Study on the Impacts of Brominated Flame Retardants on the Recycling of WEEE plastics in Europe.

sofies

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Authors and quality check

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This report has been compiled by Sofies based available data and information as well as interviews with relevant stakeholders. The analysis and conclusions reached are the views of Sofies and do not necessarily reflect the views of BSEF or its member companies.

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ATH	Aluminium hydroxide
ATO	Antimony trioxide
BBP	Butyl benzyl phthalate
BCO	Brominated carbonate oligomer
BDP	Bisphenol A diphosphate
BEO	Brominated epoxy
BFR	Brominated flame retardant
BrPA	Brominated polyacrylate
BrPS	Brominated polystyrene
BSEF	The International Bromine Council
BTBPE	Bis(tribromophenoxy) ethane
CRT	Cathode ray tube
DBP	Dibutyl phthalate
DecaBDE	Decabromodiphenyl ether
DEHP	Di(2-ethylhexyl) phthalate
DIBP	Diisobutyl phthalate
DMMP	Dimethyl methylphosphonate
EBP (DBDPE)	Decabromodiphenyl ethane
EBTBP	Ethylene bis(tetrabromophthalimide)
EN 13823	Single Burning Item test method
EN 50625	Standard on collection, logistics & treatment requirements for WEEE
EPS	Expandable Polystyrene
FPD	Flat panel display
HBCD	Hexabromocyclododecane
HIPS	High Impact Polystyrene
LHHA	Large Household Appliances
LIBS	Laser-Induced Breakdown Spectroscopy
LPCL	Low POP concentration limit in Annex IV of the POPs Regulation
MDH	Magnesium hydroxide
NIR	Near-infrared
OctaBDE	Octabromodiphenyl ether
PA6	Polyamide 6 (Nylon)
PA66	Polyamide 66 (Nylon)
PBBs	Polybrominated biphenyls
PBDEs	Polybrominated diphenyl ethers
PBT	Polybutylene Terephthalate
PC	Polycarbonate
PC+ABS	Polycarbonate / Acrylonitrile Butadiene Styrene Blend
PE	Polyethylene
PentaBDE	Pentabromodiphenyl ether
Poly-Bu-St	Butadiene styrene brominated copolymer
POM	Quantity of products placed on the market, i.e. made available on the market within the territory of a Member State on a professional basis
POP	Persistent organic pollutant
POP-BFR	BFR compound listed as POP substance under the Stockholm Convention
PP	Polypropylene
ppm	parts per million (1% = 10'000 ppm)
PPO	Polyphenylene ether
PPE+PS	Polyphenylene ether / Polystyrene blend ("Noryl")
PS	Polystyrene
PU	Polyurethane
PVC	Polyvinyl chloride
RDP	Resorcinol bis(diphenylphosphate)
TBBPA	Tetrabromobisphenol A
TBBPA-DBPE	Tetrabromobisphenol A-bis(2,3-dibromopropyl ether)
TBNPP	Tris(bromoneopentyl) phosphate
TBPT	Tris(tribromophenyl)triazine
TCP	Tricresyl phosphate
TEE	Temperature exchange equipment, also referred to as cooling and freezing equipment (C&F)
TPP	Triphenyl phosphate
TTBPT	Tris(tribromophenyl) cyanurate
UL94	UL94: Standard for Safety of Flammability of Plastic Materials for Parts in Devices and Appliances testing
WEEE	Waste Electrical & Electronic Equipment
WG	Waste generated: total quantity of WEEE resulting from EEE within the scope of Directive 2012/19/EU that had been placed on the market of that Member State, prior to any activity such as collection, preparation for reuse, treatment, recovery, including recycling, or export.
XRF	X-ray fluorescence
XRT	X-ray transmission

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Executive summary

In December 2018 the European Commission launched the Circular Plastic Alliance with the aim of boosting the EU market for recycled plastic with an initial pledge of 10 million tonnes by 2025 and with more than 230 signatories to date. This initiative is also seen as a contribution to the EU Circular Economy Action Plan launched in January 2020.

Electronic equipment is not only one of the key waste streams identified in the Circular Economy Action Plan, but also represents a relevant source of plastic waste: approximately 25% by weight of Waste Electrical and Electronic Equipment (WEEE) consists of plastics in the form of various polymers (mainly ABS, PP, PS and PC-ABS). Such plastics however contain a wide range of additives such as flame retardants, fillers, pigments and stabilisers which collectively impact the recycling of WEEE plastics.

Nowadays approximately 2.6 million tons of WEEE plastics are generated annually in Europe; Plastic containing BFR is representing about 9% of the total. **Restricted BFRs (e.g. Octa-BDE and Deca-BDE) only represent a small and rapidly declining fraction of all BFRs found in WEEE plastic streams** reflecting the restriction on the use of these substances for more than a decade (2003 for Octa-BDE, 2008 for Deca-BDE).

Unfortunately, **around half of all WEEE plastics generated in Europe do not enter official WEEE collection channels**, ending up in the waste bin, processed at substandard recycling facilities, or exported.

Out of the 1.3 million tons of WEEE plastics officially collected, **about 1 million tons is sent to specialised WEEE plastics recycling facilities** (or integrated smelters in the case of epoxy contained in printed circuit boards). The remaining 300 kt is either sent to incineration after WEEE pre-processing or lost into metal fractions as a result of sorting inefficiencies.

Specialised WEEE plastic recycling facilities apply a series of sorting stages that normally include a stepwise density separation. A high-density fraction is thereby created, containing a complex mixture of heavy plastics and various additives that is not suited for recycling and is therefore disposed of. This fraction contains more than 95% of the original BFR content, as density sorting is a highly effective way of separating Br-rich and Br-poor fractions.

55% of WEEE plastics entering WEEE plastic recycling facilities are effectively recycled, i.e. turned into regranulates that can be used in the manufacture of new plastics products.

Given the the current technical process of separating and recycling different polymers in place today in the EU, it is clear that the recycling yield would not be improved by the removal of brominated flame retardants or a switch to non-brominated flame retardants, as other FRs would also be sorted out for disposal during the conventional density-based recycling process.

Analysis contained in this report also shows that the 2,000 ppm Br limit, which was introduced as an operational threshold enabling fast and cost-effective separation of BFR-containing plastics in the WEEE CEN standards, should be reviewed in light of the decreasing share of restricted BFRs in the overall Br content.

The 2,000 ppm cut off value has the effect of reducing the volume of WEEE plastics available for recycling and increasing the volumes consigned to incineration. Recent analytical data reviewed in this study suggests that limit values for restricted BFRs would not be exceeded even with a threshold as high as 6,000 ppm Br.

Interviews and feedback from WEEE plastic recyclers confirmed that BFR plastics represent nowadays a well-controlled stream, which is easily sorted out during conventional and industrial recycling processes. They are therefore not a hindrance in of themselves to the recycling of WEEE plastics.

Concerns were however expressed by WEEE plastic recyclers on the poorly documented but potentially serious impacts of other FRs on the recycling of WEEE plastics. Some of the most widely used other FRs, organophosphates, are for instance known to negatively impact the recyclability of WEEE plastics due to chemical degradation during processing.

The overarching conclusion from this study is that the **presence of BFRs in WEEE plastics does not reduce recycling yields** more than other FRs as FR-containing plastics, as well as plastics containing other additives in significant loads (e.g. fillers), are sorted out during the recycling process.

A switch to other FRs would not improve WEEE plastics recycling and would most probably have detrimental impacts on yields and quality.

Given the EU goals to increase plastics recycling overall as a contribution to the Circular Economy, the following recommendations and actions are put forward for consideration by key stakeholders:

- Policymakers:
  - Increase the quantities of WEEE plastics reaching specialised WEEE plastic facilities by raising WEEE collection rates, enforcing compliance with EN 50625 standards, and facilitating intra-EU cross-border shipments towards state-of-the-art WEEE plastic recycling facilities (for instance by classifying shredded WEEE fractions as non-hazardous).
  - Investigate the impacts of alternative FRs on the recyclability of WEEE plastics to avoid "regrettable substitution" effects that could prove detrimental to WEEE plastics recycling performance.
  - Improve the knowledge base necessary for evidence-based policies and decisions by regularly collecting and analysing representative data on levels of BFRs and other additives in WEEE plastic streams.
  - Review the relevance of normative requirements on treatment of BFR-containing WEEE plastics (WEEE Directive and related limit value of 2,000 ppm in EN 50625) considering the reduction of restricted BFR levels over time.
  - Harmonise and ensure stability of legislation of chemical, waste and products having a direct impact on WEEE plastic recycling, to facilitate much needed investment in innovative recycling technologies.

- Recyclers:
  - Develop innovative sorting and recycling methods to recover a higher share of plastics, enabling for instance the recovery of PC-ABS, PA, or PBT polymers.
  - Seek long-lasting partnerships with producers to optimise design for and from recycling.

- Producers:
  - Adopt and implement recycled content targets to boost demand for WEEE plastic recyclates and decouple from virgin plastic prices.
  - Exchange with WEEE plastics recyclers in order to understand how the choice of polymers and additives influence the recyclability of plastics, and on this basis select polymers (and additives) used in the manufacture of EEE considering the extent to which they are currently recycled.

The following study assesses the impact caused by the presence of BFRs on the recycling of WEEE plastics. To this end, the quantities and destinations of WEEE plastics, including brominated plastics, are first assessed in chapter 2. Then, legal requirements and practices relating to the treatment of WEEE plastics are studied in chapter 3. Finally, the impact of BFRs on recycling yields, recyclate quality and recycling costs are examined in chapter 4, as well as the potential impact posed by alternate FRs such as organophosphates and mineral FRs.

1 Context and objectives

1.1 Context

Plastics from Waste Electrical and Electronic Equipment (WEEE) represent on average 25% of all WEEE annually generated by weight and consist of a complex mixture of different polymers containing a wide range of additives such as flame retardants, fillers, pigments and stabilisers. ABS, PP, (HI)PS and PC-ABS are the most commonly found polymers in WEEE, accounting for 75% of all WEEE plastics. The remaining 25% consists of various polymers including PU, PA (6/66) and PVC. Through a combination of sorting technologies based on density (e.g. Sink/Float, XRT), electric conductivity (electrostatic separation) or infra-red spectra (NIR sorting), these polymers can be separated from each other at a high degree of purity and turned into regranulates that can replace virgin materials in new products.

However, due to a number of **challenges**, including the high complexity of WEEE plastic mixtures and limitations in current plastic sorting technologies, typically **only 50 to 60% of the input material** to WEEE plastic recyclers is effectively recycled. The rest is sent for energy recovery (waste incinerators with energy recovery or as a fuel substitute in cement kilns) or, rarely, landfilling.

These process material losses are however relatively small compared to upstream losses, at the WEEE collection or WEEE pre-processing stages. Indeed, a large share (estimated at 60% in this study) of WEEE plastics arising in Europe never reaches WEEE plastic recycling facilities especially due to low WEEE collection rates or losses at the WEEE pre-processing stage. Therefore, **less than a quarter of WEEE plastics arising in Europe are effectively recycled.**

One of the challenges encountered by WEEE plastic recyclers is the presence of **legacy additives** in their input – substances that were added into plastics contained in EEE in the past but whose use has been discontinued (voluntarily or by law) due to concerns regarding human and environmental health. Such additives include low molecular weight phthalates (such as DEHP, BBP, DBP and DIBP used as plasticiser), heavy metals (such as lead and cadmium compounds used as stabilisers) and some brominated flame retardants (BFRs, such as octaBDE and decaBDE used in external housings and HBCD used in foams). Plastics containing BFRs have to be removed during the treatment process of WEEE according to the WEEE Directive Annex VII requirements so that they do not end up in the recyclates.

WEEE plastics recycling is a complex topic that involves an interplay of technical, economic and regulatory challenges. This combination of factors makes it difficult, if not impossible, to isolate a single challenge or factor as hindering the recycling of WEEE plastics more than others. Consequently, focussing on legacy additives and in particular BFRs as being the main cause for low WEEE plastic recycling rates is ill-founded and as this study shows, far from reality.

1.2 Aim and scope of the study

The current study was carried out in order to provide a better informed and quantitative basis **to assess the impact caused by the presence of BFRs on the recycling of WEEE plastics.** The inputs for the study were derived from available data and literature, exchanges with relevant stakeholders, and mass flow modelling. The specific objectives of the study were to:

- Provide a scale of the issue, by calculating and estimating **volumes of BFR plastics** arising in WEEE. This was achieved by collecting and consolidating available data, acquisition of additional information and data through exchanges with various stakeholders, and development of material flows models.

- Understand **treatment requirements and practices,** by reviewing normative requirements for treatment of BFR plastics and investigating current practices through exchanges with actors such as take-back schemes and recyclers.

- Draw conclusions on the **impact of BFR plastics on the recyclability** of WEEE plastics and compare with alternatives.

- On the basis of the findings, provide recommendations for various stakeholders such as policymakers, producers and recyclers.

2 BFR levels and BFR plastic flows

2.1 BFR levels

2.1.1 (Brominated) flame retardants

Due to the presence of electric currents in EEE and internal components generating heat, the inherent flammability of most plastics, and the widespread use of EEE in houses and offices, flammability standards are in force to protect against fire.

Flame-retarding compounds are commonly used in those plastic parts of EEE.
This is especially the case for components prone to ignition such as cables, switches and circuit breakers, printed circuit boards and outer casings (exposed sometimes to external sources of fire or heat).

A wide diversity of flame retardants is commercially available, which can be grouped into the following main groups:

- **Halogenated** flame retardants, either **brominated** (accounting in 2018 for 55% of global use of flame retardants in EEE[1]) or **chlorinated** (1%[1]). Brominated flame retardants are usually used in combination with antimony trioxide as synergist (11% of global FR use in EEE[1]), typically in concentrations equivalent to a 1/3-1/2 of the Br content[2].

- **Organophosphorus** compounds (27% global FR use in EEE[1]), such as triphenyl phosphate (TPP), resorcinol bis(diphenylphosphate) (RDP), bisphenol A diphenyl phosphate (BDP), tricresyl phosphate (TCP), and dimethyl methylphosphonate (DMMP).

- **Mineral** flame retardants, especially aluminium hydroxide (ATH) which accounted for 4% by weight of all flame retardants used in EEE globally in 2018[1]. This class also includes magnesium hydroxide (MDH) and red phosphorus.

- **Other** types of FR compounds (2%), such as nitrogen-based FRs.

The focus of the current study, brominated flame retardants (**BFRs**), includes over 80 different commercially available compounds. They can be classified into three main groups depending on how they are incorporated into polymer matrices[3]:

- **Additive BFRs**: physically blended with the polymer but not chemically bound to it. BFRs used additively include polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), 1,2-Bis(tribromophenoxy) ethane (BTBPE), ethylene bis(tetrabromophthalimide) (EBTBP) and decabromodiphenyl ethane (EBP). Tetrabromobisphenol A (TBBPA) can also be used additively, especially in ABS and HIPS. Some of these additive BFRs – PBBs, PBDEs and HBCD – are classified as POP substances under the Stockholm Convention due to their persistent, bioaccumulative and toxic (PBT) and long range transport (LRT) properties, see also 3.1.1.

- **Reactive BFRs**: chemically bound to the polymeric structure. One of the main reactive BFRs is tetrabromobisphenol A (TBBPA), used reactively in epoxy resins.

- **Oligomeric and polymeric BFRs**: bromine atoms are incorporated directly into the polymeric structure itself. Polymeric BFRs include brominated polystyrene (BrPS), brominated epoxy resin (BEO), brominated polyacrylate (BrPA) and butadiene styrene brominated copolymer (Poly-Bu-St).

2.1.2 BFR loadings in EEE plastics

BFRs, like most polymer additives, are an added cost which represents an **incentive** for manufacturers to **use as little as possible**, i.e. only in parts needing to be flame-retarded and at the minimum level that guarantees compliance with a flammability requirement or standard. Levels of BFRs needing to be added into polymers in order to reach the desired flame-retardancy depends on a number of factors such as:

- Required **flame-retardancy**, which is commonly tested and expressed using the standardised UL 94[a] ratings "V2" *(burning stops within 30 seconds on a vertical specimen, drips of flaming particles allowed)* and "V0" *(burning stops within 10 seconds on a vertical specimen, no flaming drips are allowed)*. Example of formulations are given in Table 1.

Table 1: Example of formulations required to achieve UL 94 V2 and V0 ratings[2]

Polymer	UL 94 rating	BFR content	Br content	ATO content	Sb content
HIPS	V2	8.9%	6.0%	2.4%	2.0%
HIPS	V0	14.9%	10.0%	4.0%	3.3%
ABS	V2	8.6%	6.0%	3.6%	3.0%
ABS	V0	14.3%	10.0%	6.0%	5.0%

- **BFR compound** used, some compounds being more reactive than others. For instance, to achieve a V0 rating in ABS, EBP would need to be added at a 15% level, and TBBPA at 20% (Table 2).

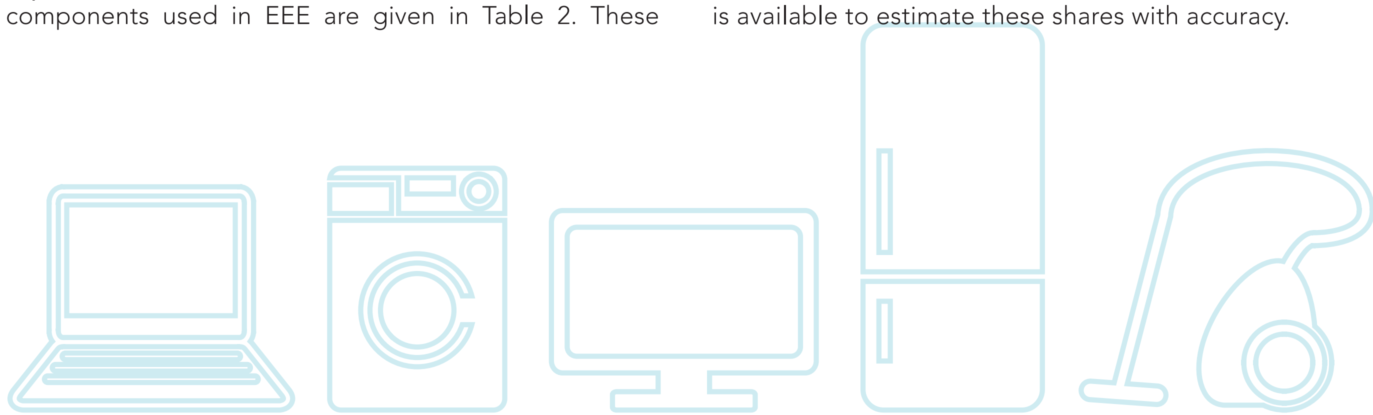
- **Polymer** considered, as they may differ in their intrinsic flammability. For instance, as much as twice the amount of EBP would need to be added to PP than to HIPS in order to achieve the same level of flame-retardancy (Table 2).

- Presence of **synergist**, in particular antimony trioxide (ATO) which, due to its synergetic effect, may considerably reduce the required levels of BFRs to be added.

Typical BFR loadings used in various polymers and components used in EEE are given in Table 2. These figures are further consolidated in order to estimate the range of BFR loading and corresponding Br content in specific polymers, when they are brominated (Table 3).

This indicates that, for instance, brominated ABS in WEEE typically contains between 10% and 22% of BFR, with a corresponding Br level of 8% to 14%. A significant share of ABS is however not brominated. Taking the example of PE, a very small fraction of PE found in WEEE is brominated but when it is, it contains 23-27% of BFR, corresponding to 19-22% Br.

As far as Epoxy resin is concerned, most is used in fabrication of printed circuit boards with the BFR – typically TBBPA – covalently bonded into the resin matrix. These ratings on "proportion of polymer stream containing Br" should be considered as indicative only, as too little data is available to estimate these shares with accuracy.



[a] UL 94, the Standard for Safety for Tests for Flammability of Plastic Materials for Parts in Devices and Appliance, is a plastics flammability standard released by Underwriters Laboratories.

Table 2: Typical loadings of common BFR compounds in WEEE plastics, by component and polymer.
Substances marked with an asterisk are no longer used, historical loading data is however provided (compilation from BSEF Members data and literature[2]).

Component		Connectors				External Casings					Foams		PWB
Polymer		PA6	PA66	PBT	PC	ABS	HIPS	PC-ABS	PE	PP	EPS	XPS	Epoxy
BFR	%Br												
OctaBDE*	79%					15%							
DecaBDE*	83%					10%	10%		27%	26%			
BCO	55%			13%	13%								
BEO	52%	21%	21%	16%	21%	22%	14%						
BrPA	71%			11%									
BrPS	67%	21%	21%	13%									
BTBPE	69%					18%	16%						
EBP	82%	15%		11%		15%	11%		25%	20%			
EBTBP	67%			13%			13%						
HBCD*	75%										<1%	<3%	
Poly-Bu-St	10%										<1%	<3%	
TBBPA	64%					20%		20%					25%
TBBPA-DBPE	67%						3%			7%			
TBNPP	70%									3%			
TBPT	73%					15%	15%						
TTBPT	67%					17%	13%						

Table 3: Range of BFR and Br content in polymers when brominated. Proportion of polymers containing Br refers to the share of the polymer stream that is brominated, e.g. most Epoxy found in WEEE is brominated, most PE is not.

Polymer	BFR loading if brominated		Br content if brominated		Proportion of polymer stream containing Br
	min	max	min	max	
ABS	10%	22%	8%	14%	medium
HIPS	3%	18%	2%	11%	medium
Epoxy	20%	30%	14%	18%	high
PP	3%	26%	2%	22%	low
PA6	15%	21%	11%	14%	low
PA66	21%	21%	11%	14%	low
PBT	11%	16%	8%	9%	low
PE	23%	27%	19%	22%	very low

2.1.3 BFR levels in WEEE plastics

As mentioned above, plastics from EEE to which BFRs are added to achieve flame-retardancy can contain from 2% up to 22% of bromine, equivalent to 20,000-220,000 ppm. However, most EEE plastics (around 90%) are not brominated, as BFRs are only added to specific product types and components that require flame-retardancy. For this reason, average BFR levels in mixed WEEE plastic fractions are substantially below these functional Br levels.

A large number of studies have been carried out to determine the levels of BFRs in mixed WEEE plastic fractions. Such studies, if based on scientifically robust sampling and testing methods, allow the monitoring of trends in BFR levels in various WEEE categories. As such, they can provide a sound basis for policymaking, standards setting, and operational decisions, for instance, to identify WEEE categories requiring specific treatment due to elevated levels of restricted BFRs.

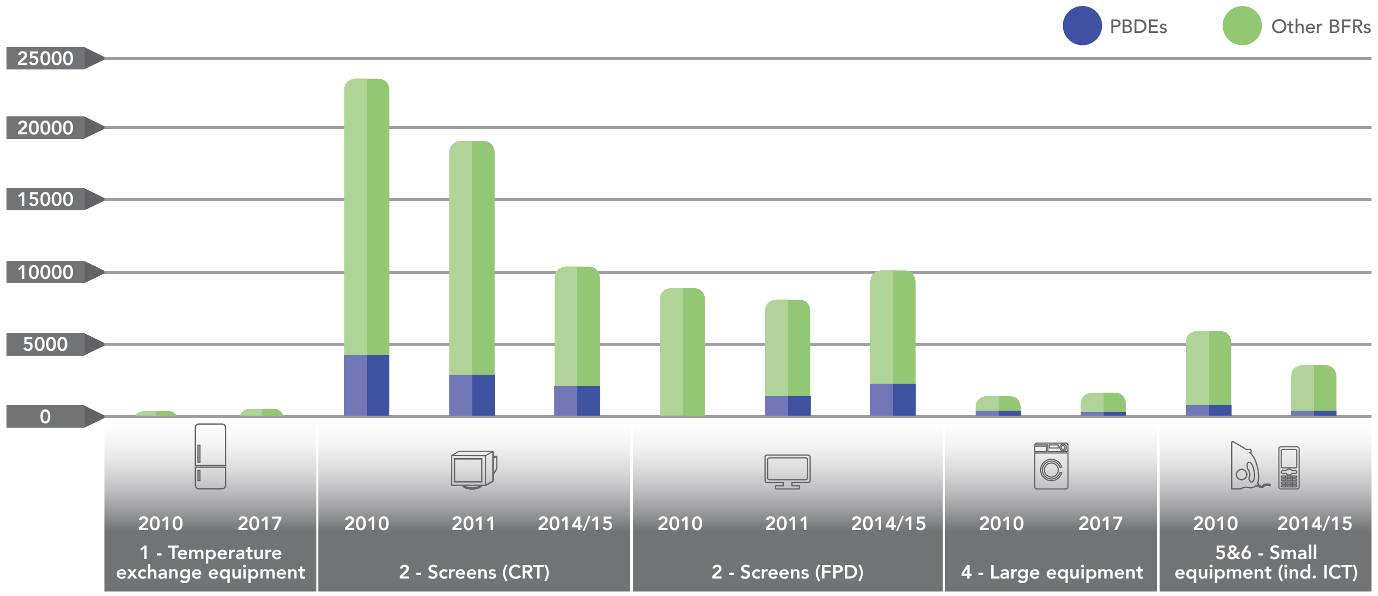
Eight of such studies were reviewed here and relevant data was extracted and consolidated. Only those studies looking at BFR levels in **representative samples of unsorted WEEE plastic mixtures** were considered.

Studies based on sampling methods which could present a statistical bias, such as only analysing Br-rich parts after field screening using e.g. handheld XRF devices, were not included. In total, data from 5 studies[4–8] **were retained**, representing a total of **367 samples**. Results are given in Table 4. Furthermore, the temporal evolution of Br, TBBPA and PBDE levels is illustrated in Figure 1.

Table 4: Mean and median Br, PBB, HBCD, PBDE and TBBPA levels (ppm) in unsorted WEEE plastics. Data from 5 studies, 367 samples[4–8]. "BDL": below detection limit; "-": not measured / reported. Share of PBDEs and TBBPA in the total Br content was estimated considering a Br content of 71% in PentaBDE, 79% in OctaBDE, 83% in DecaBDE and 59% in TBBPA.

Category	Sampling year	# samples	Br		ΣPBBs		HBCD		Penta+OctaBDE		DecaBDE		ΣPBDEs		TBBPA		%PBDEs in total Br	%TBBPA in total Br	Reference
			Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median			
1 – Temp. exch. equipement	2010	12	245	210	BDL	BDL	BDL	BDL	BDL	BDL	92	BDL	92	BDL	5	BDL	31%	1%	Wäger et al. 2011
	2017	30	-	BDL	-	-	-	-	BDL	BDL	BDL	BDL	BDL	-	-	-	-	-	Drage et al. 2018
	2017	15	353	293	BDL	BDL	BDL	BDL	3	BDL	49	25	103	81	102	14	12%	17%	Haarman et al. 2018
2 – Screens	2017	43	-	320	-	-	-	-	38	BDL	1900	BDL	1938	-	-	-	-	-	Drage et al. 2018
2 - Screens (CRT)	2010	14	23571	15500	104	85	357	BDL	1486	665	3700	3450	5186	3995	16964	2975	18%	42%	Wäger et al. 2011
	2011	6	19167	19000	BDL	BDL	42	BDL	974	839	2600	2400	3574	3457	7553	6970	15%	23%	Taverna et al. 2017
	2014-2015	8	10394	-	34	34	552	276	574	-	1933	-	2507	-	3335	-	20%	19%	Hennebert et al. 2018
2 - Screens (FPD)	2010	6	8950	7900	BDL	BDL	BDL	BDL	32	BDL	67	BDL	98	BDL	1253	805	1%	8%	Wäger et al. 2011
	2011	6	8117	8150	BDL	BDL	BDL	BDL	11	12	1700	1500	1711	1511	2705	2375	17%	20%	Taverna et al. 2017
	2014-2015	8	10014	-	BDL	BDL	15	8	18	-	2708	-	2725	-	2100	1050	23%	12%	Hennebert et al. 2018
4 - Large equipment	2010	6	1083	1135	BDL	BDL	BDL	BDL	BDL	BDL	450	150	450	150	18	BDL	34%	1%	Wäger et al. 2011
	2017	57	-	0	-	-	-	-	BDL	BDL	19	BDL	19	-	-	-	-	-	Drage et al. 2018
	2017	21	1541	1300	BDL	BDL	8	BDL	17	BDL	147	48	201	170	222	52	9%	9%	Haarman et al. 2018
5 - Small equipment	2010	14	3258	1450	9	BDL	BDL	BDL	71	BDL	343	300	414	300	719	275	10%	13%	Wäger et al. 2011
	2017	29	-	1	-	-	-	-	BDL	BDL	170	BDL	170	-	-	-	-	-	Drage et al. 2018
6 - Small ICT	2010	6	11767	13000	8	BDL	BDL	BDL	450	295	883	700	1333	1575	3485	3675	9%	17%	Wäger et al. 2011
	2017	78	-	18	-	-	-	-	17	BDL	260	BDL	277	-	-	-	-	-	Drage et al. 2018
5&6 – Small equipement incl. ICT	2014-2015	8	3503	-	BDL	BDL	157	79	72	-	378	-	450	-	843	422	11%	14%	Hennebert et al. 2018

Figure 1: Breakdown of total bromine content (ppm) in unsorted WEEE plastic samples, based on mean levels as given in Table 4 (values for small appliances (categories 5 & 6) were here grouped).



A number of observations can be made from these results:

- Median BFR levels are typically lower than average levels, due to the usually **bimodal distribution**, with many particles with nil or low concentration, and a small number of particles parts with high concentrations. These small number of high-Br particles strongly influence average levels[9].

- Across WEEE categories, BFR levels are highest in **screens** (average Br level around 10,000 ppm, i.e. 1% in 2014-2015 for both CRT and FPD screens), followed by **small equipment** (~3,500 ppm Br on average in 2014-2015). Large household appliances contain relatively little (~1,500 ppm Br on average in 2017), and temperature exchange equipment almost none (~350 ppm Br on average in 2017).

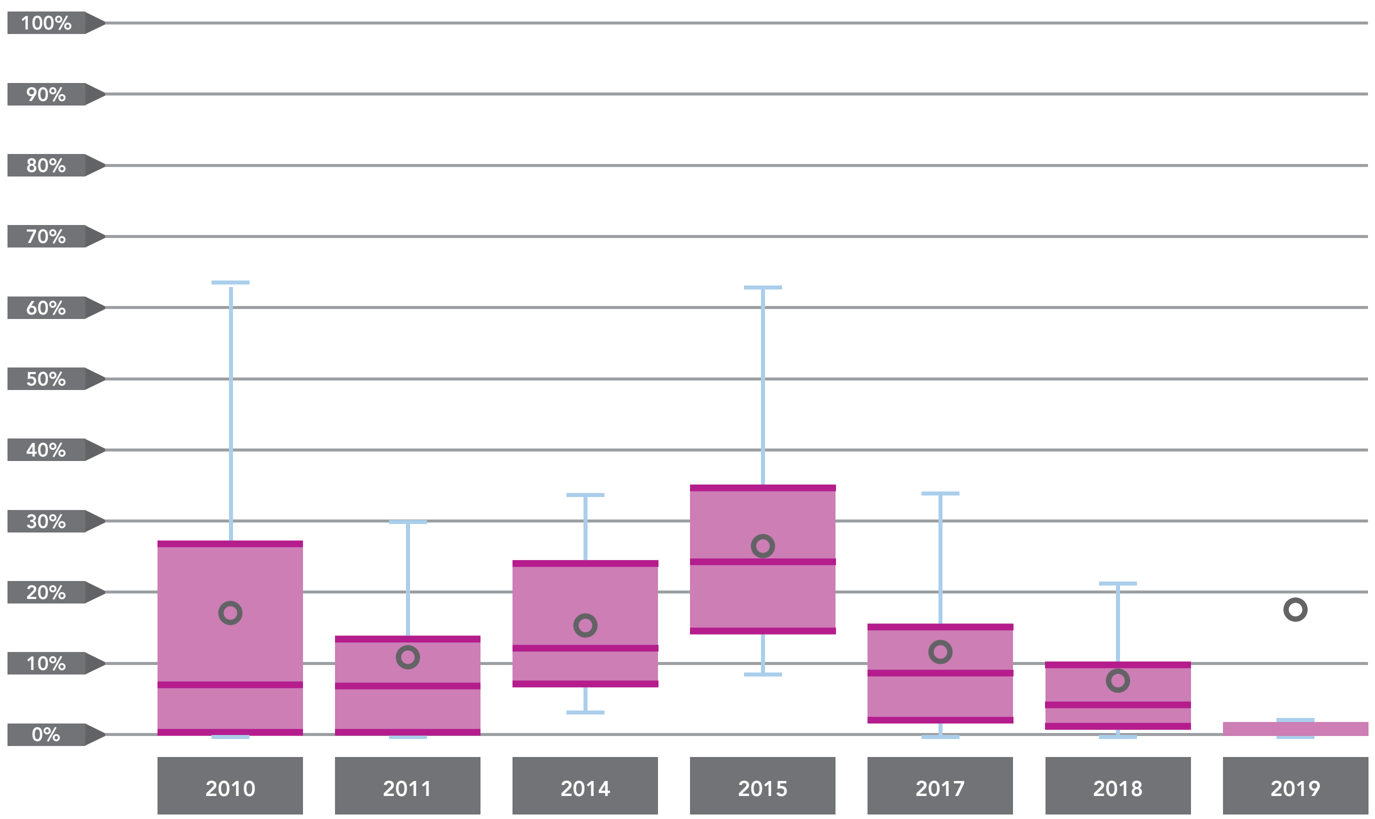
- Among the restricted BFR substances – PBBs, PBDES and HBCD –, only PBDEs are found at relevant levels.

- Out of the total Br content measured, the **share attributable to PBDEs** varies between 1% and 34%, and between 1% to 42% for TBBPA. Most of the total Br content can therefore not be attributed to the presence of PBDEs nor TBBPA. This may be due to several factors, including the presence of other common BFR compounds such as EBP which represent about 20% of the total Br content on average[6,8,10]

- Over the period of time considered, BFR levels show a **decreasing trend** in CRT screens (halving of Br levels between 2010 and 2014-2015) and small appliances (40% decrease of Br levels between 2010 and 2014-2015). This could indicate the growing use of other flame retardants such as mineral FRs and organophosphorus compounds. On the other hand, BFR levels in FPD screens as well as large equipment appear to have remained relatively stable.

In order to investigate in more detail the evolution of the share of PBDEs in the total BFR content, a larger set of data was considered, including the studies referred to above as well as 3 other recent studies that were previously excluded either because they applied a biased methodology including XRF-screening to select samples for BFR analysis[11], or because the sampled material didn't correspond to unsorted WEEE plastic mixtures but rather processed WEEE plastics (regrinds or regranulates)[10] or articles presumably made of WEEE plastic recyclates[12]. It was assumed that these methodological variations didn't affect the relative share of PBDEs in the total BFR content. The resulting dataset, including 354 samples, is illustrated in Figure 2.

Figure 2: Share of total Br attributable to PBDEs. Data from 7 studies, 354 samples[4,6–8,10–12].
The boxes show the range from first to third quartiles, with the median dividing the box. Dots show the average values.
Values below detection limit were considered as null.



Results show considerable variability in the share of PBDEs relative to the total Br content of samples, with yearly median levels ranging from 0% up to 25%. Despite this variability, **a downwards trend** is clearly visible from 2015 onwards, indicating a phasing out of PBDEs in waste stream. Median levels reached 4% in 2018 (109 samples) and 0% in 2019 (57 samples), meaning that **PBDEs were not found in approximately half of the samples** tested in those years. High PBDE levels may still be found in single particles, which raise average (as opposed to median) levels up to 9% in 2018 and 17% in 2019.

In summary, the analysis carried out above indicates that the levels of **BFRs in WEEE plastics have decreased significantly over the last ten years, as has the share of PBDEs** in the total BFR content. BFR levels are low in

2 BFR levels and BFR plastic flows

large household appliances (~1,500 ppm Br in 2017) and very low in temperature exchange equipment (~350 ppm Br in 2017). **Screens and small appliances** contain higher levels of BFRs (respectively ~10,000 ppm and ~3,500 ppm), but with **little or no PBDEs nowadays** (10-20% of total Br content).

Reducing levels of PBDEs are a clear indication that the regulatory restrictions introduced between 12 and 17 years ago are now manifesting themselves in WEEE streams across the board.

High PBDE levels (up to 10-20% i.e. 100,000-200,000 ppm in single particles) might still be found sporadically, as some devices becoming wastes nowadays would have been manufactured before the entry into force of regulatory restrictions on the use of PBDEs in EEE (Marketing & Use Directive and, later, RoHS Directive : 2003 for Penta & OctaBDE, 2008 for DecaBDE). In view of these trends, mean PBDE levels can be expected to **further decrease in the coming years.**

2.2 BFR plastic flows

2.2.1 WEEE plastic composition

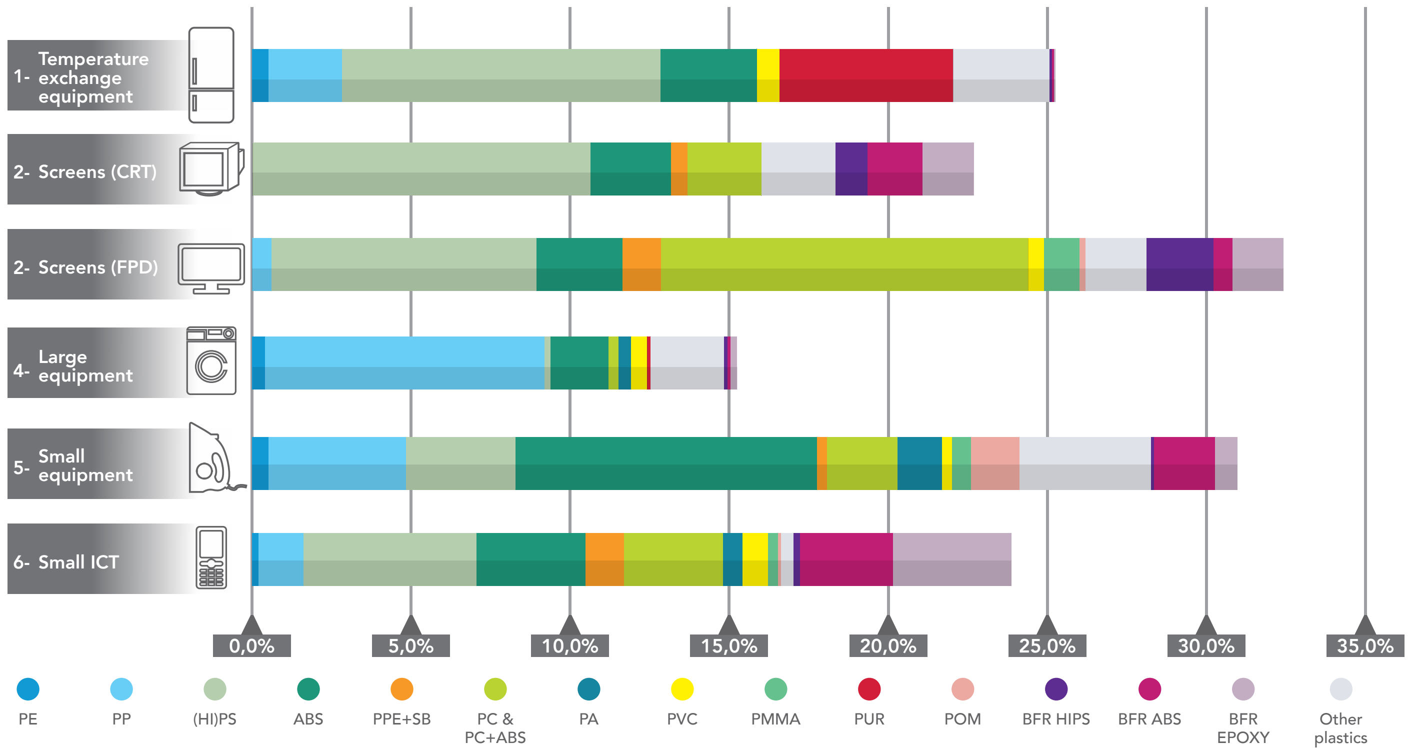
A **wide range of polymers and additives** can be found in WEEE plastic fractions. Within the framework of the current study, a large database on WEEE plastics composition at the WEEE category level[b] was developed. Lamps were not included in the scope due to the marginal share they represent in the overall mass of WEEE generated (around 0.5%[13]), and the general lack of data on their composition.

More than **800 data points** were compiled in total, from a wide variety of sources including published studies[4,13–17] as well as process data (typically resulting from batch tests) provided by WEEE recyclers, WEEE plastic recyclers and take-back schemes. Data includes information on both the overall share of plastics in different equipment types or categories, as well as on the relative shares of various polymers (including distinction between BFR-free and BFR-containing for ABS, HIPS and Epoxy resins). The consolidated results, based on averaging data considered to be of high quality[c], are displayed in Figure 3.

[b] 6 WEEE categories according to Annex III of the WEEE Directive (2012/19/EU) : **1 - Temperature Exchange Equipment** (TEE) such as refrigerators, air-conditioning equipment, and heat pumps / **2 - Screens, monitors, and equipment containing screens** having a surface greater than 100 cm² such as monitors, televisions, laptops and tablets / **3 – Lamps**, such as fluorescent, LED, HID, and LPS lamp bulbs and tubes / **4 - Large equipment**, which includes any EEE not included in Categories 1, 2, or 3 that has at least one external dimension (L, W, H) greater than 50 cm, such as washers, dryers, electric stoves, large medical equipment and photovoltaic panels / **5 - Small equipment**, which includes any EEE not included in other categories, having all external dimensions (L, W, H) inferior to 50 cm and not being an IT equipment (Category 6), such as vacuum cleaners, microwaves, small kitchen appliances, and consumer electronics / **6 - Small IT and telecommunication communications equipment**, which includes any EEE not included in other categories with all external dimensions (L, W, H) less than 50 cm that is used for IT, computing, or communications, such as smartphones, desktop computers, GPS equipment, printers, routers, and fax machines.

[c] Composition data was considered of high quality if obtained through documented and scientifically robust sampling and analysis methods, mainly batch tests (as described by EN 50625 standard) to determine overall plastic share, and manual or mechanical sorting of representative samples to determine relative shares of polymers. In the case of large and small household appliances, a comprehensive database of BOM (bill of materials) data was also considered as being of high quality.

Figure 3: WEEE plastics composition, per category. FPD refers to flat panel displays monitors and TVs but also, in the scope of this study, laptops and tablets.



The following observations can be made:

- Temperature exchange equipment (TEE) contains 25% of plastics in total, mainly PS (40%), PUR (22%), PP (9%) and PVC (3%). BFR plastics represent **less than 1%** of the plastic fraction in TEE.

- CRT screens have a plastic share of 23%, mainly HIPS (47%), ABS (11%), PC-ABS (10%), BFR ABS (7%), BFR Epoxy (7%) and BFR HIPS (5%). The overall share of BFR plastics is **19%**.

- FPD screens (also including laptops and tablets) are made of 32% plastics, mainly PC-ABS (36%), HIPS (26%), ABS (8%), BFR HIPS (7%) and BFR Epoxy (5%), PMMA (3%) and BFR ABS (2%). The overall share of BFR plastics is **13%**.

- Large equipment contains only 15% plastics, mainly PP (57%), ABS (12%), PA (3%), PE (2%) and PC/PC-ABS (2%). BFR plastics account for about **3%** of the total plastic share.

- Small equipment (non-ICT) consists of 31% plastics, mainly ABS (30%), PP (14%), HIPS (11%) and PC-ABS (7%). BFR plastics represent **9%** of the plastic fraction.

- Small ICT equipment have a 24% plastic content, mainly HIPS (23%), ABS (14%), BFR Epoxy (16%), PC-ABS (13%), BFR ABS (12%), 6% of PP and 5% of PPE-SB. BFR plastic account for **29%** of small ICT equipment plastics.

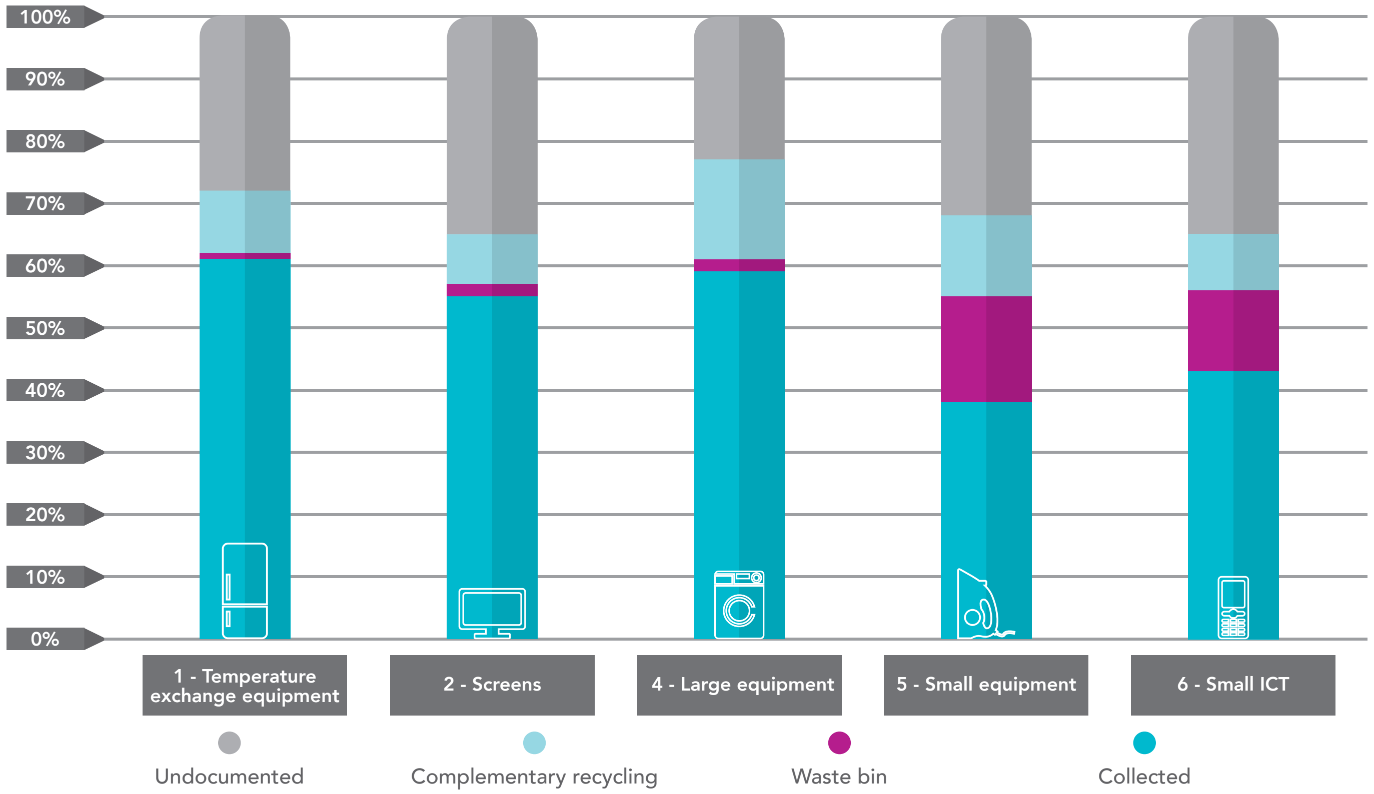
Hereafter in this report these consolidated composition data are combined with data on the overall quantities of WEEE generated, collected and treated in Europe, to give a quantified picture of the current fate of WEEE plastics in general, and BFR plastics in particular.

2.2.2 WEEE plastic flows

In order to quantify the volumes of WEEE plastics flowing through existing end-of-life channels, it is first necessary to understand the **destinations of WEEE that has been generated**. Several studies have been conducted in the past to give a comprehensive picture of WEEE flows in Europe, recently combined as part of the ProSUM project[13].

Based on ProSUM data, updated with newly available information[18] for WEEE categories 1, 4 and 5, the fate of WEEE generated is depicted in Figure 4.

Figure 4: Destinations of WEEE arising in Europe



Of the 10.9 million tons of WEEE arising annually in Europe[13], **only half is collected** through official WEEE take-back channels. Some 12% are treated through so-called **complementary recycling** which refers to the treatment of WEEE mixed with other ferrous or non-ferrous metal scrap, typically under substandard conditions (e.g. lack of depollution) and escaping official WEEE accounting. About 7% is improperly disposed of in the **waste bin** and ends up either incinerated or landfilled. Finally, **30% of all WEEE generated has an undocumented fate**, including **export** either for reuse, recycling or disposal abroad.

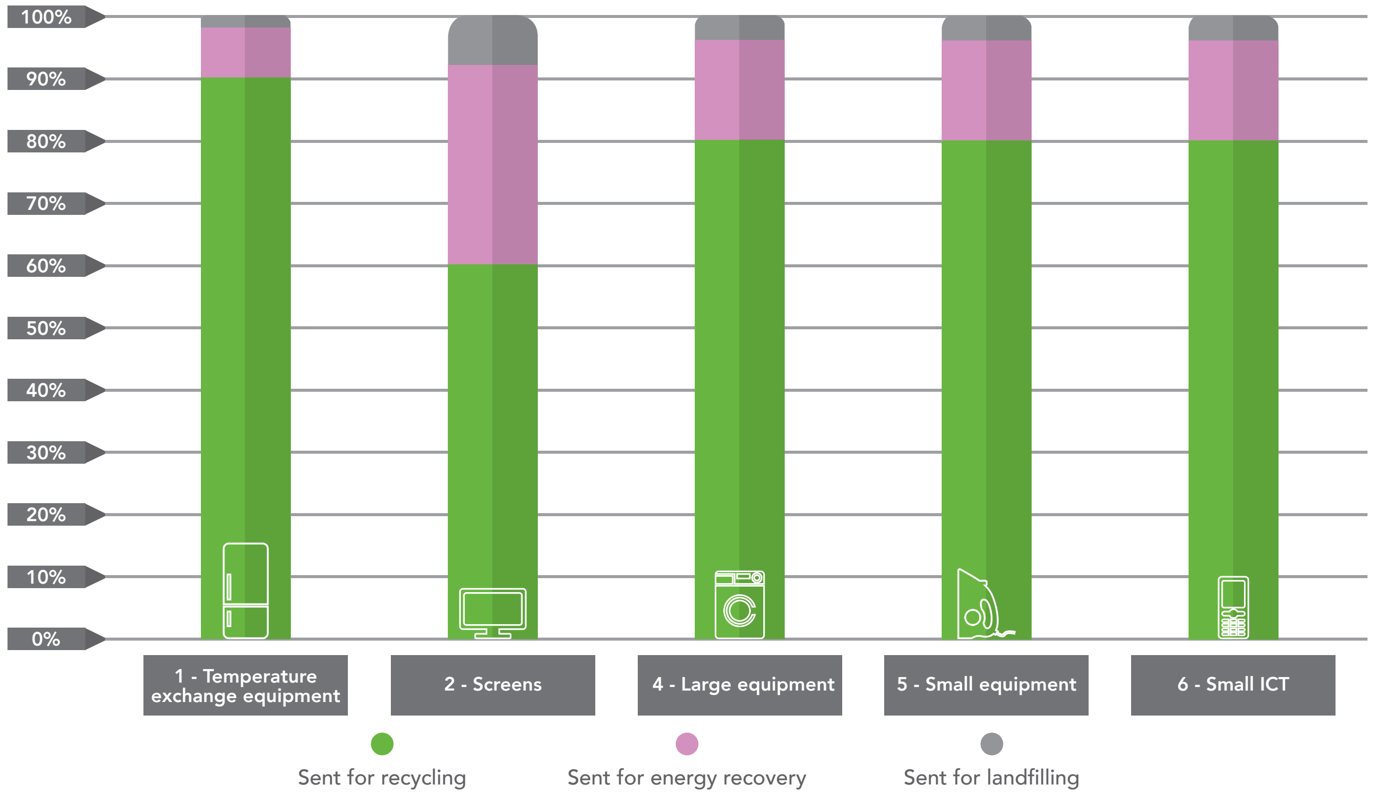
WEEE plastics follow the same routes as WEEE to the point where they are separated from other materials, i.e. during manual or mechanical treatment. When WEEE is collected through official channels, it undergoes **pre-processing** operations that include both manual and mechanical separation processes aiming at removing hazardous substances as well as recovering valuable ones.

These processes concentrate the various materials constituting WEEE into relatively homogeneous fractions for further treatment, either recycling, incineration or landfilling. WEEE plastics are thereby concentrated into one or several fractions which can be sent to various downstream operators. Epoxies present in printed circuit boards are usually sent to copper smelting facilities aimed at recovering the precious metal content, whereby the plastic content acts as reducing agent and fuel substitute. Other plastics can be either sent to specialised WEEE plastics recycling facilities, or to disposal through energy recovery (incineration or co-processing) or landfilling.

The split between these downstream treatment routes vary depending on equipment categories, level of enforcement of quality standards, as well as regional and temporal economic conditions. The actual share of each route in Europe had to be estimated based on the following considerations informed by exchanges with stakeholders:

- High share sent for recycling (90%) of plastics from TEE due to the efficiency of pre-processing technologies, producing relatively pure plastics fractions, and the high intrinsic value of plastics found in TEE;
- Relatively low share sent for recycling (60%) of plastics from screens, as in some countries (e.g. France) these plastics (especially from CRT) may be classified as hazardous waste and can therefore not be received by plastic recyclers that typically do not have licenses to treat hazardous waste;
- Relatively high share sent for recycling (80%) of plastics from other large and small appliances, driven by both the intrinsic value of plastics and ambitious mandatory recycling rates;
- Among the fraction not sent for recycling, a share of 80% energy recovery and 20% landfilling was assumed. This is higher than the 68:32% split reported by Plastics Europe for plastic packaging waste[19], considering that the ambitious recovery targets for WEEE should lead to a higher share of incineration (e.g. 85% recovery target for TEE and large equipment as per Annex V of the WEEE Directive).

Figure 5: Destination of WEEE plastics in WEEE collected

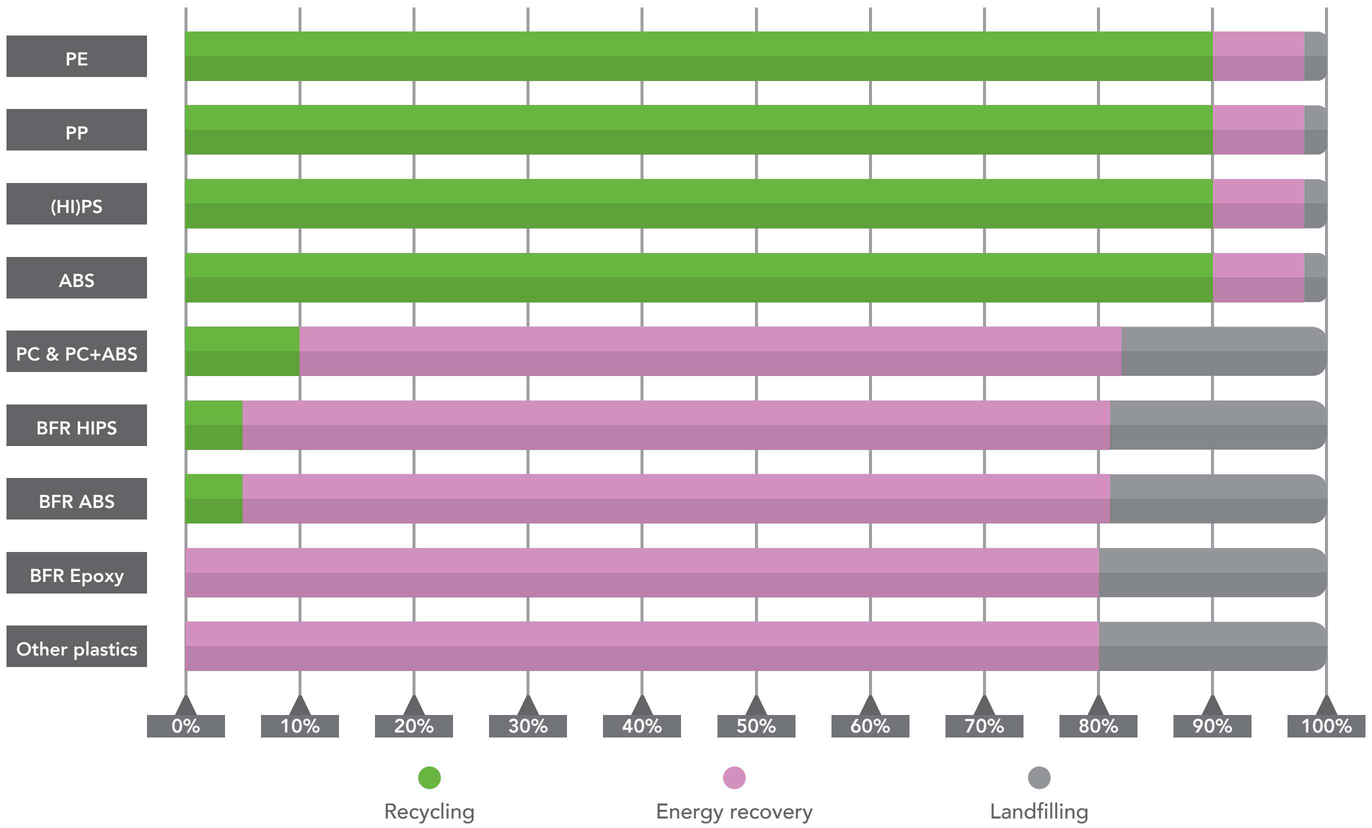


2 BFR levels and BFR plastic flows

WEEE plastics sent to **WEEE plastic recycling facilities** undergo a series of sorting steps whereby target plastics are recovered and turned into regranulates. For most WEEE plastic recyclers, target plastics are PS, ABS, PP and PE. One WEEE plastic recycling company is also able to recover PC-ABS[20]. Other polymers found in WEEE are usually not recovered, for both technical (e.g. sorting challenges) and economic reasons (e.g. missing market or low prices) and are disposed of by incineration or landfilling (see also 3.2.2). Here also, a general lack of data makes it impossible to estimate the fate of WEEE plastics entering WEEE plastic recycling facilities with accuracy. The following assumptions were drawn to fill this data gap:

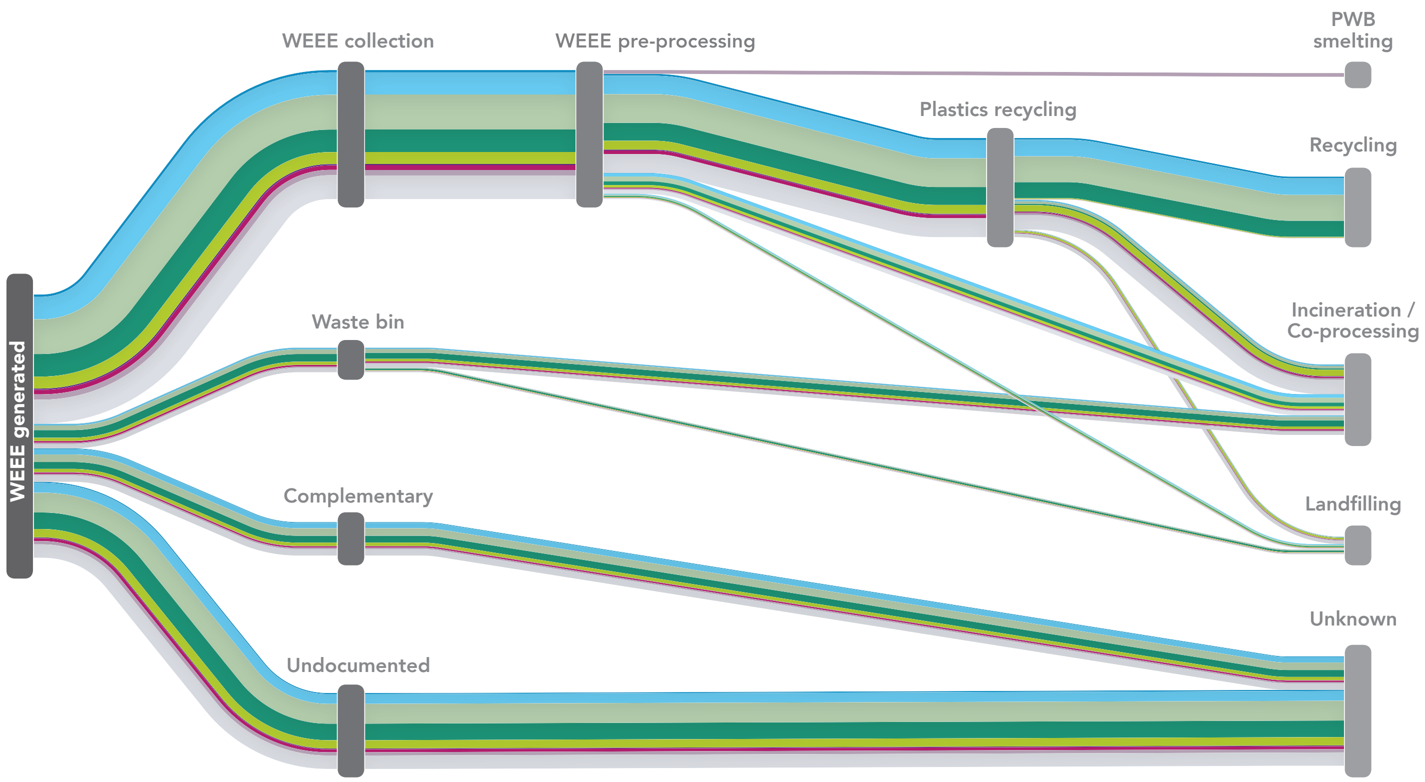
- Common target polymers (PE, PP, PS and ABS) are recycled at 90%, 10% being inevitably lost due to sorting inefficiencies
- 10% of PC-ABS (and PC) ending up in WEEE plastic recycling facilities are recycled, as only one company treating about 50 kt of WEEE plastics annually reports being able to do so[20].
- 5% of BFR ABS and BFR HIPS are unintentionally recycled, as conventional density-based sorting methods have been shown to have a removal efficiency of at least 95%[21].
- Other plastics are not considered to be recycled other than in marginal amounts.
- Among the non-recycled fraction, a split of 80:20% assumed between energy recovery (incineration or co-processing) and landfilling for the same reasons as provided above.

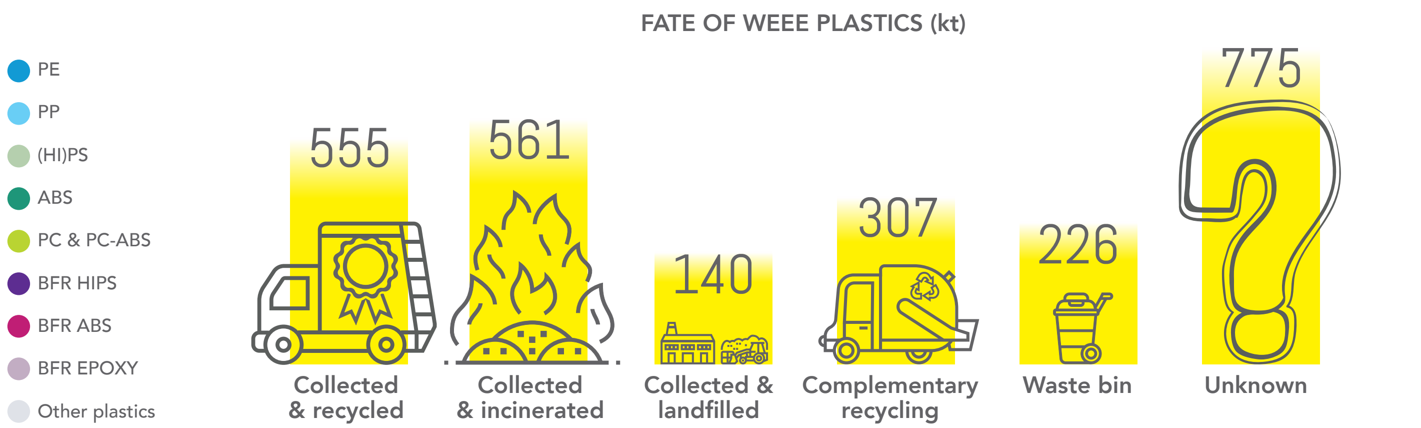
Figure 6: Output of WEEE plastics recycling, by plastic type. In the case of BFR Epoxy, energy recovery mainly refers to treatment of printed circuit boards in copper smelters, whereby the epoxy acts as fuel substitute (and reducing agent).



Combining these figures and estimations with the data on WEEE plastic composition presented in 2.2.1, it becomes possible to provide an overview of the current fate of WEEE plastics generated annually in Europe (Figure 7).

Figure 7: Fate of WEEE plastics, 2020, EU-28 + Switzerland & Norway





Complementary recycling which refers to the treatment of WEEE mixed with other ferrous or non-ferrous metal scrap, typically under substandard conditions (e.g. lack of depollution) and escaping official WEEE accounting.

2 BFR levels and BFR plastic flows

In total, **2.6 million tons of WEEE plastics are generated annually**, mainly comprised of PP (20% of total), ABS (19%), (HI)PS (18%) and PC/PC-ABS (7%). **Brominated plastics represent about 9% of the total**, mainly BFR ABS (4%), BFR Epoxy (3%) and BFR HIPS (1%). The remaining 27% includes other engineering polymers such as PA6, PA66, POM, PBT and PMMA.

About **half of all WEEE plastics arising (1.3 Mt) are channelled into official WEEE collection** streams, whereby **ultimately 22% are recycled** (560 kt), 22% energetically valorised (555 kt), and 5% landfilled (140 kt). 12% of all WEEE plastics (307 kt) follow complementary recycling routes, and 9% are thrown into the waste bin (260 kt), therefore ending up incinerated or landfilled. Undocumented destinations of WEEE account for 30% of all WEEE plastics arising (775 kt).

The 555 kt of **WEEE plastic regranulates** are used in the manufacture of a variety of products, among which EEE represent a marginal share. The plastic post-consumer recycled content of EEE has indeed been estimated below 1%[22]. Considering that about 12 Mt of EEE are annually placed on the European market[13], containing on average some 25% plastics, it can be estimated that **less than 30 kt tons of WEEE plastic regranulates are incorporated into new EEE products** (5% of WEEE plastic regranulates produced). More common markets for WEEE plastic regranulates include automotive parts, flowerpots, clothes hangers and transport pallets.

There are various reasons for the relatively **low share of "closed-loop" recycling** of WEEE plastics (WEEE to EEE). On the one hand, very little of the EEE used in Europe is actually produced in Europe, most being produced in Asia. Local demand however exists for the above-mentioned types of products, for which large manufacturing capacity exists in Europe. On the other hand, EEE manufacturers are often reluctant to use WEEE plastic regranulates due to concerns over quality and potential presence of problematic substances.

The estimated 555 kt of WEEE plastic regranulates produced annually mainly consist of PP (200 kt), PS (170 kt) and ABS (160 kt). These volumes can be compared to the overall consumption of these polymers in Europe, estimated at respectively 9,900 kt, 3,300 kt and 900 kt[19]. **Current production of WEEE plastic regranulates therefore represents 2%, 5% and 18% of the EU consumption of PP, PS and ABS**, respectively. The overall theoretical potential, considered here as the quantities of PP, PS and ABS in WEEE plastics generated, reaches 520 kt PP, 460 kt PS and 500 kt ABS. In the hypothetical scenario that 100% of these plastics were recycled, this would meet 5%, 14% and 56% of the total EU consumption of PP, PS and ABS.

Fate of BFR-containing plastics

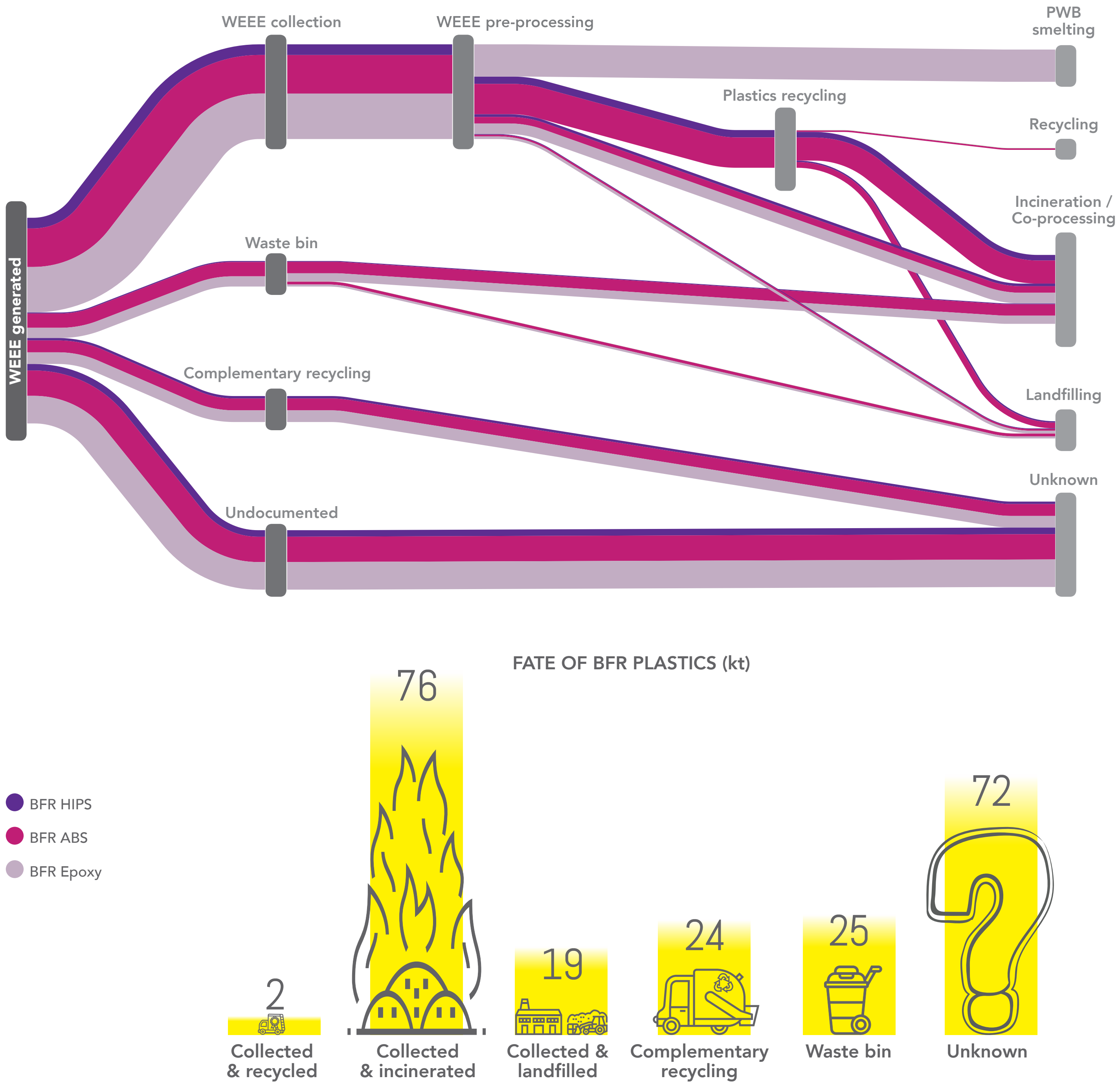
In order to better visualise the fate of the brominated plastics arising in WEEE generated, BFR-containing plastics are isolated in Figure 8. It appears **that 220 kt of BFR plastics arise annually in WEEE, 45% being collected** (98 kt), 12% thrown in the waste bin (25 kt), 11% treated in complementary recycling (24 kt) and 33% being part of WEEE with an undocumented destination (72 kt).

Out of the 98 kt of BFR plastics present in WEEE collected, 76 kt are incinerated (incl. 22 kt of BFR Epoxy in smelters), 19 kt landfilled and only 2 kt are recycled, representing 1% of the total quantity of BFR plastics generated, and 2% of BFR plastics collected.

In other words, **98% of BFR plastics collected can be currently separated and disposed of through official WEEE recycling channels**. However, **55% of all BFR plastics generated are not actually entering these channels**, as a result of **improper sorting of WEEE by consumers or substandard WEEE treatment practices**.

An unknown but potentially significant share of these uncollected BFR plastics might end up in uncontrolled plastic recycling settings, potentially contaminating recyclates streams due to an absence of BFR removal. Such "bad recycling practices" can be evidenced by the presence of too high levels of POP-BFRs in children toys and food-contact articles made on the Asian continent, for instance in China or Turkey[23].

Figure 8: Fate of BFR plastics from WEEE, 2020, EU-28 + Switzerland & Norway



Complementary recycling which refers to the treatment of WEEE mixed with other ferrous or non-ferrous metal scrap, typically under substandard conditions (e.g. lack of depollution) and escaping official WEEE accounting.

3 Treatment of WEEE plastics containing BFRs

3.1 Normative requirements

Over the past decades, evidence of the persistence, bioaccumulation potential and toxicity (PBT properties) of some BFR substances has led to **regulatory restrictions** on their production, use and recycling. Such restrictions can be found in various legislations, related to **chemicals** (e.g. REACH regulation), **products** (e.g. RoHS Directive) **or wastes** (e.g. Waste Framework Directive, WEEE Directive).

Chemicals and products regulations do not directly apply to wastes but may do so once wastes reach the so-called end-of-waste status, i.e. they have undergone a recovery operation and have become a product. **End-of-waste criteria for plastics, including those from WEEE, have long been debated and no consensus could be reached yet.**

The point after which chemicals and products legislation applies in the waste treatment and recovery chain is therefore uncertain at present. Within its 2018 call for a broad discussion on issues related to the interface between chemical, product and waste legislation, the European Commission recognised the need to clarify and harmonise end-of-waste criteria for plastics [24].

Given the uncertainty of the application of product and chemical regulation, this study focused on requirements from **waste regulations** that directly apply to waste plastics containing BFRs. These include:

- **POP** (persistent organic pollutant) regulations that stipulate how a waste material containing POPs above a certain limit value must be treated;
- **Waste classification** regulations that determine whether a waste material shall be classified as hazardous or not;
- **WEEE Directive** that sets rules for the collection, treatment and recovery of waste electrical and electronic equipment;
- **WEEE treatment standards** that lay down how WEEE shall be handled in practice (EN 50625 series). Although not a regulation per se, WEEE treatment standards may be legally (or contractually) binding, making compliance with them also mandatory.

Hereafter, these waste-related rules and their prescriptions regarding WEEE plastics containing BFRs and associated substances are further described.

3.1.1 POP regulation

Persistent organic pollutants (POPs) are chemical substances characterised by their potential toxicity, persistence in the environment, biomagnification and bioaccumulation. Their production, use and unintentional release is restricted at the international level by the Stockholm Convention on Persistent Organic Pollutants. Currently, 28 compounds or group of compounds are listed as POPs under the Stockholm Convention, either in its Annex A (Elimination), B (Restriction) or C (Unintentional production). Annex A includes 5 BFR compounds, referred to as **POP-BFRs**:

- Hexabromobiphenyl (hexaBB), listed in 2009;
- Commercial pentabromodiphenyl ether (c-pentaBDE, consisting mainly of tetraBDE and pentaBDE), listed in 2009;
- Commercial octabromodiphenyl ether (c-octaBDE, consisting mainly of hexaBDE and heptaBDE), listed in 2009;
- Hexabromocyclododecane (HBCD), listed in 2013;
- Commercial decabromodiphenyl ether (c-decaBDE consisting mainly of decaBDE), listed in 2017.

In the European Community, the restrictions of the Stockholm Convention have been implemented with the European POP Regulation ((EC) No 850/2004).

The EU POP Regulation prescribes how a waste material must be treated if it contains POPs above certain limit values (so-called "low POP concentration limit" (**LPCL**), Annex IV). Currently, a LPCL of **50 ppm** is set for hexaBB, of **1,000 ppm** for HBCD, and of **1,000 ppm** for PBDEs (sum of c-pentaBDE, c-octaBDE and c-decaBDE). The LPCL for PBDEs is to be reviewed by the European Commission by July 2021[25].

Waste whose concentration exceeds the limits must be disposed of or recovered such a way that the **POP content is destroyed or irreversibly transformed** (Art. 7). Disposal or recovery operations that may lead to recovery, recycling, reclamation or re-use of POPs is prohibited. The following disposal and recovery methods for waste that exceeds the lower limit value are permitted (Annex V):

- Physico-chemical treatment (D9);
- Incineration without energy recovery (D10);
- Incineration, using the waste to generate energy (R1);
- Recycling and reclamation of metals (R4).

Recycling of plastics are therefore not a permitted treatment method for wastes containing POPs above the low POP content. Pre-treatment operation prior to destruction or irreversible transformation may however be performed, provided that the POP substance is isolated from the waste during the pre-treatment is subsequently disposed of through one of the above-listed disposal and recovery methods. POP-containing waste can therefore go through a separation process concentrate the POP content, as well as produce a fraction almost free of POP-BFRs (below the LPCL).

It should be noted that different limit values apply to POPs in products, corresponding to the "unintentional trace contaminant" threshold (**UTC**) set by Annex I of the Regulation. The UTC level is 500 ppm for the sum of PBDEs and 100 for HBCD (no UTC set for hexaBB). Therefore, WEEE plastics may currently be recycled if they contain up to 1,000 PBDEs and 1,000 ppm HBCD, however WEEE plastic regranulates (products) must contain less than 500 ppm PBDEs and 100 ppm HBCD. The UTC level for PBDEs is also to be reviewed by the European Commission by July 2021[25].

3.1.2 Waste classification

In the European Community, the classification of hazardous or non-hazardous waste is regulated in the Waste Framework Directive 2008/98/EC (**WFD**). Waste is considered as hazardous if it has one or more of the **hazardous properties** listed in Annex III of the WFD (HP 1 to HP15). Commission Regulation (EU) No 1357/2014 defines limit values for different hazardous properties. National legislations prescribe how the classification of waste as hazardous or non-hazardous affects requirements regarding accepted treatment method, required authorisations for treatment facility receiving the waste, transboundary shipments, and other aspects.

In practice there are **considerable differences** in how plastics containing BFRs are classified **among European countries**[26]. Some countries classify waste as hazardous waste if low POP concentration limits are exceeded, others only consider hazardous properties and limit values set by Commission Regulation (EU) No 1357/2014. France represents a unique case, where both origin of waste (in terms of product type) as well as total bromine content are considered to classify WEEE plastics as hazardous or not27. For instance, Br-rich fractions resulting from Sink/Float or XRT sorting (see 3.2.3) are classified as hazardous waste if they originate from CRT screens, but as non-hazardous if they originate from FPD screens. WEEE plastics recycling facilities typically have no license to receive and treat hazardous waste, so that classification of WEEE plastic fractions as hazardous directly reduces recycling yields.

As a result, is often difficult to ensure the proper and necessary movement of the waste from one country to another to ensure treatment in specialised processes and fulfilment of the capacity of existing facilities.

3.1.3 WEEE Directive

The EU WEEE Directive (2012/19/EU) sets rules for the collection, treatment and recovery of waste electrical and electronic equipment. Its **Article 8** stipulates that all separately collected WEEE shall undergo appropriate treatment, which shall as a minimum include the removal of all fluids and a **selective treatment** in accordance with Annex VII.

Annex VII of the WEEE Directive lists the substances, mixtures and components that have to be **removed from any separately collected WEEE**. These include two BFR-containing components:

- *plastic containing brominated flame retardants*
- *printed circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimetres*

The WEEE Directive doesn't specify how these two types of materials shall be treated after their removal. It also does not specify substances and/or thresholds applicable to define whether plastics are considered as containing BFRs or not.

3.1.4 EN 50625 standards

After the entry into force of the WEEE Directive, the European Commission mandated CENELEC to develop what has become the EN 50625 series of standards, which sets normative requirements for the collection, transport and treatment of WEEE in compliance with the Directive. The EN 50625 series includes 5 European Standards (EN) and 6 Technical Specifications (TS).

The EN 50625 standards are legally binding for WEEE treatment facilities in Belgium, Ireland, France, Lithuania and the Netherlands. In some countries, such as Switzerland, compliance to EN 50625 is part of the contractually binding duties of WEEE treatment operators towards producer responsibility organisations (PROs). European organisations representing EEE producers, WEEE take-back schemes and WEEE recyclers are calling for an EU-wide mandatory implementation of the EN 50625 standard series[28].

Annex A of EN 50625-1 (General treatment requirements) specifies how substances, mixtures, and components listed in Annex VII of the WEEE Directive shall be removed from WEEE. With regards to **plastics containing BFRs**, the standard lays down the following requirements:

- A.6.2: Plastic fractions resulting from the treatment of TEE and LHHA *"shall be deemed free of BFRs and may be recycled"*
- A.6.3.1: *"Plastic fractions from other appliances than those detailed in A.6.2 shall be deemed to contain brominated flame retardants except if there is evidence to the contrary i.e. if it is contained in a report that utilizes statistically and scientifically accepted methods and has been issued by an independent body"*
- A.6.3.2: *"Plastic fractions containing any BFRs shall be segregated from plastic fractions that do not contain BFRs and the resulting fractions shall be treated according to the appropriate legislation. Any plastic fraction that is not separated as above shall be considered as a BFR fraction and shall be managed accordingly.*

NOTE 1: This segregation activity can be carried out by a downstream operator.

NOTE 2: Annex VII of Directive 2012/19/EU prescribes the removal of all plastics containing brominated flame retardants into an identifiable stream before the end of the recycling process.

NOTE 3: Annex V of Regulation 850/2004 on persistent organic pollutants details requirements regarding the disposal and/or treatment of plastic fractions containing certain BFRs"

Normative requirements for the separation of plastics containing BFRs are further specified in TS 50625-3-1:

- 8.3 (CRT screens) / 8.5 (FPD screens) / 10.3 (small appliances): *"For the plastics fractions that can contain Brominated Flame Retardants (i.e. plastics from all categories of WEEE except large appliances and cooling and freezing appliances):*

  a) the treatment operator shall ensure the segregation of these BFRs (by downstream monitoring) if:

  1) the total concentration of bromine is known to be above 2,000 ppm, or

  2) it is assumed to be above 2,000 ppm, or

  3) if the treatment operator makes no declaration regarding the BFR content. The plastic fractions that contain the Brominated Flame Retardants shall be treated according to the appropriate legislation. Any plastic fraction that is not separated, as above, shall be considered as a BFR fraction and shall be managed accordingly

  b) if the total bromine concentration is below 2,000 ppm, the treatment operator complies with the depollution requirement for BFR".

Annex B of TS 50625-3-1 describes how the plastic fractions shall be sampled and analysed in order to demonstrate that they are free of BFRs. 10 single samples representative of at least 10 tons of input material shall be sampled during a batch process of the relevant treatment stream (i.e. CRT screens, FPD screens or small appliances). These 10 samples shall be mixed, and a representative subsample shall be sent to a laboratory for analysis of either total bromine or restricted BFRs (which are referred to as those restricted by the POP regulation in EN 50625-1, Annex A.6.1). Clause 4.4 of TS 50625-3-1 stipulates that analysis of bromine shall be conducted according to the analytical standard EN 14582 but does not specify a standard for the analysis of restricted BFRs.

In sum, the EN 50625 standard series requires the **separation of BFR-containing plastics for plastic fractions resulting from the treatment of screens** (WEEE category 2) **and small appliances** (categories 5 and 6). It introduces a **separation threshold of 2,000 ppm** Br to distinguish between fractions considered as containing BFRs (>2,000 ppm Br) and those considered BFR-free (<2,000 ppm Br). **Alternatively, concentrations of restricted BFRs** (POP-BFRs) can be analysed to determine whether the fraction shall be considered as containing BFRs or as being BFR-free.

BFR-free fractions may be recycled, while BFR-containing fractions shall be "treated according to the appropriate legislation", referring to the POP regulation (850/2004) which sets requirements for the treatment of plastics containing POP-BFRs above the LPCL (hexaBB, HBCD, PBDEs) (see 3.1.1).

The 2,000 ppm Br separation threshold was introduced as a practical measure to facilitate the separation (and its monitoring) of BFR-containing plastic fractions in operational settings.

Plastic sorting technologies cannot distinguish between restricted and non-restricted BFRs. At most, a sorting based on total bromine can be applied by XRT or XRF sorting, and the most commonly used method for separating BFR-containing fractions – the Sink/Float method – is simply based on the higher density of plastic particles containing BFRs (at functional levels) (see 3.2.3).

The monitoring of the efficiency of BFR plastic separation processes is also simpler, faster and cheaper when based on the total Br content rather than specific BFRs, as the latter requires GC-MS analysis which has to be performed by a competent laboratory, takes several days up to three weeks and may costs several hundreds of euros per sample.

When it was defined, the 2,000 ppm threshold corresponded to a total Br level below which exceedance of the LPCL for POP-BFRs was **statistically unlikely** due to the fact that POP-BFRs only represent a small share of the total Br content. As described in 2.1.3, this share has been steadily decreasing over the past decade, as a result of restrictions on the use of POP-BFRs.

As shown in Figure 10, a comparison of BFR levels in unsorted WEEE plastics measured in 2010[4] and 2015/2017[6,7] reveals that the **total Br level corresponding to the LPCL for PBDEs** (i.e. 1,000 ppm) **is now considerably higher than a decade ago** (6,100 ppm in 2015/2017 vs 2,500 ppm in 2010). In other words, around 2010 WEEE plastics containing more than 2,500 ppm of Br were likely to contain above 1,000 ppm of PBDEs. As PBDEs are now much more rare, it is statistically unlikely to find them above 1,000 ppm when the total Br content is below 6,000 ppm.

In view of the considerable reduction in the share of POP-BFRs in the total Br content of WEEE plastics observed over time, the **statistical considerations that served as a basis for setting the 2,000 ppm threshold in the WEEE CEN Standards have probably become obsolete**.

The adequacy of this threshold in relation to current BFR levels should therefore be reviewed, and its level may need to be adjusted upwards.

An increase in the separation threshold for brominated plastics (e.g. up to 6,000 ppm Br) **will have the immediate effect of reducing the volume of WEEE plastics that need to be separated prior to recycling, thus increasing WEEE plastics recycling yields**.

3 Treatment of WEEE plastics containing BFRs

Figure 9: Average BFR levels (ppm) in WEEE plastics[4,6,7]

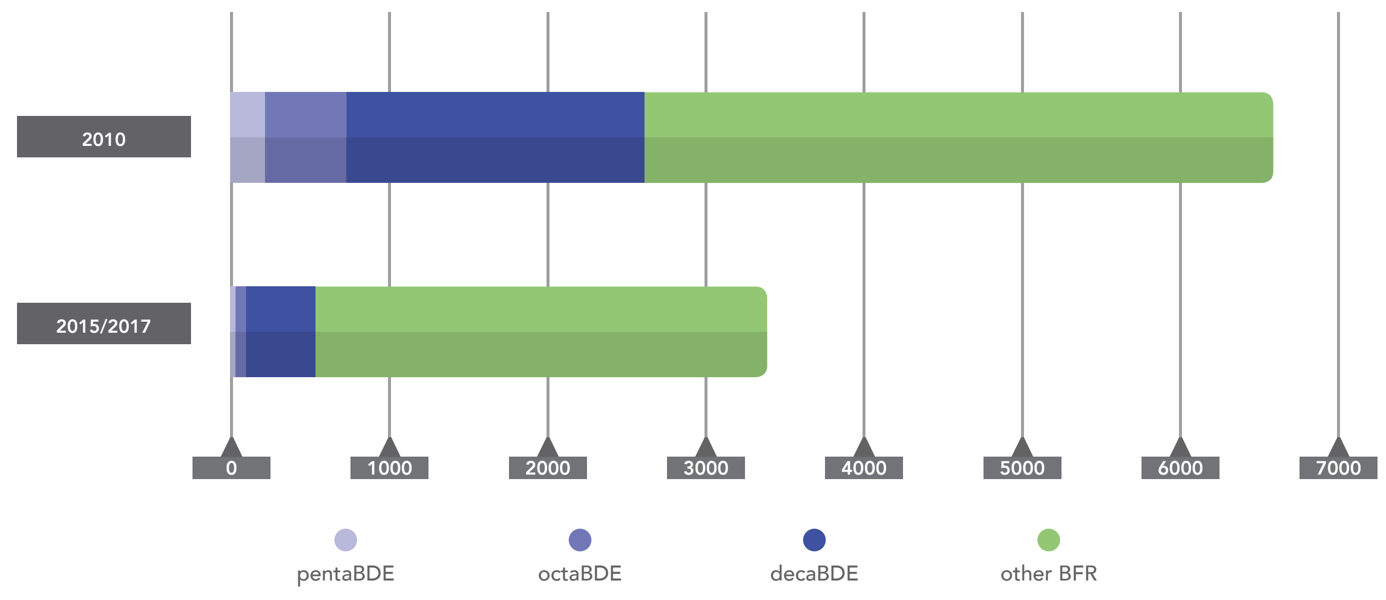
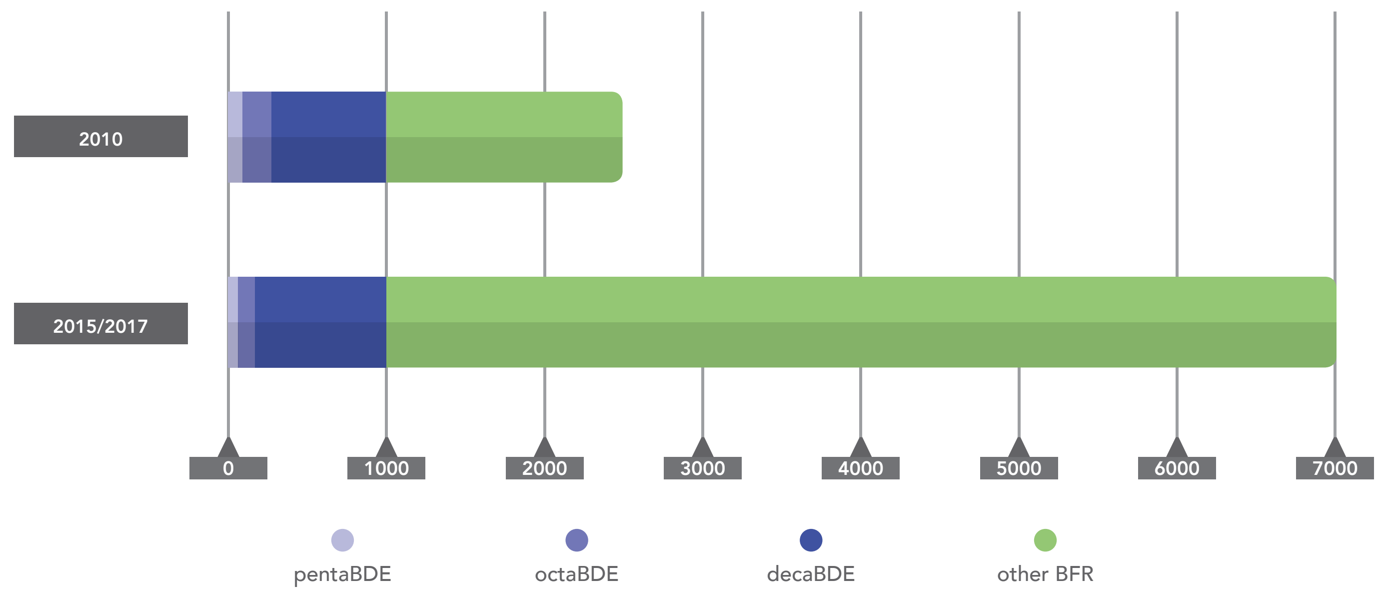


Figure 10: Total Br level (ppm) corresponding to 1,000 ppm PBDEs



3.2 Treatment processes

3.2.1 WEEE pre-processing

After collection, WEEE undergoes a complex series of manual and mechanical processes aiming primarily at **removing hazardous substances** (such as polychlorinated biphenyls, mercury, chlorofluorocarbons or leaded glass) and **recovering valuable materials** (such as steel, aluminium, copper, gold or silver). A distinction is typically made between WEEE **pre-processing** – where materials are separated from each other through manual or mechanical methods – and **end-processing** (or final treatment) – where fractions produced through pre-processing are either recycled, incinerated or landfilled.

At the WEEE pre-processing stage, **plastic fractions** may arise in the following forms:

- Plastic items resulting from the **manual dismantling of WEEE**, such as external casings and printed circuit boards. Plastic fractions other than printed circuit boards are typically shredded after manual dismantling, either in a WEEE shredder or dedicated plastic shredder, in order to reduce volume and optimise transports towards end-processing facilities (recycling, incineration or landfilling).
- Plastic-rich fractions resulting from **mechanical WEEE pre-processing**, which often correspond to a residual fraction after the removal of metals by magnetic separation, eddy-current or other sorting technologies. Due to their material composition, printed circuit boards typically end up in non-ferrous metal fractions.

Printed circuit boards are typically sent to integrated smelters to recover copper and other precious metals. In Europe, such integrated smelters include Umicore (Belgium), Aurubis (Germany), and Boliden (Sweden). Organic materials in printed circuit boards (e.g. Epoxy) serve as reducing agent in the smelting process.

Mixed plastic fractions, on the other hand, can be sent for plastic recycling, incineration or landfilling. Plastic recycling is usually the preferred option, not so much for economic reasons as to achieve the minimum recycling rates set by the WEEE Directive. Indeed, recycling is not always the most cost-effective option, as depending on mixed WEEE plastic prices and transport distance, recycling may in some contexts be more expensive than incineration for WEEE treatment operators. Reaching the mandatory recycling targets however require the recycling of WEEE plastics[29].

At the WEEE pre-processing stage, mixed WEEE plastics may undergo a **first sorting process** aiming at isolating a Br-rich fraction, based on XRT, XRF or density separation methods. This step may be motivated by normative requirements (e.g. EN 50625 requirement to segregate BFR-containing plastics prior to recycling), administrative constraints (e.g. waste classified as hazardous unless it has undergone a BFR separation process) or economic reasons (pre-sorted WEEE plastic fractions have a positive market value).

3.2.2 WEEE plastics recycling

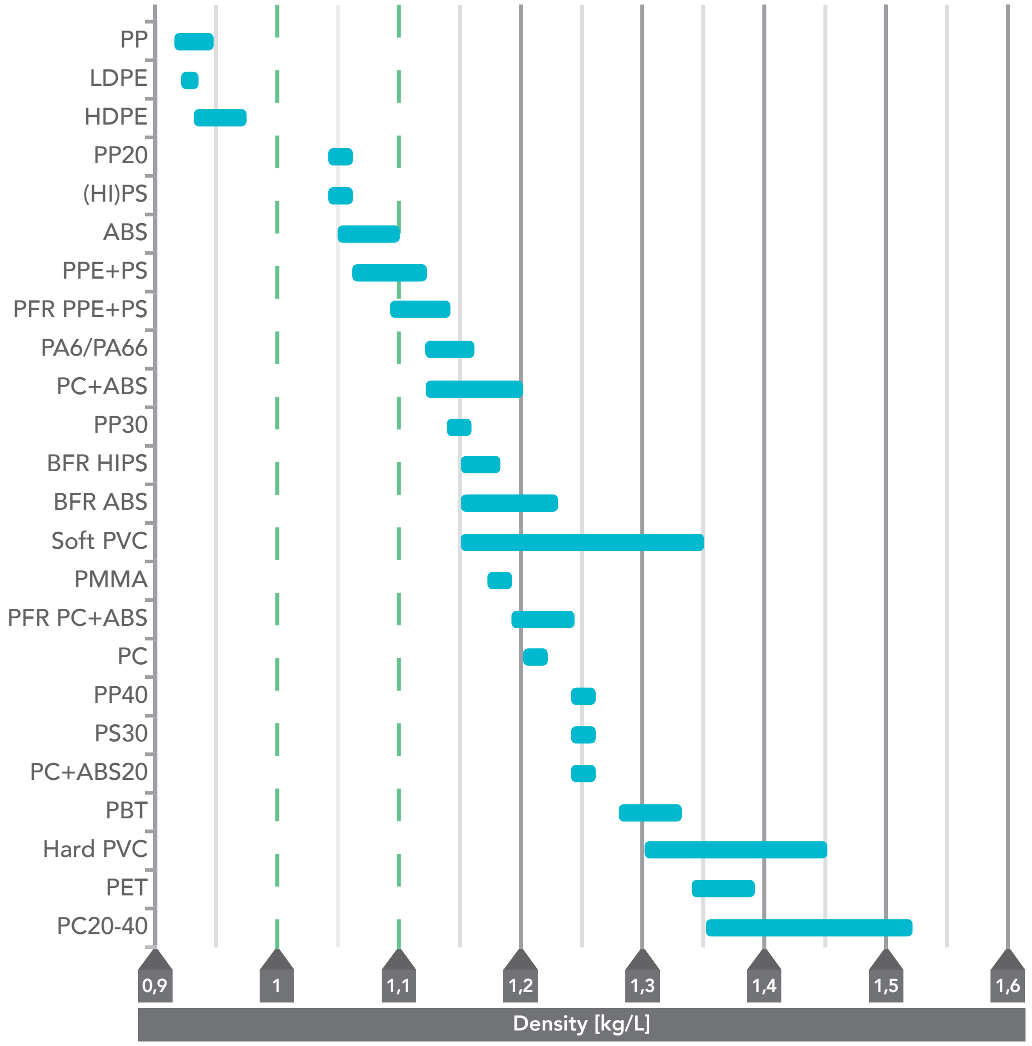
Mixed WEEE plastics sent for plastic recycling undergo a series of dedicated processes aiming at creating **homogeneous and additive-poor plastic fractions** that can be turned into plastic regranulates suitable to replace virgin plastics in new products. Homogeneity refers here to both **polymer types** and **additive content**, as customers demand pure plastics consisting of either single or compatible polymers with no or little additives (apart from antioxidants and specifically required additives such as pigments, UV stabilisers, etc.). This offers both flexibility in the use of plastics regranulates, and a guarantee of quality (e.g. stable composition, absence of problematic additives). **WEEE plastics containing significant loads of additives, whether fillers, flame retardants, plasticisers or others, must therefore be sorted out prior to recycling.**

Various technologies are applied to sort WEEE plastics by both type and additive content. Most commonly, mixed WEEE plastic fractions are first cleaned of their non-polymeric impurities (e.g. wood, paper, minerals, metals), for instance through air classification, magnetic sorting or eddy current separation. Plastic fractions are subsequently size-reduced (shredded) in order to optimise the efficiency of further sorting processes[30]. The resulting mixture of plastic flakes is then subjected to a series of **density-based sorting** processes (**"Sink/Float"** method), which use the differences in density of WEEE plastics to create more homogeneous fractions. Typically, two density sorting steps are applied: one at a density of **1.0** kg/L (corresponding to the density of freshwater) and one at a density of about 1.1 kg/L (achieved by the addition of a sorting medium such as sodium chloride).

As shown in Figure 11, this two-step sorting process allows to create three fractions:

- One fraction with a density lower than 1 kg/L, containing additive-poor polyolefins (PP and PE)
- One fraction with a density between 1 and 1.1 kg/L, containing additive-poor ABS and PS, as well as PP containing 20% glass-fiber, talc or other mineral fillers. PPE+SB ("Noryl") is also found in this density range, however in small amounts due to limited use.
- One with a density higher than 1.1 kg/L, containing a complex and highly heterogeneous mixture of polymers loaded with various additives, including BFRs, PFRs, phthalates and heavy metals.

Figure 11 : Density range of common WEEE plastics[16,31–33]. PFR = organophosphorus flame retardants. BFR = brominated flame retardants. PP20/30/40/50 = PP filled with 20/30/40/50% glass-fibre, talc or other mineral fillers. PS30 = PS filled with 30% glass-fibre. PC20-40 = PC with 20-40% glass-fibre. PC-ABS20 = PC-ABS filled with 20% glass-fibre



The first two fractions are relatively homogeneous and can be further sorted using **electrostatic separation** methods. These enable the separation of particles based on differences in the electrical conductivity of particles and work best with relatively homogeneous fractions, consisting or two or three plastic types. Through electrostatic sorting, pure PP and PE fractions can be sorted from the <1 kg/L fraction, and pure ABS and PS fractions from the 1-1.1 kg/L fraction.

These pure PP, PE, ABS and PS fractions can subsequently be turned into regranulates, usually with a compounding step in between (mixing with masterbatch of additives). It should be noted than monopolymer streams are always formed. Mixtures of PP and PE, as well as of PS and ABS, are also compounded and used in the plastics industry.

The fraction with a density higher than 1.1 kg/L is commonly referred to as the **"waste fraction"** as its heterogeneity is too high to enable recovery of pure plastic fractions. Most plastic being black or dark in colour, near-infrared sorting technologies cannot be applied. This fraction is typically **disposed of by incineration, co-processing in cement kilns or landfilling**. This fraction is generally classified as **hazardous waste** due to its content in problematic substances including **POP-BFRs** and **heavy metals** (e.g. antimony, cadmium, lead).

One major European WEEE plastic recycling company reports being able to recover a pure PC-ABS fraction[20], which could theoretically be achieved through further sorting of the >1.1 kg/L fraction using a combination of density sorting and electrostatic separation. No information is however available on the actual technologies applied. The conventional WEEE plastic treatment processes described above are illustrated in Figure 12.

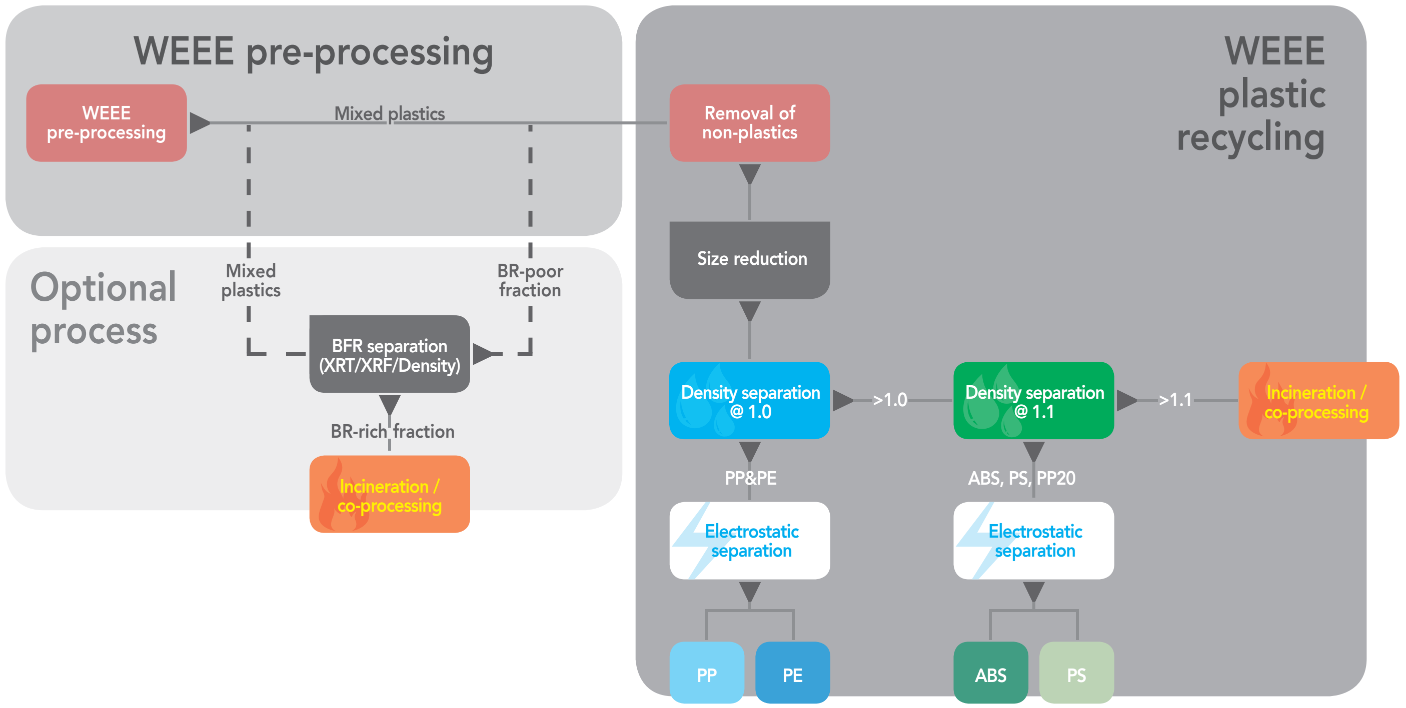


Figure 12 : Conventional WEEE plastic treatment processes

3 Treatment of WEEE plastics containing BFRs

3.2.3 Separation of Br-rich fraction

As seen in 3.1, the WEEE Directive required the segregation of plastics containing BFRs during the treatment of WEEE, and the EN 50625 series of standards specifies the modalities of this segregation. Plastics from screens and small appliances must undergo a BFR separation method able to separate:

- A Br-rich fraction that shall be "treated according to the appropriate legislation", referring to the POP regulation (850/2004) which requires that plastics containing POP-BFRs above the LPCL are disposed of or recovered such a way that the POP content is destroyed or irreversibly transformed (see 3.1.1).

- A Br-poor fraction that can be recycled, containing either less than 2000 ppm Br or POP-BFRs below the LPCL (i.e. 1000 ppm for PBDEs, 1000 ppm for HBCD and 50 ppm for hexaBB).

Several methods can be used to identify and separate Br-rich plastic fractions during WEEE treatment operations. They can be broadly divided into manual and mechanical methods:

- **Manual methods** require the inspection of each individual plastic piece, usually before shredding, either fully manually (based on markings or on the source (product) of plastics), or semi-manually (with the help of hand-held instruments);

- **Mechanical methods** that can be run in batch or continuously, usually after shredding.

Six methods were considered as potentially effective to separate BFR plastics, listed in Table 5. These methods are hereafter reviewed with regards to their **effectiveness** in separating Br-rich WEEE plastic fractions, **selectivity, technology readiness** and **cost**.

- **Effectiveness** refers to the extent to which the method is able to segregate BFR plastic loads and is related to both the frequency of false negatives (BFR plastics not identified as such) and quantification limits (Br concentration below which the technology is not able to identify BFR plastics).

- **Selectivity** relates to whether the sorting method is capable of separating BFR plastics in a targeted manner, i.e. the produced Br-rich fraction is mainly composed of BFR plastics.

Table 5 : Overview of BFR plastic sorting technologies

Method		Based on	Effectiveness	Selectivity	TRL	Cost
ISO markings	Manual	FR content according to ISO markings	– –	+	++	– –
Source segregation	Manual	Knowledge of BFR hotspots	– –	+	++	– –
Sink/Float	On-line	Density of flakes	++	– –	++	++
X-ray transmission (XRT)	On-line	Density of atoms	+	–	++	+
Laser-Induced Breakdown Spectroscopy (LIBS)	Manual	Atomic composition	?	?	+	?
	On-line		?	?	–	?
X-ray fluorescence (XRF)	Manual	Atomic composition	++	++	++	– –
	On-line		++	++	+	–

- **Technology readiness level** (TRL) is an indicator of the maturity of the method, i.e. the extent to which it is operational, commercially available and readily implemented in operational settings.

It should be noted that little information is publicly available to evaluate and compare these technologies against these criteria. The ratings given here, partly based on previous research[21], should therefore be considered as indicative only.

Effectiveness

- ISO labels are notoriously insufficient, either because they are missing, incomplete or even incorrect[34]. Furthermore, WEEE plastics are typically found in a shredded form so that ISO labels become irrelevant.

- Source segregation requires having detailed knowledge about the exact WEEE types, models and components that contain BFRs. No such exhaustive database exists at the moment.

- The Sink/Float method is highly effective, allowing >95% of the Br load to be sorted out into the sinking fraction if the right density is set (around 1.1 kg/L)[21]. Due to the significant density gap between BFR-free and BFR plastics, slightly lower or higher density thresholds are equally effective.

- Sensor-based sorting methods (XRF, LIBS, XRT) can all be considered as effective, as they can reliably detect Br when present at functional levels (i.e. 5-15% range). XRT is however considered less reliable, as their accuracy can be negatively impacted by the presence of interfering elements in the matrix. Insufficient information was found on LIBS to assess the effectiveness of the method.

- Effectiveness can also be assessed based on residual Br levels measured in the supposedly Br-free fraction. These residual levels can reach up to 4,000 ppm following on-line XRT sorting[7], 1,500 ppm following Sink/Float[21], and 1,000 ppm following on-line XRF sorting[34,35]. These residual Br-levels may however considerably vary for the same technology based on the state of input material (particle size, moisture, dirt, etc.) and specificities of the technology (parameters, model, etc.).

Selectivity

- Visual separation, based on either ISO labels and/or source segregation, would be selective if reliable information was available, which is unfortunately not the case as discussed above.

- The Sink/Float method has poor selectivity, as WEEE plastics often have overlapping densities. The Br-rich fraction resulting from sorting also contains non-brominated materials such as relatively dense polymers (e.g. PBT, PC-ABS, PA6) as well as plastics containing non-brominated additives (e.g. mineral fillers, mineral or phosphorus flame retardants). For plastics from small appliances (categories 5 & 6), the sinking fraction reportedly contains only 15-30% of brominated flakes[36,37], whereas in screens a share of about 70% was observed[38]. As discussed in 3.2.2, non-brominated plastics in the sinking fraction include a wide range of polymers containing various additives. These plastics would anyway be sorted out during the recycling process due to both technological challenges (in sorting) and market demands (for pure, additive-poor, recyclates).

- Being also based on density, XRT sorting suffers from relatively poor selectivity as well, albeit to a lesser extent as it "reads" the density of atoms and can therefore operate a finer separation than the Sink/Float method. Experience shows that XRT sorting of plastics from CRT screens produces a reject fraction (Br-rich fraction) representing about 25% of the input, whereas with the Sink/Float method this share rises to about 30%[37].

- XRF is a much more selective method, as it separates materials based on their actual atomic composition. Trials on comparable WEEE plastic samples have resulting in a reject fraction representing 30% of the input when using on-line XRT, and only about 10% when using on-line XRF sorting[35].

- Insufficient information was found on LIBS to assess the selectivity of the method.

Technology readiness level

- Most of the considered technologies and methods are already used in WEEE pre-processing and WEEE plastics recycling operations, with the exception of on-line LIBS-based methods.

- Hand-held LIBS devices have been used in several sampling studies[34,38], and is reported by be used in operational settings in some WEEE pre-processing facilities[37]. On-line LIBS sorting machines appear to only have been applied in research projects (e.g. CloseWEEE project).

- As far as XRF is concerned, a wide range of hand-held XRF devices are commercially available. Commercial on-line sorting technologies exist as well, however their cost currently prevents larger implementation (see below).

Cost

- Visual separation methods (ISO labels and/or source segregation) have very low initial cost (training of employees) but high operating costs due to the relatively expensive manual labour in (Western) Europe. This alone makes it economically unfeasible to systematically sort BFR-containing plastics based on such manual methods, including hand-held sensor-based techniques (XRF, LIBS).

- Due to its simplicity, the Sink/Float method can be considered as relatively inexpensive, the main operating cost component being those related to wastewater treatment. The ubiquity of Sink/Float separation methods in WEEE plastics sorting facilities (see 3.2.2) however means that only a fraction of the costs can be allocated to the function of sorting out the Br-rich fraction. Indeed, Sink/Float separation would be applied in any case, whether BFR sorting is necessary or not, due to the need to separate different plastic types during the recycling process.

- On-line XRF sorting machinery can potentially replace on-line XRT sorters which are commonly used by WEEE pre-processors to reduce Br levels in their plastic outputs sent to WEEE plastic recyclers, however it costs about 50% more[35]. This higher cost is currently not justified despite higher effectiveness and selectivity of XRF compared to XRT (see above).

- No information could be found on the cost of LIBS sorting technologies.

In conclusion, each method has its strengths and weaknesses, and the choice of which method to apply depends on a number of factors, including the economic and regulatory context, but also the possible synergistic effects offered by certain methods.

- The **Sink/Float** method offers several advantages, in particular the fact that it is a widely used method in the sorting of WEEE plastics, and that it is highly effective in sorting out BFR-containing particles.

- **On-line XRT and XRF** sorting methods also offer advantages such as their higher selectivity and also the fact that they can be implemented in a variety of operational settings and sorting lines, whereas the Sink/Float method requires sorting lines adapted to wet processes (both in terms of infrastructure and operating license).

- **Manual methods** (visual or with hand-held XRF or LIBS) are generally too time- and labour- consuming for routine application.

In reality, a **combination of methods** can be, and often is, used. For instance, external casings can be screened using hand-held XRF devices and BFR-containing items can be sorted out.

Later in the WEEE pre-processing chain mixed plastic fractions resulting from mechanical treatment can undergo online XRF or XRF sorting to remove Br-rich particles (as well as particles containing other problematic substances such as heavy metals or chlorine).

The resulting Br-poor fraction can be sent to a WEEE plastic recycler where a stepwise Sink/Float separation process will be applied to recover pure PP, PE, ABS and PS fractions, while residual BFR plastics will be contained in the dense fraction to be disposed of by incineration, co-processing or landfilling.

It should however be noted that **both recycling yields and BFR removal efficiency would not be significantly changed if the first two sorting steps (at the WEEE pre-processing stage) were not applied**, as ultimately the stepwise Sink/Float separation process would anyway separate BFR-free target plastics (PP, PE, ABS, PS) from BFR-containing fractions.

3.2.4 Treatment of Br-rich fraction

Several technologies are appropriate to treat Br-rich fractions produced through BFR sorting processes. If these fractions contain POP-BFRs above the LPCL, the treatment process should ensure that POP-BFRs are destroyed or irreversibly transformed (see 3.1.1).

If these fractions are classified as hazardous by local or national legislation, which is often the case due to elevated levels of both POP-BFRs and heavy metals (e.g. antimony, cadmium, lead), treatment options are limited to facilities licensed to receive and treat hazardous waste[d].

The most commonly applied treatment technologies are **incineration**, either in municipal waste incinerators or in hazardous waste incinerators (depending on waste classification), co-processing in **cement kilns**, or as reducing agent in **non-ferrous metal smelters**. POP-BFRs can effectively be destroyed or irreversibly transformed in incineration plants, cement kilns or smelters provided that a minimum temperature of 850°C is maintained for at least 2 seconds[39].

These operating conditions are required for all municipal and hazardous waste incineration plants by Article 50 of the Industrial Emissions Directive (2010/75/EU). Temperatures are typically above 1000°C in furnaces of cement kilns and metal smelters[39]. Specific measures may however be implemented in such installations due to potential corrosion by bromine, emission of brominated dioxins and furans, and presence of leachable antimony in the ashes, slags and air pollution control residues[40].

Despite it not being considered as preferred treatment option, and not permitted in many countries, Br-rich fractions may also be **landfilled** in some countries. We estimated in 2.2.2 that approximately 20% of the BFR plastics occurring in WEEE collected end up being landfilled. This figure is however uncertain, and was previously estimated at only 1% for decaBDE in WEEE plastics[41].

Several studies have showed that BFRs as well as co-occurring heavy metals can leach from non-sanitary landfills into adjacent soils and water bodies[40]. These risks are limited or non-existent in modern landfills, but the disadvantage remains that any POP-BFRs that may be present are not destroyed or irreversibly transformed.

Solvent-based recycling technologies may become a suitable treatment option for Br-rich WEEE plastic fractions. In particular, the **CreaSolv** process, which has been developed and tested since 2002, could enable the recovery of valuable materials such as ABS, PS, bromine and antimony trioxide (ATO) from the Br-rich fraction produced by WEEE plastic sorting processes[42–44].

The CreaSolv process consists of four main steps. First, input material (e.g. Br-rich WEEE plastic fraction) is brought into contact with a specific solvent formulation allowing selective dissolution of target polymers (ABS & PS). Secondly, the residual solids are removed from the solution by fine filtration or centrifugation, leaving the target polymers in solution along with some associated additives such as BFRs.

In a third step, the target polymers are selectively precipitated, whereas the additives remain behind in the solvent. Finally, the wet target polymer mixture is dried to produce solid matter that could be further refined to produce ABS and PS regranulates. Despite the apparent benefits of the technology, **its implementation is still hampered** by economic and technical challenges.

3.3 Efficiency of WEEE plastic recycling

Recycling efficiency usually refers to the ratio of produced recycled materials over the quantity of waste entering the recycling process. It can be assessed at different scales depending on the denominator:

- The **"recycling yield"** refers here to the ratio of produced WEEE plastic regranulates over the **input to WEEE plastic recycling** facilities.

- The **"collected recycling rate"** refers to the ratio of produced WEEE plastic regranulates over the overall quantity of WEEE plastics present in **WEEE collected**.

- The **"overall recycling rate"** refers to the ratio of produced WEEE plastic regranulates over the overall quantity of WEEE plastics present in **WEEE generated**.

These recycling efficiencies are calculated based on the results of the WEEE plastic flows modelling results presented in 2.2.2 (Figure 13).

[d] In France, based on analysis campaigns, Br-rich fractions are classified differently depending on their origin[53]. Br-rich fractions resulting from the treatment of small appliances and CRT screens are considered both POP and hazardous, whereas Br-rich fractions from the treatment of FPD screens are considered POP and non-hazardous.

3 Treatment of WEEE plastics containing BFRs

Figure 13: WEEE plastic recycling efficiency

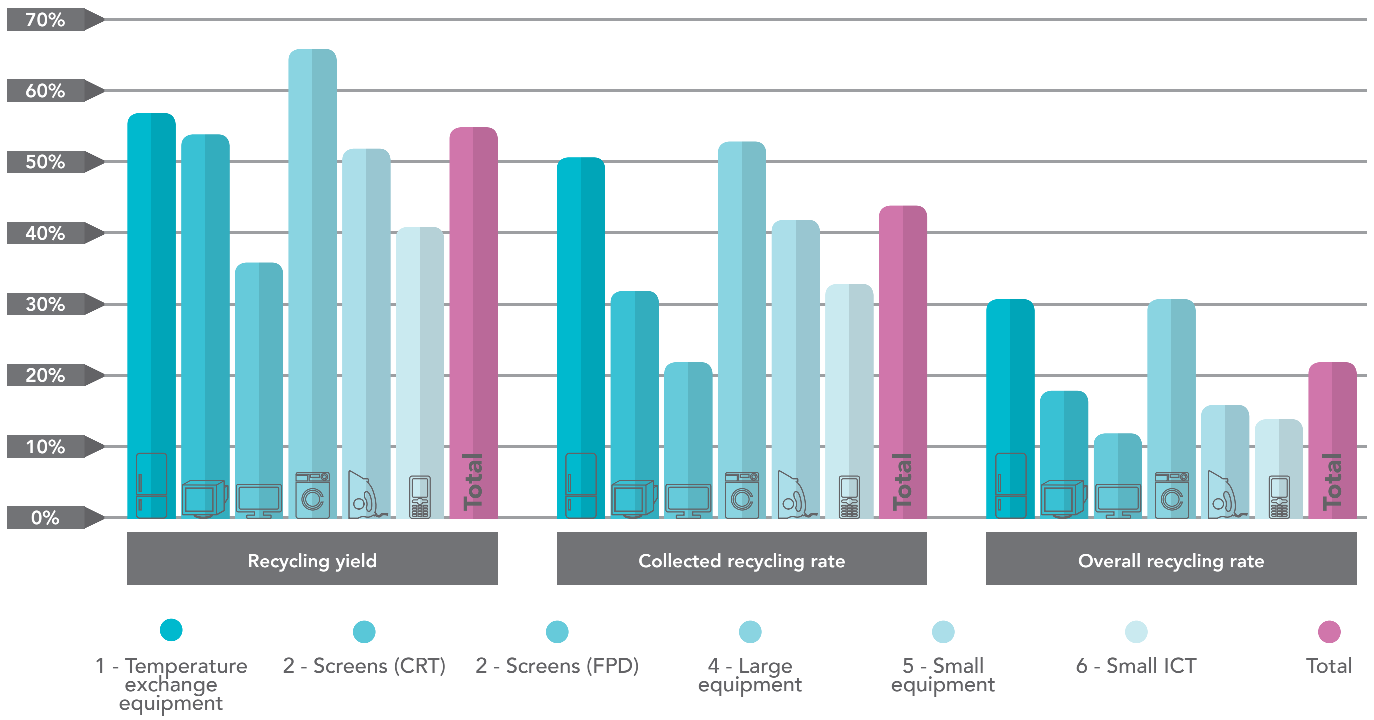
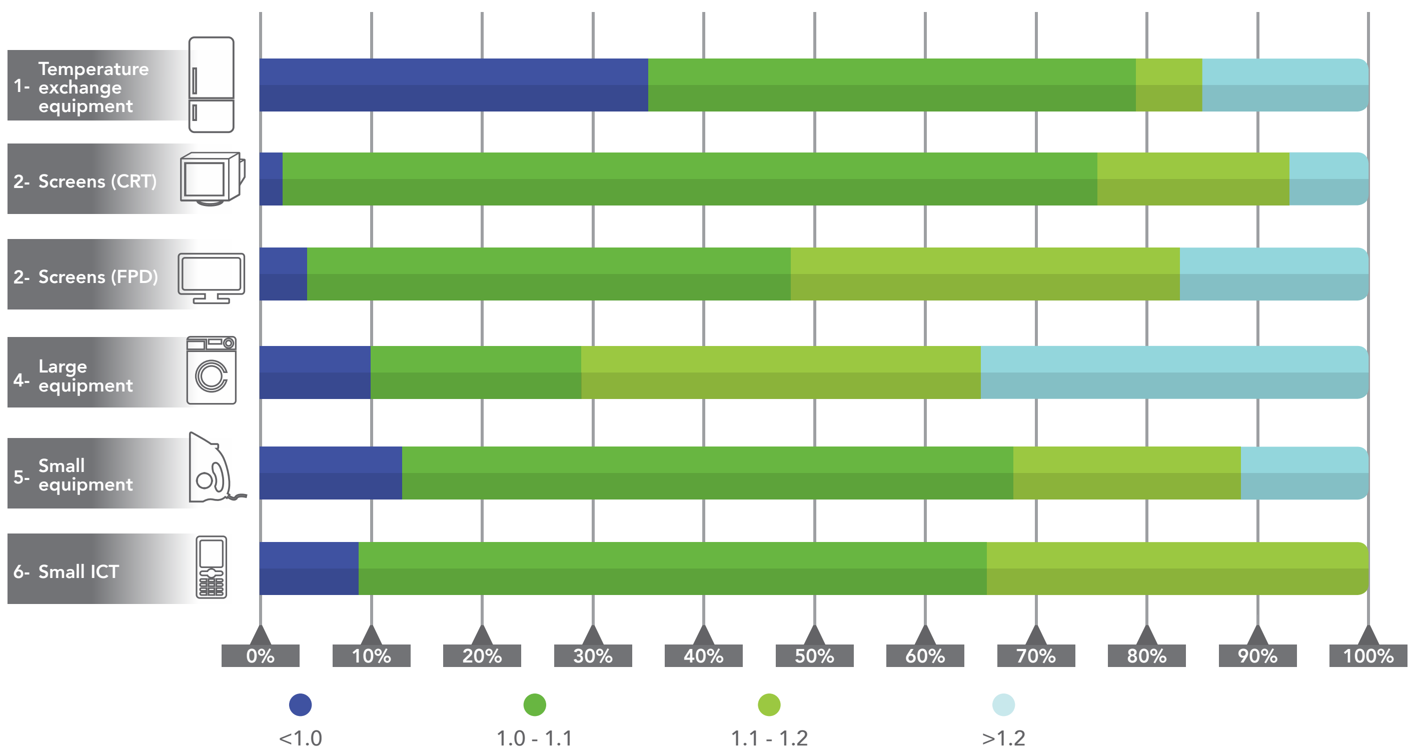


Figure 14: Densimetric profile of WEEE plastics (in kg/L)



The **recycling yield** ranges between 36% (FPD screens) and 57% (TEE), with a yield of 55% across all WEEE categories. This means that, **on average, 55% of WEEE plastics entering WEEE plastic recycling facilities will actually be turned into regranulates**.

This yield is mainly influenced by the composition of WEEE plastics, particularly the share of target polymers (PP, PE, ABS, PS and eventually PC-ABS) as well as the densimetric profile. Indeed, as described in 3.2.2, WEEE plastics recycling typically involves a two-step density sorting process whereby a low density (<1.0 kg/L), a medium density (1-1.1 kg/L) and a high density (>1.1 kg/L) fraction are produced.

The low and medium density fractions subsequently undergo electrostatic separation enabling the sorting of homogeneous PP, PS, ABS and PS fractions.

The high-density fraction is typically too heterogeneous and complex to enable further sorting and usually disposed of. As shown in Figure 14, low and medium density fractions represent together about 79% of plastics from TEE, 75% for CRT screens, 48% for FPD screens, 29% for large appliances, 68% for small equipment and 66% for small ICT.

These represent the upper boundary of recycling yields if such a two-step density sorting process is applied, from which the share of non-target polymers in the low and medium density fractions is further deducted. **Actions to increase the recycling yields** could take place at two different stages of the (W)EEE lifecycle:

- At the design stage, by favouring the use of plastics that can effectively be sorted and recycled through state-of-the-art WEEE plastic recycling processes. For instance, by using additive-poor PP, PE, ABS and PS whenever possible, or avoiding the use of plastics that can interfere with current density and electrostatic-based recycling processes (e.g. non-target polymers having a density lower than 1.1 kg/L).
- At the recycling stage, by developing and implementing sorting technologies that are able to increase the share of plastics that can be recycled, enabling for instance the recycling of common WEEE plastics such as PC-ABS.

The **collected recycling rate** ranges from 22% for FPD screens up to 51% for TEE and amounts to 44% in total. Besides the actual composition of WEEE plastics, this rate is also influenced by the share of collected WEEE plastics that are not reaching WEEE plastic recycling facilities due to sorting inefficiencies (e.g. plastics transferred into metal fractions) or the disposal of the plastic-rich fraction by incineration or landfilling at the WEEE pre-processing stage.
This collected recycling rate **could be further improved** by ensuring that WEEE plastics collected are systematically and efficiently channelised towards WEEE plastics recycling facilities by WEEE treatment operators.

The **overall recycling rate** of WEEE Plastics - but generally speaking of other fractions as well - is relatively low, due to the fact that a large share of WEEE generated is still not collected or ending up in the waste bin or following other routes. It ranges from 12% (FPD screens) up to 31% (TEE and large equipment) and reaches 22% across all WEEE categories.

The main **lever for action** to raise this rate would be to implement measures to increase WEEE collection rates in the EU.

4 ∘ Impact of BFRs on WEEE plastic recycling

4.1 Impacts on recycling yields

As described in 3.3, the recycling yield refers to the ratio of produced WEEE plastic regranulates over the input to WEEE plastic recycling facilities. In practice, this yield reaches about 55% for WEEE plastics. The remaining 45% cannot be sorted using conventional sorting technologies and/or are unsuitable for recycling due to detrimental impacts on quality or lack of demand.

The 55% that are recycled consist of so-called **target polymers** – typically additive-poor PP, PE, ABS, PS. These are the most abundant plastic types in WEEE and can be easily sorted from others using a combination of density sorting and electrostatic separation. The resulting products have a homogeneous and stable composition, which is key to customer acceptance.

Plastics containing **high loads of additives** (fillers, flame retardants, stabilisers, etc.) are not suitable for recycling, as flexibility in use is restricted and stability in composition cannot be guaranteed. Furthermore, the presence of additives might have a detrimental impact on the mechanical, rheological or aesthetic properties of recycled plastics (see 4.2). Lastly, presence of a heterogeneous mix of additives represents a quality risk due to many additives being known or suspected of being hazardous (e.g. PBDEs, SCCPs, PFOS, low molecular weight phthalates, Pb, Cd, etc.).

The removal of polymers with high loads of additives through density sorting (around 1.1 kg/L) is therefore inherent to WEEE plastic recycling processes, regardless of the BFR content. In that sense, **BFRs do not hamper recycling yields any more than other FRs** (e.g, phosphorus-based or mineral FRs) that would also be sorted out during the recycling process. The commonly used PC-ABS and PFR mixtures indeed have a density around 1.20 kg/L[18], and mineral FRs such as ATH and MDH need to be added at loadings of at least 60% in order to achieve good flame retardancy[45], which would bring the density of polymers containing them up to around 1.80 kg/L[e].

In fact, BFRs have the advantage of being easily sortable by density-based methods which is not the case for some other FRs. For instance, another commonly used substitute is the blend of PPO/PS polymer ("Noryl") with the FR resorcinol bis(diphenyl phosphate) (RDP). The PPO/PS/RDP blend has a medium density (around 1.08 kg/L) and can therefore not be sorted out using conventional density sorting processes[f]. **Potential detrimental effects of non-halogenated FRs on WEEE plastic recycling yields** is clearly a poorly researched topic that would require further examination and consideration by policy makers.

In summary, it can be concluded that the **presence of BFRs in WEEE plastics does not reduce recycling yields** more than other FRs as FR-containing plastics, as well as plastics containing other additives in significant loads (e.g. fillers), **are sorted out** during the recycling process.

Replacing BFRs by other FRs would therefore do little to increase recycling yields, and could even further reduce yields if substitutes were to become restricted while difficult to segregate, as illustrated with the case of the PPO/PS - RDP mixture.

4.2 Impacts on recyclates quality

Quality is defined by ISO 9000 as the degree to which a set of inherent characteristics of an object fulfils requirements. As far as plastic recyclates (regranulates) are concerned quality mainly refers **to mechanical, rheological and aesthetics properties**. These parameters are mainly influenced by purity (polymers, additives, contaminants) as well as chemical ageing processes[48].

Purity is a key factor influencing the quality of recyclates. Presence of incompatible polymer mixtures or unwanted additives can impact negatively the properties of produced recyclates. Most plastics are **immiscible**, meaning that they will not form a single phase when melted. Compatibility varies depending on plastic types. For instance, HIPS can tolerate as much as 5% of ABS impurity but only 1% of PC or PC-ABS. PC-ABS can in turn tolerate up to 1% of HIPS without recyclate quality being too negatively impacted. PP is to some extent compatible with PE, and as much as 10% PE can be present in PP recyclates[31]. Conventional WEEE plastic sorting processes, based on stepwise density separation followed by electrostatic sorting, is able to achieve sufficient purities for the target polymers PP, PE, ABS and PS.

Some **additives** have detrimental impacts on mechanical and rheological properties of recyclates. Fillers such as talc, calcium carbonate or glass fiber influence the viscosity, stiffness, thermal stability, shrinkage and impact strength, and may also cause wear of processing equipment[48]. Fluctuating compositions and levels of such additives therefore cause **undesirable fluctuations** in properties of recyclates. Therefore, such additives must be sorted out during the recycling process.

Flame retardants may also impact negatively quality of recycled plastics. In a study by Imai et al.[49] the impacts of both brominated (BEO and TBBPA) and phosphorus (Organophosphates) flame retardants on the **recyclability** of WEEE plastics were simulated. **BFRs were found to be superior to PFRs**.
PFR-containing plastics showed mechanical deterioration (in terms of impact strength, melt flow rate) and a reduced fire grade after one extrusion cycle, whereas BFR-containing plastics maintained their original properties and fire retardancy during four extrusions. Statler et al. showed that BFR-containing polymers maintain FR ratings (V0) after as many as eight extrusions[50].

In their review on the effects of **chemical ageing** on the FR-containing plastics, Vahabi et al.[51] concluded that halogenated compounds and mineral fillers are more resistant to ageing in comparison to phosphorus compounds, which are very sensitive to hydrolysis. All organophosphates are indeed known to be susceptible to hydrolysis – they decompose to phosphoric acids under heat and humidity[4]. These acids degrade the polymeric structures and cause brittleness.

The findings presented above indicate that, **from a purely technical perspective, BFRs are preferable to PFRs when it comes to plastic recyclates quality**. In reality, BFRs are however sorted out during the recycling process as part of the conventional density sorting method. This means, BFR levels in recyclates are too low to have a noticeable effect on quality.
In a recent study by Andersson et al.[52], total bromine levels averaged 380 ppm (max 1,189 ppm) in 47 samples of PS, ABS, PP and PE recyclates originating from WEEE (in a few cases ELV) and having undergone density sorting. The sum of restricted BFR levels (PBDEs and HBCD) averaged 58 ppm, with a maximum of 186 ppm in one ABS sample from ELV. The UTC level of 500 ppm for PBDEs was not exceeded in any sample, whereas that for HBCD (100 ppm) was exceeded in two samples (max 160 ppm) the origin of which (WEEE or ELV) is not specified.

In **summary**, the quality of WEEE plastic recyclates is influenced by a number of parameters including the purity and content in various additives.

Several additives adversely affect the quality of recyclates, however BFRs have been shown to have remarkably few negative effects. In contrast, organophosphate FRs, which are often considered as the most suitable alternative to BFRs, are known to negatively impact the quality of recyclates, mainly due to the tendency of these substances to degrade into acid compounds that cause brittleness of recyclates. Overall, relatively little research has been conducted on the impact of various types of FRs on the recyclability of WEEE plastics. In particular, impacts of mineral fillers such as aluminium hydroxide (ATH) and magnesium hydroxide (MDH) are poorly known. However, both ATH and MDH need to be added at loadings of at least 60% in order to achieve good flame retardancy[45], which inevitably leads to a brittleness that poses a problem both for product durability and recyclability.

4.3 Impacts on recycling costs

Besides yields and quality, costs are another key factor determining the viability of WEEE plastic recycling operations. WEEE plastics recycling entails both costs related to the sorting, regranulation as well as disposal processes, and revenues resulting from the sale of valuable products such as target plastic recyclates but also recovered ferrous and non-ferrous metal impurities. A **simple economic analysis** is provided in Table 6. It is not intended to provide an accurate assessment of the economic performance of WEEE plastics recycling activities in Europe, but rather to give some general orders of magnitude. The prices of recyclates also include industrial scrap (and not only post-consumer), and therefore reflect an upper range. Due to lack of information, investment and operating costs related to the sorting and regranulation processes are not considered.

These figures indicate that revenues provided by the sale of recyclates exceed costs related to the disposal of the non-target fraction. This balance however considers relatively high recyclates prices and does not include investment and operating costs related to sorting and granulating operations. In reality WEEE plastic recyclers sometimes charge a gate fee, indicating that overall recycling costs may exceed revenues from the sale of recyclates only.

[e] Assuming blends of 40% PP and 60% ATH or MDH, and densities of 0.92 kg/L for PP, 2.42 kg/L for ATH and 2.34 kg/L for MDH.
[f] RDP is included in the CoRAP list of substances and currently under assessment as Endocrine Disrupting[46]. If RDP were to be restricted, this could have severe consequences on WEEE plastic recycling yields due to the technical difficulty in sorting. Several other common phosphorus-based FRs are the subject of concerns over potential toxicity, so that some speak of "regrettable substitution"[47]

4 Impact of BFRs on WEEE plastic recycling

Table 6: Simple economic assessment of WEEE plastic recycling

Fraction		Cost/revenue (EUR/t)	Share in WEEE plastic output	Effective cost/ revenue	Comment
Target fraction	PP	830	20%	166	Quantities of recycled target polymers based on calculations presented in 2.2.2. Prices based on plastiker.de (February 2020 prices considered, to exclude temporal effects resulting from COVID-19 crisis)
	PE	740	2%	11	
	ABS	1630	16%	261	
	HIPS	790	17%	135	
	PC-ABS	1690	1%	10	
Non-target fraction (high-density)		-150 (M) -550 (H)	45%	-68 (M) -248 (H)	Estimate of average disposal costs in Europe, for municipal (M) or hazardous (H) waste (incineration or landfill)
Net balance (EUR/t input)			**516**	**336**	Doesn't include investment and operating costs related to recycling processes (e.g. sorting and granulation machinery, labor, quality testing, etc.).

Furthermore, the net balance is strongly influenced by whether the non-target fraction is classified as hazardous or not. As discussed in 3.2.2, this fraction is often classified as hazardous waste due to its content of problematic substances, including POP-BFRs but also heavy metals (e.g. Sb, Cd, Pb), chlorine and low molecular weight phthalates. Little information exists on the classification of this fraction in different European countries.

Regarding the **impact of BFRs on WEEE plastic recycling costs**, the following considerations can be made:

- The separation of BFR containing plastics in an inherent part of the conventional WEEE plastic recycling process, which entails the separation and disposal of the higher density fraction not suitable for recycling. This density sorting process would be applied regardless of whether BFRs are present or not in the input, as it is key to recovering homogeneous and additive-poor target polymer fractions. The **investments and costs associated with these separation processes can therefore not be attributed solely to the presence of BFRs.**
- Similarly, **costs related to the disposal of the high-density fraction cannot be attributed only to the presence of BFRs**, as this fraction would anyway be disposed due to its unsuitability for recycling. The presence of POP-BFRs in that fraction does contributes to the fact it may be classified as hazardous, which negatively impacts the overall economic balance. However, this fraction contains many other problematic additives, such as heavy metals, chlorine and low molecular weight phthalates, so that it could be considered hazardous even if POP-BFRs were absent. The lack of information and harmonization regarding the classification of this fraction in various European countries however prevents a more detailed analysis.
- As seen in 4.1, replacing BFRs by **other FRs** such as organophosphates or mineral fillers would not reduce the share of material to be disposed of, as plastics containing additives must generally be sorted out during the recycling process. In fact, this share may even be increased as some other FRs are more difficult to sort and as such, may in fact reduce the yield.

5 Findings and recommendations

This study set out to provide a better understanding of the impacts caused by BFRs on the recycling of plastics from WEEE. To this end, the quantities and destinations of WEEE plastics, including brominated plastics, were first assessed.
Then, legal requirements and practices relating to the treatment of WEEE plastics were studied. Finally, the impact caused by BFRs on recycling yields, recyclate quality and recycling costs were examined, also considering the potential impact posed by alternate FRs such as organophosphates and mineral FRs.

The overarching conclusion from this study is that the **presence of BFRs in WEEE plastics does not reduce recycling yields** more than other FRs as FR-containing plastics, as well as plastics containing other additives in significant loads (e.g. fillers), are sorted out during the recycling process.
A switch to other FRs would not improve WEEE plastics recycling and would most probably have detrimental impacts on yields and quality

Key findings are summarised hereafter:

- Some 2.6 million tons of WEEE plastics are generated annually in Europe, BFR plastics representing about 9% of the total. BFR plastics mostly consist of ABS, PS and epoxy resins, with a BFR content typically ranging between 10% and 30% depending on the type of BFR compound, polymer and required flame retardancy level. Restricted BFRs (POP-BFRs, i.e. PBDEs & HBCD) only represent a small and rapidly declining fraction of all BFRs found in WEEE plastic streams.
- Half of all WEEE plastics generated do not enter official WEEE collection channels, ending up in the waste bin, substandard recycling facilities, or exported. Indeed, only half of WEEE generated in Europe is currently collected through official WEEE take-back channels.
- Out of the 1.3 million tons of WEEE plastics officially collected, about 1 million tons is sent to specialised WEEE plastics recycling facilities (or integrated smelters in the case of epoxy contained in printed circuit boards), the rest being directly sent to incineration (or, rarely, landfilling) after WEEE pre-processing, or lost into metal fractions as a result of sorting inefficiencies.
- Specialis ed WEEE plastic recycling facilities apply a series of sorting steps that normally include a stepwise density separation followed by further sorting processes (e.g. electrostatic separation). A high-density fraction is thereby created, containing a complex mixture of heavy plastics and various additives that is not suited for recycling and is therefore disposed of. This fraction contains more than 95% of the original BFR content, as density sorting is a highly effective way of separating Br-rich and Br-poor fractions.
- About 55% of WEEE plastics entering recycling facilities are effectively recycled, i.e. turned into regranulates that can be used in the manufacture of new products. This recycling yield would not be significantly affected by a switch to non-brominated flame retardants, as alternative FRs would also be sorted out during the conventional density-based recycling process. Alternative FRs would also end up in the high-density fraction which is disposed of due to its complexity and presence of various detrimental additives.
- This conventional WEEE plastic recycling process fulfils the requirements of the WEEE Directive, which specifies that BFR plastics needs to be segregated during the treatment of WEEE. The EN 50625 standards specifies the modalities of this segregation; WEEE plastics (from screens and small appliances) must undergo a BFR separation process creating a Br-poor fraction that can be recycled, containing either less than 2,000 ppm Br or POP-BFRs below the LPCL (i.e. 1,000 ppm for PBDEs, 1,000 ppm for HBCD), and a Br-rich fraction that must be disposed of. This requirement is effectively fulfilled through density separation.
- Analysis contained in this report shows that the 2,000 ppm Br limit, which was introduced as operational threshold enabling fast and cost-effective analysis, should be reviewed in view of the decreasing share of restricted BFRs in the overall Br content. Recent analytical data suggests that limit values for restricted BFRs would not be exceeded even with a threshold as high as 6,000 ppm Br.
- These findings, supported by interviews and feedback with WEEE plastic recyclers, confirm that BFR plastics represent a well-controlled stream, which is easily sorted out during conventional recycling processes.

5 Findings and recommendations

- The WEEE plastic recycling industry is however concerned by the eventual setting of unrealistically low limit values for restricted BFRs. Current sorting technologies can easily meet current limit values, however as with any waste sorting technology there are fundamental limits to sorting efficiencies. Some of the previously proposed limit values, such as 10 or 50 ppm for decaBDE, are challenging if not impossible to detect accurately in laboratory settings.

- Another concern expressed by WEEE plastics recyclers is the poorly documented but potentially serious impacts of alternative FRs on the recycling of WEEE plastics. Some of the most widely used alternative FRs, organophosphates, are for instance known to negatively impact the recyclability of WEEE plastics due to chemical degradation during processing.

Based on these findings, the following set of **recommendations** can be considered:

- For **policymakers**:
  - Increase the quantities of WEEE plastics reaching specialised WEEE plastic facilities by raising WEEE collection rates, enforcing compliance with EN 50625 standards, and facilitating intra-EU cross-border shipments towards state-of-the-art WEEE plastic recycling facilities (for instance by classifying shredded WEEE fractions as non-hazardous)
  - Investigate the impacts of other FRs on the recyclability of WEEE plastics (sorting challenges, impact on recyclates quality, potential hazardousness, etc.) to avoid "regrettable substitution" effects that could prove detrimental to WEEE plastics recycling performance.
  - Improve the knowledge basis necessary for evidence-based policies and decisions by regularly collecting and analysing representative data on levels of BFRs (and other additives) in WEEE plastic streams. Ideally, such data should be collected following harmonised sampling and testing methodologies, and centrally available in the form of a data repository (e.g. similar to the Urban Mine Platform[g]).
  - Review the relevance of normative requirements on treatment of BFR-containing WEEE plastics (WEEE Directive and EN 50625) considering the reduction of restricted BFR levels over time. In particular, the statistical relevance of the 2,000 ppm Br sorting threshold, arbitrarily defined a decade ago, should be investigated.
  - Harmonise and ensure stability of legislation of chemical, waste and products having a direct impact on WEEE plastic recycling, to facilitate much needed investment in innovative recycling technologies.

- For **recyclers**:
  - Develop innovative sorting and recycling methods to recover a higher share of plastics, enabling for instance the recovery of PC-ABS, PA, or PBT polymers. Such innovative methods also include solvent-based recycling technologies in combination with conventional mechanical methods. Several H2020 projects are currently ongoing, such as the PolyCE, Plast2bcleaned and NONTOX projects[h].
  - Seek long-lasting partnerships with producers to optimise design for and from recycling.

- For **producers**:
  - Adopt and implement recycled content targets to boost demand for WEEE plastic recyclates and decouple from virgin plastic prices.
  - Exchange with WEEE plastics recyclers in order to understand how the choice of polymers and additives influence the recyclability of plastics. In the manufacture of EEE, select polymers (and additives) considering the extent to which they are currently recycled.

[g]http://www.urbanmineplatform.eu
[h]https://www.polyce-project.eu, https://plast2bcleaned.eu, http://nontox-project.eu

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