collection systems. Improvements on the collection rates increases the total volume of potential feed materials for the NONTOX concept.

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APPENDIX 1 - General flow sheets of specialised WEEE treatment

Following process flow-charts show the principles in treatment of Small Domestic Appliances, CRT TVs and Monitors, Refrigerators & Freezers and LCD TVs and Monitors. Flow-charts are provided by NONTOX project partners.

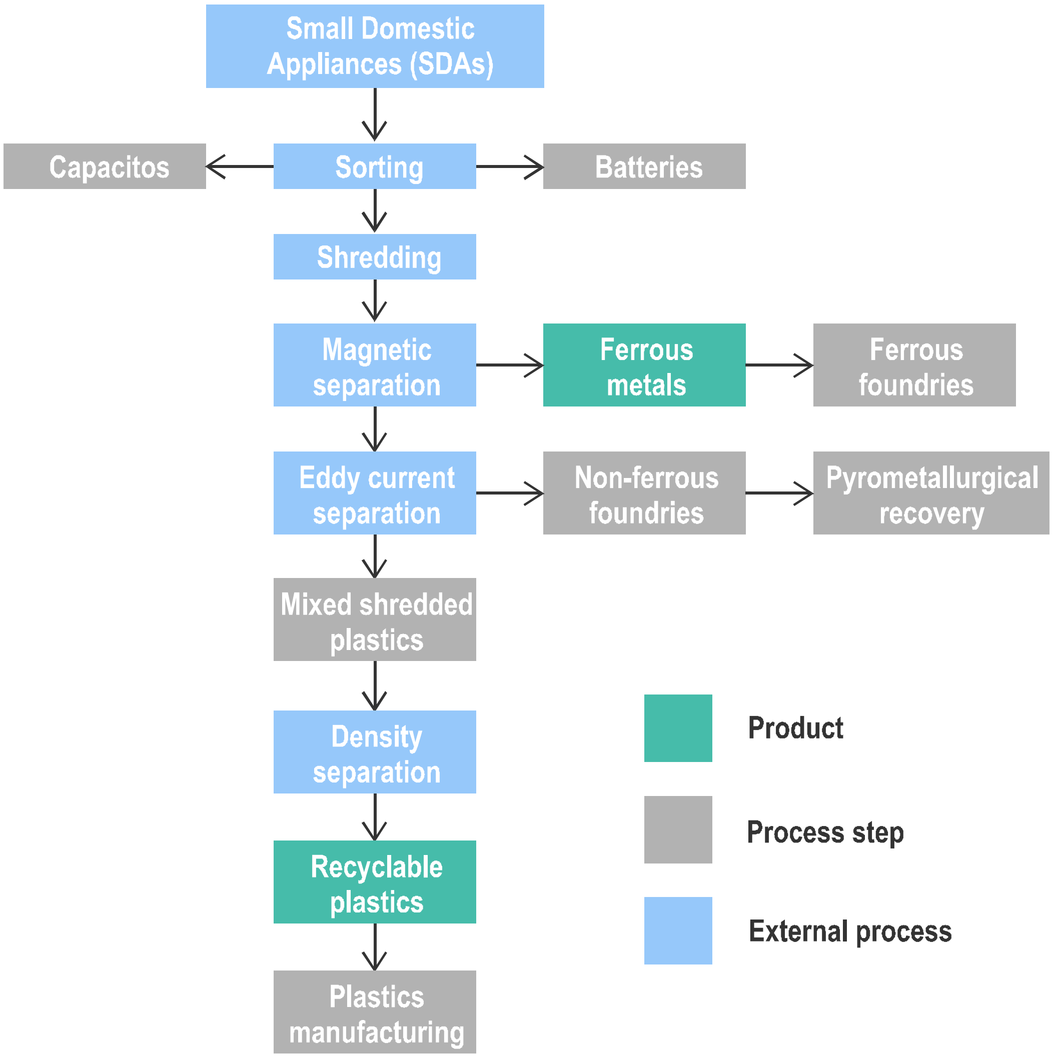

Figure A.1. General treatment scheme for Small Domestic Appliances

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820895.

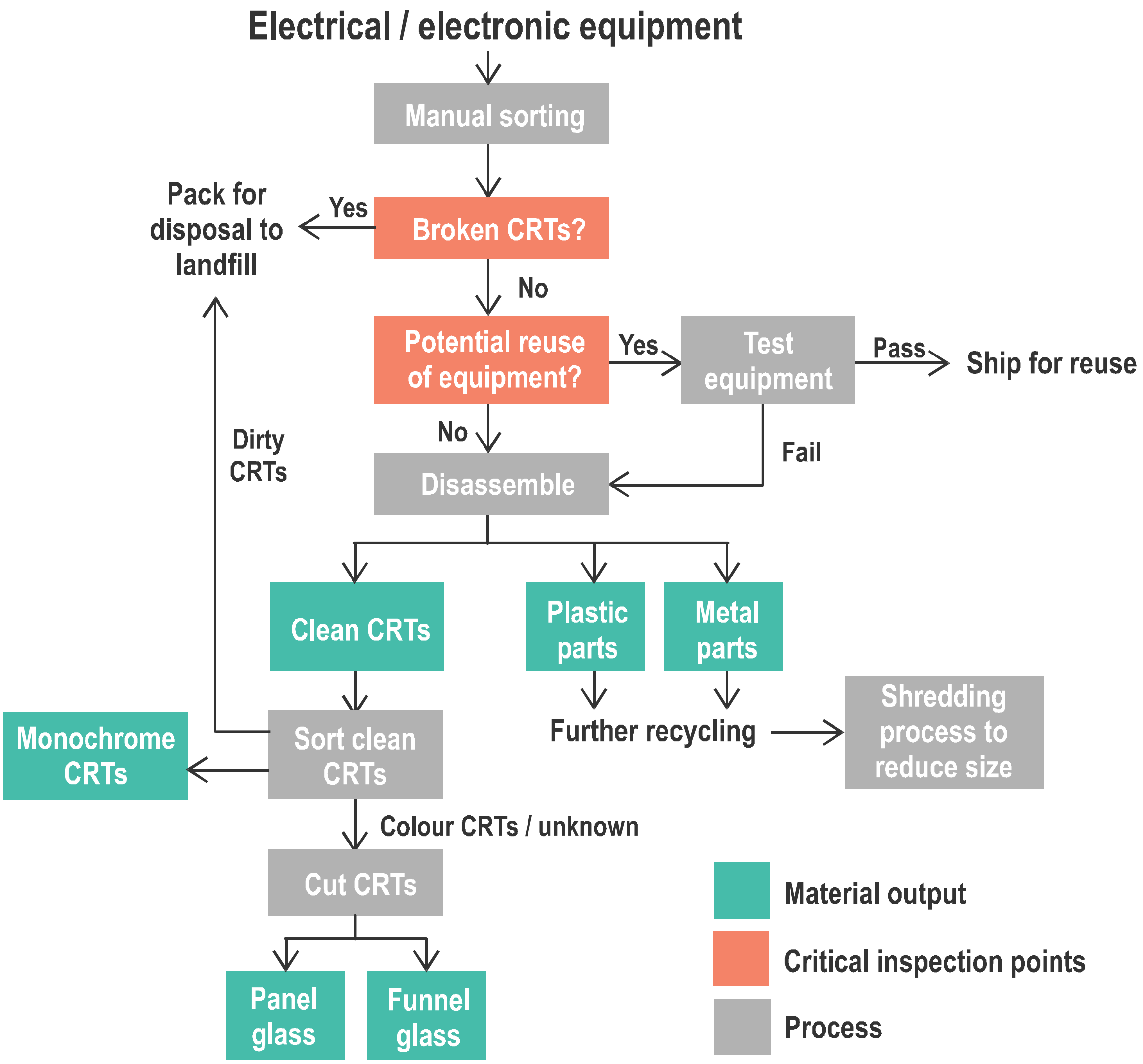

Figure A.2. Treatment scheme for CRT -TVs and Monitors

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 820895.

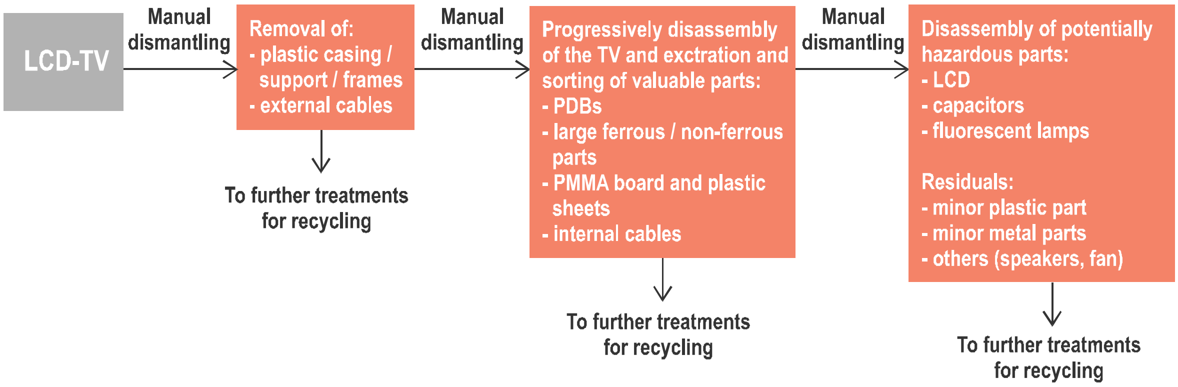

Figure A.3. Typical treatment scheme for LCD-TVs

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