The International Bromine Council

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Brominated Flame Retardants and the Circular Economy of WEEE Plastics

State of Play

Recent developments regarding composition of WEEE plastics, levels of brominated flame retardants, regulatory context and technological advances

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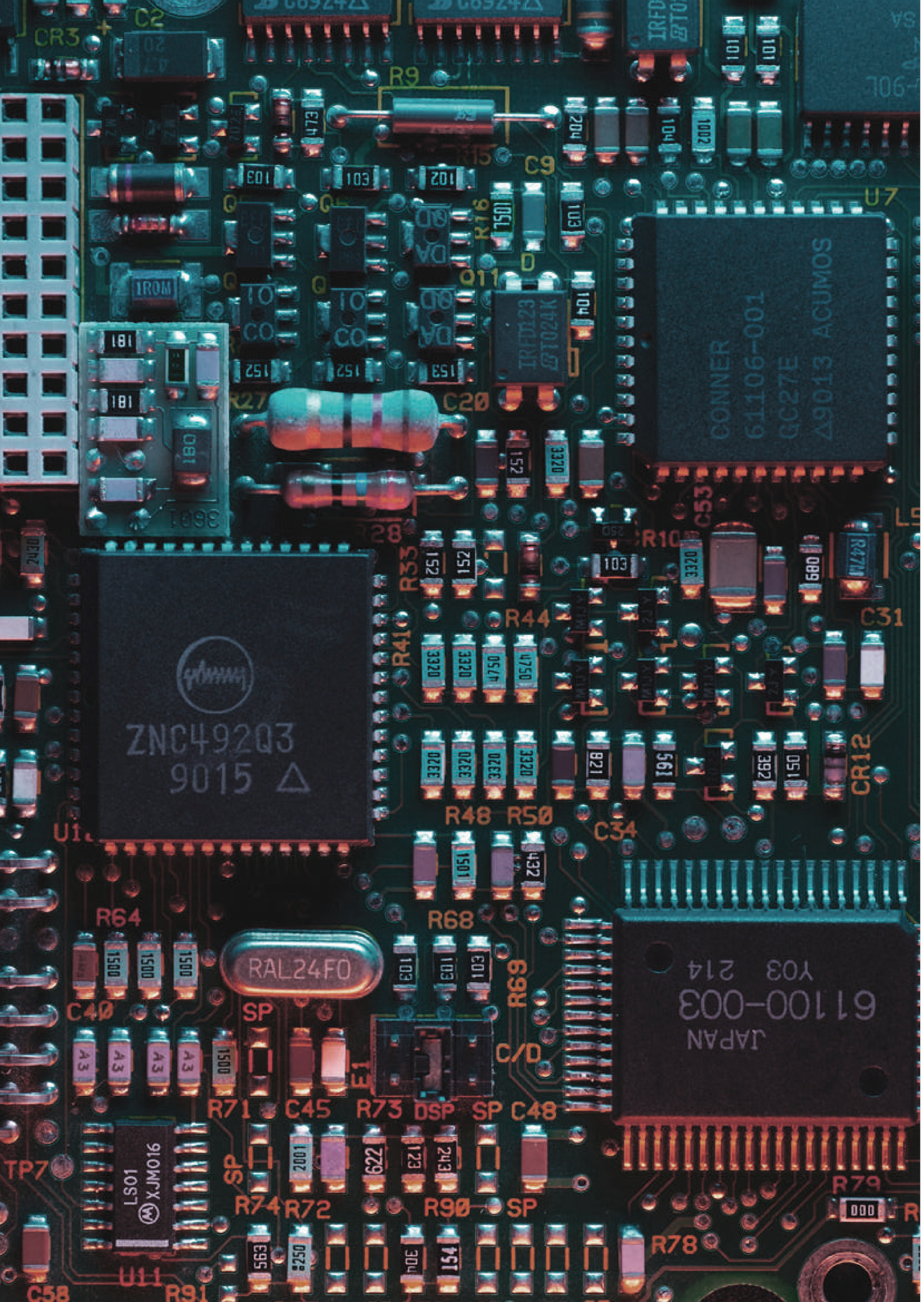

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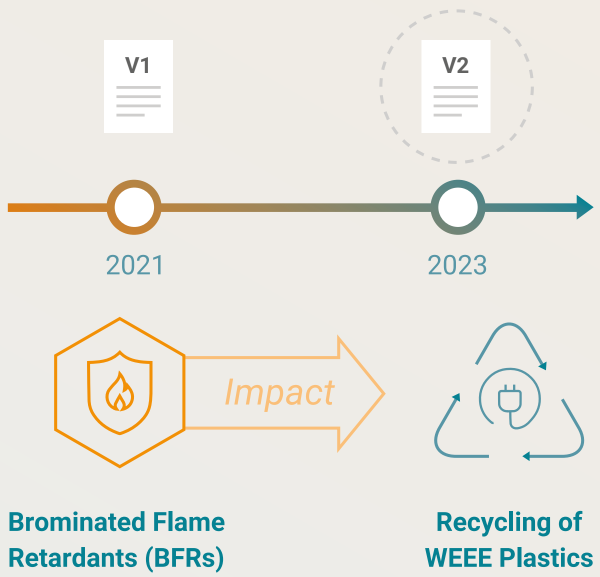
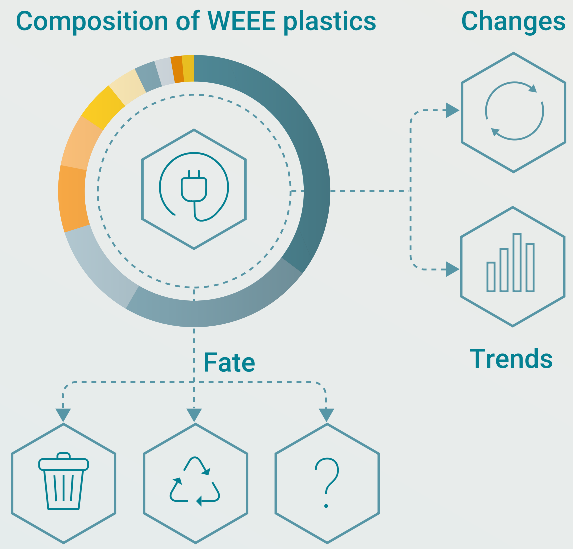
Executive summary

This study is an **update to a previous study conducted in 2020** that examined the **impact of Brominated Flame Retardants (BFRs) on the recycling of Waste Electrical and Electronic Equipment (WEEE) plastics in Europe**.

The update aims to provide **new information and insights** since the previous study, and focuses on several key areas:



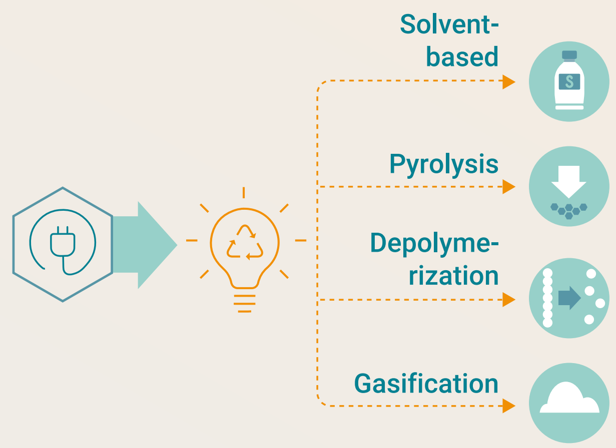


Firstly, it aims to present **updated data on the composition and fate of WEEE plastics**, specifically looking at trends in BFR levels and the current recycling capacity in Europe. The **goal** is to **identify any significant changes or trends** that have occurred since the previous study.

Technological and regulatory developments

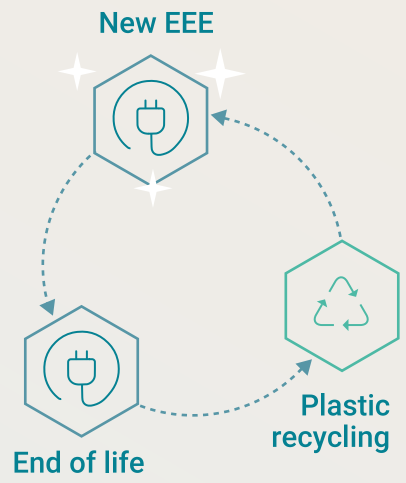
Secondly, the study discusses **technological and regulatory developments in handling WEEE plastics containing BFRs**. It highlights any advancements that have been made since the previous study in terms of how these plastics are handled and moved, taking into account new technologies and regulations.

Emerging technologies for the treatment of WEEE plastics



Thirdly, the study assesses the **potential of emerging technologies** such as solvent-based recycling, pyrolysis, or depolymerisation for treating WEEE plastics. These innovative methods have the potential to **enhance the recycling process and overcome challenges** associated with traditional mechanical recycling.

WEEE plastics and circular economy



Lastly, the study aims to identify **challenges and opportunities related to the incorporation of recycled plastics into new Electrical and Electronic Equipment (EEE)**. This includes assessing the **quality and safety of recycled plastics** and identifying any **regulatory barriers** that need to be addressed. The ultimate goal is to **promote the use of more recycled plastics** in new EEE and foster a **more circular economy**.

Overall, this study provides a comprehensive **overview of the current state of WEEE plastics recycling in Europe** and presents **opportunities for improvement.** By addressing these key areas, the study intends to **assist stakeholders** in the recycling industry **and policymakers** in making informed decisions to enhance the sustainability and efficiency of WEEE plastics recycling.

Key Findings

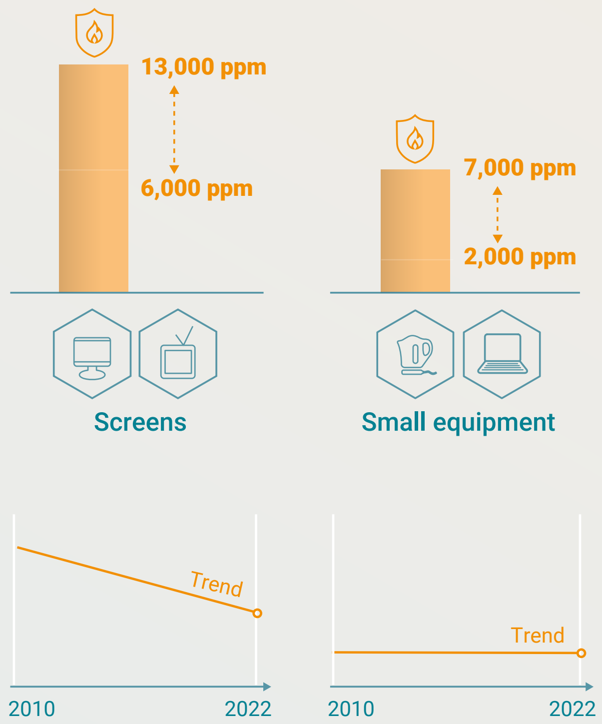
BFR Levels in WEEE Plastics:

- BFR levels in mixed (unsorted) WEEE plastics vary across categories. **Screens have the highest BFR levels**, ranging between 6,000 and 13,000 ppm of bromine (Br) from 2020 to 2023. **Small equipment follows** with BFR levels of 2,000 to 7,000 ppm Br during the same period.

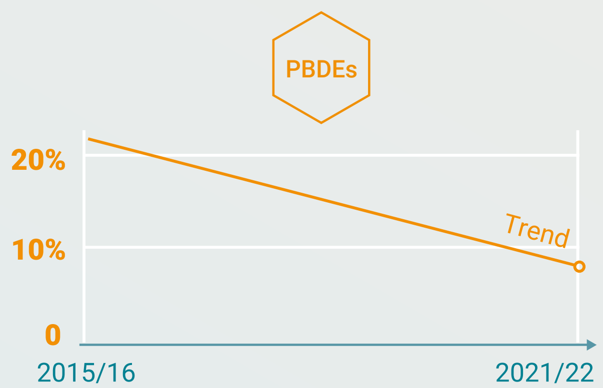
- Over the period from 2010 to 2022, BFR levels in **screens** have generally **decreased**. BFR levels in **small equipment and large equipment** have remained relatively **stable**.

- **PBDEs** (Polybrominated diphenyl ethers) account for a **small and declining proportion of the total bromine content** in recent samples. The **average share of PBDEs** in the total bromine content **has decreased** from above 20% in 2015-2016 to below 10% in 2021-2022. However, **occasional high PBDE levels may still be found** in WEEE streams due to the presence of older devices manufactured before regulatory restrictions were in place.

Average BFR levels in mixed WEEE plastics



Share of PBDEs in total Br content

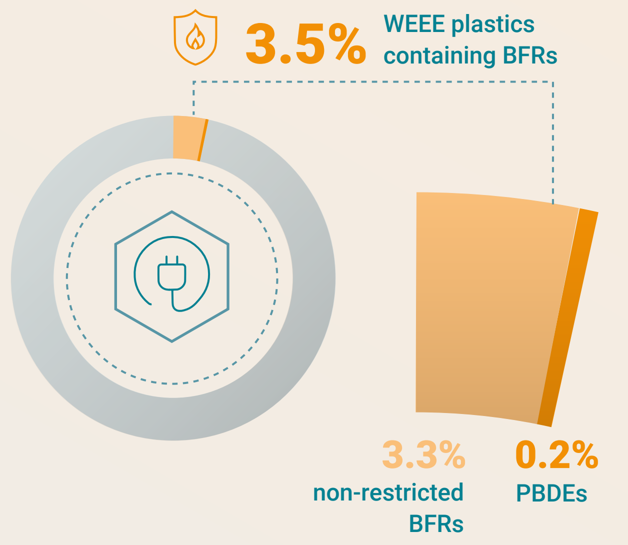


- WEEE plastics contain an **average of 3.5% BFR-containing plastics,** including 0.2% of PBDE-containing plastics and 3.2% of non-restricted BFRs. The proportion of brominated plastics varies across categories, with screens and small equipment containing around 7-8% of brominated plastics, while large equipment and cooling appliances contain much lower proportions.

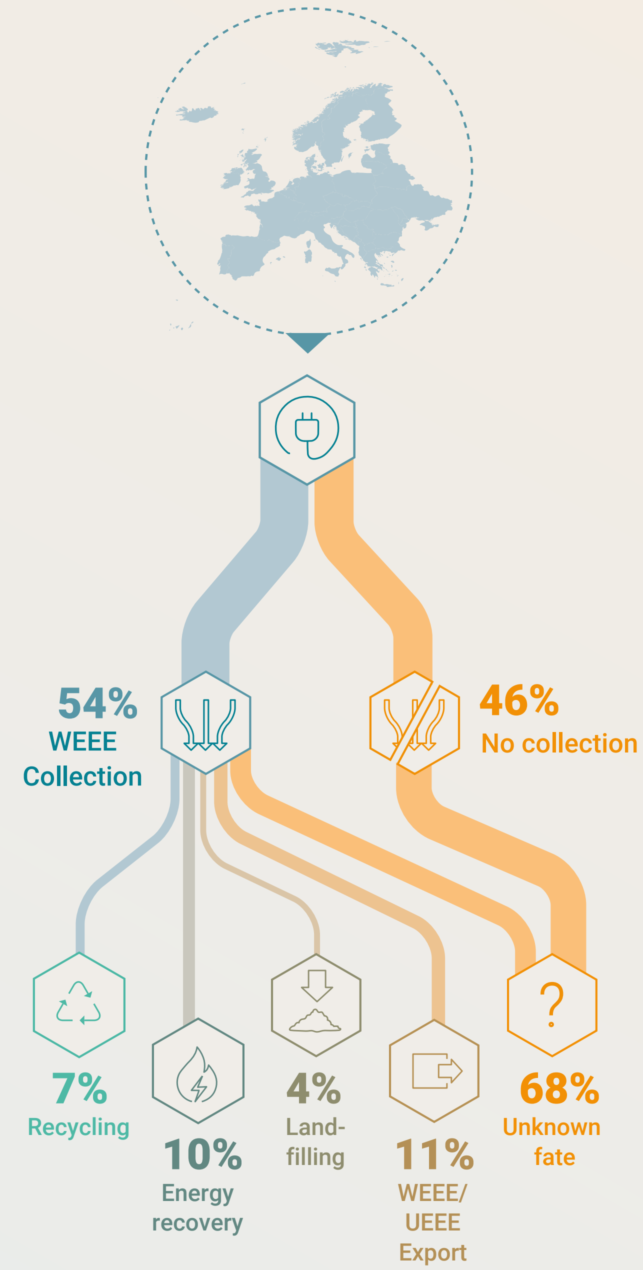
Fate of WEEE Plastics in Europe:

- In 2021, Europe generated approximately **2.6 million tonnes of WEEE** plastics, **but only 54%** (1.4 million tonnes) **were collected through official WEEE channels**. Out of the collected amount, only **0.4 million tonnes reached specialised WEEE plastic recycling companies** in Europe (15% of total).

- Around **46% of all WEEE plastics manage to evade official collection**. Some are treated as scrap metal or disposed of with mixed waste, while others are exported outside Europe, legally or illegally. When considering the final destinations of all WEEE plastics arising in Europe, **68% have an unknown fate**, raising concerns about unsafe recycling practices or improper disposal. This includes WEEE plastics escaping formal WEEE collection,



WEEE plastic waste in Europe



as well as leakages in official WEEE treatment channels.

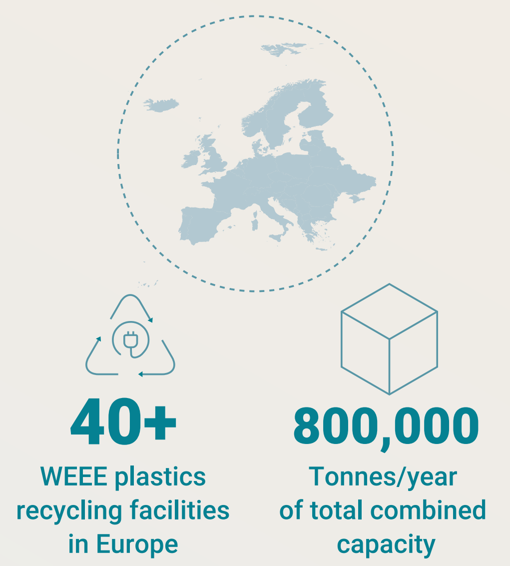
• Europe has **more than 40 companies specialising in WEEE plastics sorting and recycling**, with an estimated combined capacity of around **800,000 tonnes per year**. However, this total may include some double counting, as different companies may be involved in different steps of the supply chain, e.g. some companies may only carry out pre-sorting, others only final sorting and compounding.

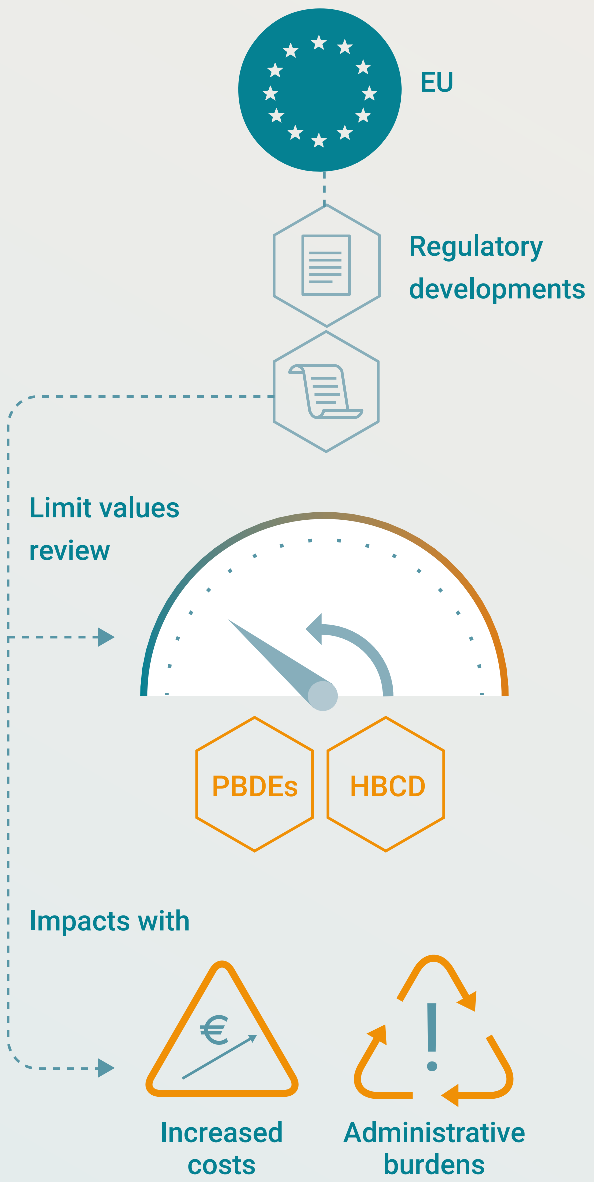
Regulatory Developments:

• **The European Commission has reviewed the limit values for hexabromocyclododecane (HBCD) and PBDEs in waste, resulting in lowered limits**. The proposed thresholds for PBDEs are expected to decrease further by 2027.

• Proposed changes in waste shipments regulations may impact the proper management of WEEE plastics. **Increased costs and administrative burdens** related to the movement of waste could potentially **hinder the recycling of WEEE plastics** and **create challenges for cross-border waste trade**.

Recycling WEEE plastics in Europe





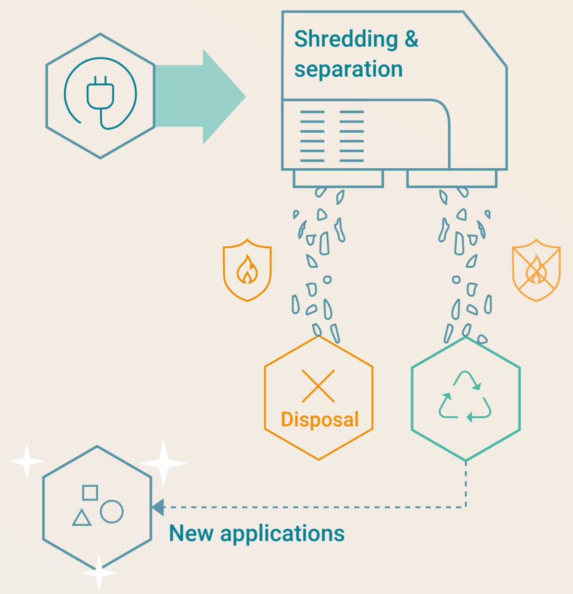
Conventional and Emerging Technologies for Handling WEEE Plastics:

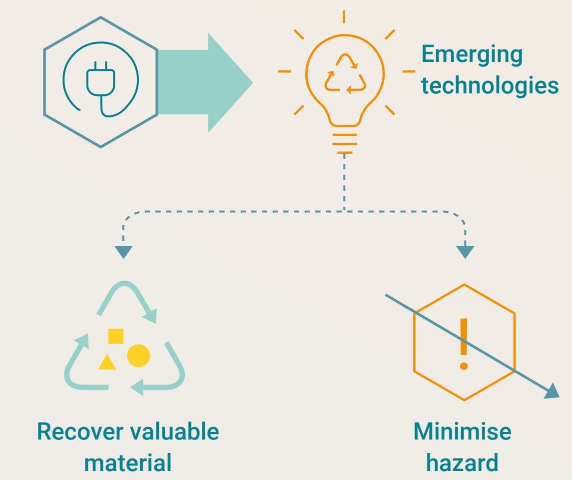
• **Conventional recycling processes** involve **mechanical shredding and sorting** of WEEE plastics to separate plastics with high levels of BFRs and other additives, allowing for the creation of **homogeneous and additive-poor plastic fractions**. These fractions are suitable for **recycling into new products**.

• **Emerging technologies**, such as solvent-based recycling, pyrolysis, or depolymerisation, **offer alternative approaches** for handling WEEE plastics. These technologies aim to **recover valuable materials** and **eliminate or minimise the release of hazardous substances** during processing.

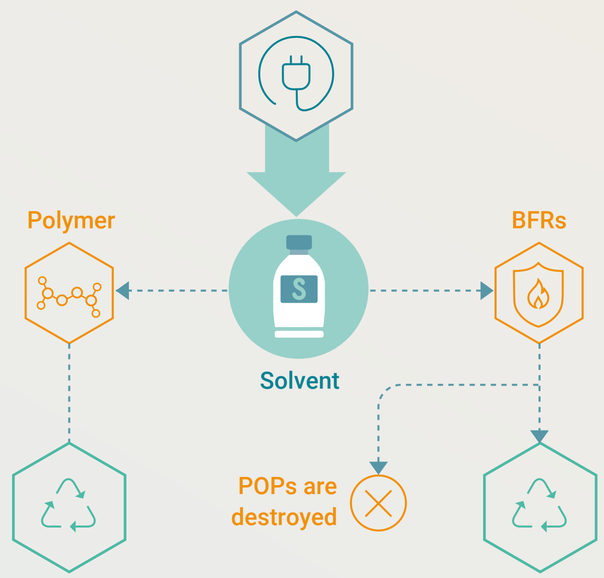
• **Solvent-based recycling has shown promise in separating WEEE plastics containing BFRs**. In this process, the plastic is **dissolved in a solvent**, the polymer forms a gel with an anti-solvent and the BFRs remain in the solvent. The polymer gel is dried to produce a recyclate. The solvent is recovered and the remaining BFRs, including POPs, are concentrated. The POPs must be destroyed above 850 degrees Celsius, eventually followed by bromine recovery. The recovered bromine can be reused for new BFRs and the process is approved as a

Conventional recycling process





Solvent-based recycling

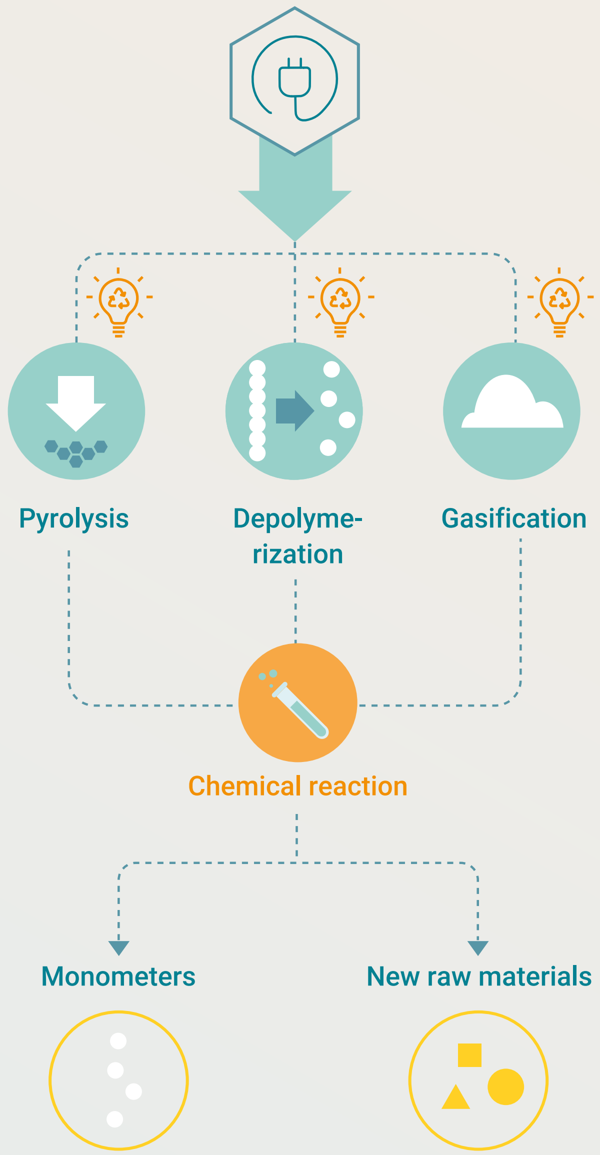


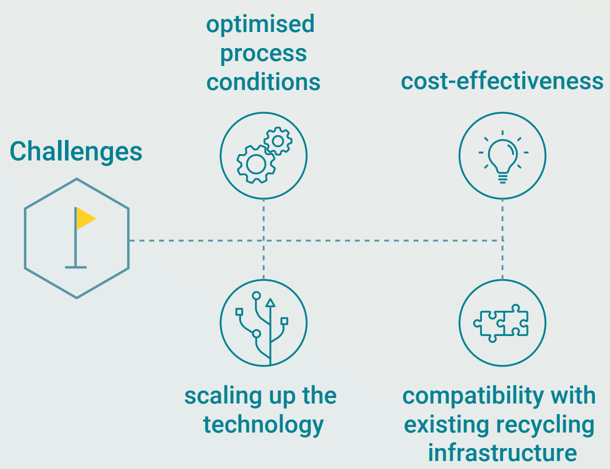
pre-treatment process in the Basel Convention Technical Guidelines .

- Other emerging technologies include **chemical recycling processes such as pyrolysis, gasification and depolymerisation**. These processes **convert polymers into monomers** through a chemical reaction or **produce new raw materials** (e.g. oil or syngas) through chemical modification, changing the chemical structure of plastics. These technologies are particularly interesting for **treating the hard-to-recycle fractions** from mechanical recycling processes. However, they are not mature and their application to WEEE plastics is still at a **very early stage of development**. Furthermore, these technologies are currently **not allowed** as pre-treatment processes in the Basel Convention Technical Guidelines and are therefore not allowed for WEEE plastics containing POPs above the "low POP content limit" (LPCL).

- While solvent-based recycling and other emerging technologies hold **potential**, there are **challenges to their widespread implementation**. Although they may work effectively for pre-sorted polymers, challenges for their use include the need for optimised process conditions, cost-effectiveness, scaling up the technology, and ensuring compatibility with existing recycling infrastructure.

Other emerging recycling technologies





Recommendations

Strengthen collection systems:

Improve separate collection rates of WEEE has the largest impact in regard to the correct disposal of BFRs, this being greater than reducing the UTC (Unintended Trace Contaminants) value in plastics. This can be achieved through effective awareness campaigns, convenient collection points, and mandatory collection targets, allowing for enhanced cooperation between stakeholders to prevent illegal exports and ensure proper recycling processes.

Harmonised regulations:

Harmonised regulations on BFRs, including PBDEs and HBCD, at the international level to facilitate consistent practices and avoid conflicting requirements. Consider the practicality of UTC levels and the availability of reliable analytical methods.

Promote technological advancements:

Encourage research and development in solvent-based recycling and chemical recycling technologies to improve their efficiency, scalability, and cost-effectiveness. Support pilot projects and collaborations between industry and academia, including through reducing constraints posed by intellectual property.

Enhance data collection:

Establish a standardised and centralised database to collect and analyse data on the composition, fate, and recycling capacity of WEEE plastics. This will provide a better understanding of the current state and support evidence-based decision-making.

Encourage circular economy practices:

Promote the use of recycled plastics from WEEE in the manufacturing of new Electrical and Electronic Equipment (EEE). Facilitate collaboration between WEEE recyclers and EEE manufacturers to overcome technical and logistical challenges.

Conclusion

Improving the state of WEEE plastics recycling in Europe requires a comprehensive approach that addresses collection, sorting, regulatory frameworks, and technological advancements. By implementing the recommended measures, Europe can enhance resource utilisation, minimise environmental impact, and move closer to achieving a circular economy for WEEE plastics. It is important to remember that the **WEEE plastics recycling industry and its processes only emerged during the last fifteen years** and are, therefore, still relatively undeveloped compared to other material recycling, such as the metal recycling processes. To attain the same level of development and achieve the implementation of these recommendations, **continued collaboration and knowledge-sharing among stakeholders is crucial**.

1 Introduction

1.1 Context

In 2018, the European Commission launched the **Circular Plastic Alliance** to boost the EU market for recycled plastic with an initial pledge of 10 million tonnes (Mt) by 2025 and with more than 300 signatories to date. This initiative contributes to achieving the **EU Circular Economy Action Plan** launched in 2020.

Electronic equipment is not only one of the key waste streams identified in the Circular Economy Action Plan but also represents **a significant 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). This represents an estimated **total of 2.6 million tonnes in Europe**. Such plastics also contain a wide range of additives such as flame retardants, fillers, pigments and stabilisers. Plastics found in WEEE are often engineering polymers, these being types of plastic materials that are highly durable and rugged and as a result have high market value and good theoretical recyclability.

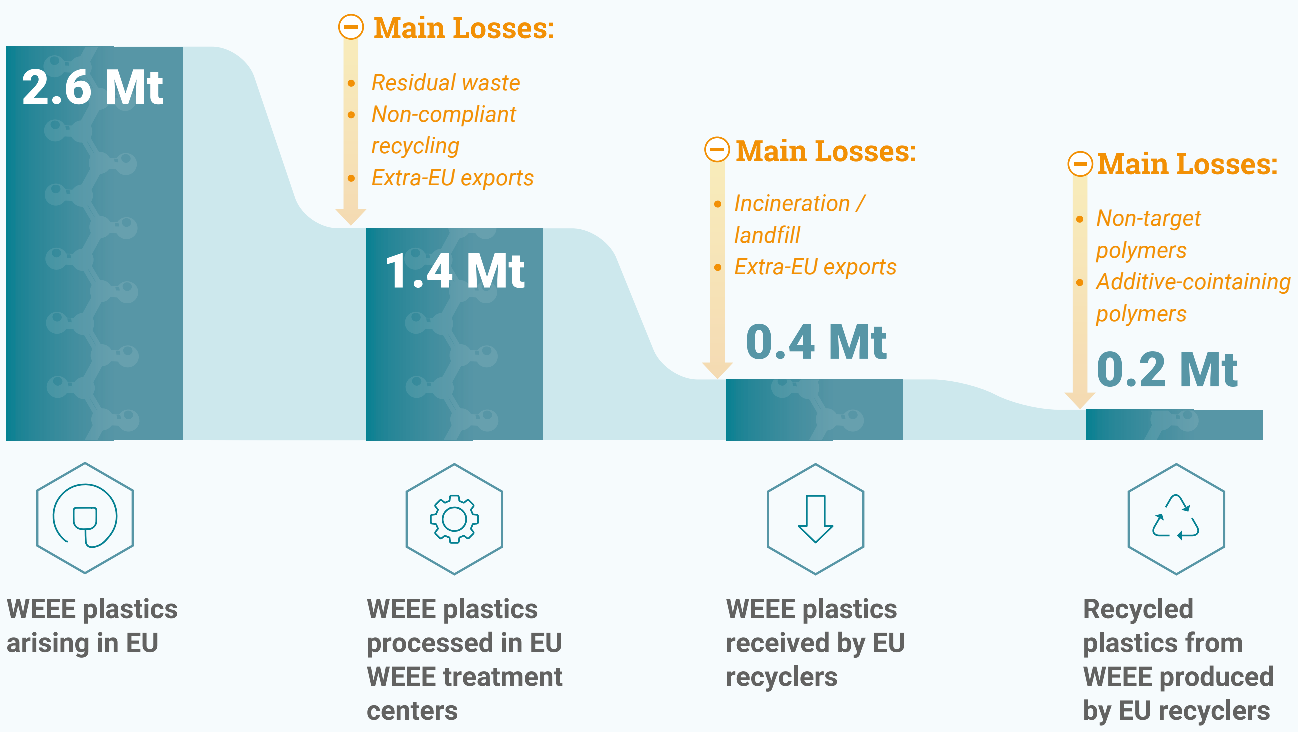


Figure 1: Graphic visualisation of the current flows of WEEE plastics in Europe. See Chapter 2.2.1.1 for information on the data sources.

In reality, **only a small part of the recycling potential is realised today**. The way in which WEEE and its plastics are managed is indeed characterised by **numerous losses** along the value chain, as illustrated with estimates for Europe in Figure 1.

The reasons for such a loss of potential are multiple and intertwined.

Firstly, **only just over half of the WEEE produced in Europe reaches the designated WEEE collection points**. Indeed, the collection rate for WEEE in Europe has been estimated at 54% in 2021[3].

The **remaining 46% of WEEE escapes from separate collection**. Leakage includes poorly sorted WEEE that ends up in **residual waste** or **scrap metal**, and inadequate treatment streams where WEEE ends up in incineration, landfill or material recovery without depollution. A significant proportion, although difficult to quantify[4], leaves the European territory in the form of **exports** of used equipment for re-use abroad, or even exports of waste for cheaper treatment.

When WEEE does reach authorised **WEEE treatment centers**, plastics typically end up in the residual shredded fraction once all metallic parts have been removed (magnetically or through eddy-current separation). As with all waste sorting processes, some plastics are however lost as impurities to the metal scrap fractions, in which they will end up incinerated. Plastic-rich fractions from WEEE treatment are sometimes **sent for incineration/landfill** or sold to traders who **export them outside Europe**, rather than being sent to **WEEE plastics sorting/recycling facilities in Europe**.

Once they arrive at **specialised WEEE recycling facilities**, plastics from WEEE undergo a series of sorting steps based on **density, electrostatic properties, infrared spectra** and/or other sensor-based techniques. Overall, **about 50% of the input is transformed into secondary plastics** fed into the market. The other half, made of a complex mixture of non-target polymers and additives, is currently considered non-recyclable and is sent for disposal. Generally, through incineration, however, landfilling may still be practised in some countries in the EU.

Specialised WEEE plastic recyclers face several challenges that affect their ability to efficiently and sustainably recycle WEEE plastics. These challenges include:

1. **Supply-side** challenges: The **low WEEE collection rates** are a significant issue as they limit the quantity of plastic waste that is available for recycling. Additionally, **administrative burdens in intra-EU shipments** can create significant barriers for recyclers, particularly those that operate across multiple countries due to mixed plastics requiring notifications. Furthermore, **competition with extra-EU exports of plastic waste** can be a challenge for WEEE plastic recyclers, as it reduces the amount of waste that is available for local recycling efforts.

2. **Technical limitations** in sorting: The high **heterogeneity** of plastic waste, particularly in the case of WEEE, can pose significant challenges for recyclers. Sorting plastic waste is a complicated process as there are different types of plastics with **varying compositions and properties**, mainly due to design choices that don't sufficiently take into account end-of-life sorting challenges..

Furthermore, some **additives** in plastics, including both restricted and non-restricted substances, can complicate the conventional recycling process due to their impacts on density-based sorting technologies. Finally, **black plastics**, which are commonly used in electronic devices, can also be problematic as they are difficult to sort using near-infrared sorting technologies.

3. Barriers to investment: Recyclers face several barriers when it comes to investment in recycling facilities. **Regulatory uncertainty** creates significant challenges for recyclers, particularly when it comes to changes in regulations or the introduction of new regulations that impact the recycling industry, such as lowering UTC values. **Volatile prices** can also be problematic, particularly when it comes to the sale of recycled plastics, which can impact the profitability of recycling efforts. Finally, **low-profit margins** can create challenges for recyclers as it limits their ability to invest in new technologies and equipment that can improve their recycling processes.

4. Demand-side challenges: There are **hard-to-meet demands in terms of volumes and purity** for recycled plastics. Recyclers may struggle to meet the volume requirements of manufacturers and other customers, particularly if they have limited access to plastic waste. Additionally, the purity of recycled plastics can be a challenge, particularly when it comes to meeting the strict requirements of customers in specific industries, such as the food and beverage industry. Even for less sensitive applications (e.g. electronics), some OEMs impose stricter limits than those required by law.

Overall, these challenges make it difficult for WEEE plastic recyclers to operate efficiently and sustainably. Overcoming them will require significant efforts from industry players, policymakers, and other stakeholders.

1.2 Aim and Scope of the Study

This study aims to provide an update to a previous study conducted in 2020[5], which investigated the impacts caused by the presence of BFRs on the recycling of WEEE plastics in Europe (hereinafter referred to as "the previous study").

In particular, this update primarily aims to:

- Provide **updated figures on the composition and fate of WEEE plastics**: In particular, on trends in BFR levels as well as on the current recycling capacity of WEEE plastics in Europe. The focus will be on relevant changes or trends that have occurred since the previous study was conducted.
- Discuss **technological and regulatory developments** regarding the handling of WEEE plastics containing BFRs: Here also, the focus will be on technological and regulatory changes that have occurred since the previous study related to handling and movement of WEEE plastics that contain BFRs.
- Assess the **potential of emerging technologies** such as solvent-based recycling, pyrolysis or depolymerisation to treat plastics from WEEE: These new technologies could potentially improve the recycling process and address some of the challenges faced by traditional mechanical recycling methods.
- Identify the **challenges and opportunities related to the incorporation of recycled plastics** into new EEE: This includes assessing the quality and safety of the recycled plastics and identifying any regulatory barriers that may need to be addressed. By identifying these challenges and opportunities, the study aims to facilitate the incorporation of more recycled plastics into new EEE and promote a more circular economy.

Overall, the study aims to provide a **comprehensive overview of the current state of WEEE plastics recycling in Europe and identify opportunities for improvement**. By addressing these four key areas, the update can help stakeholders in the recycling industry and policymakers **make more informed decisions and take action to improve the sustainability and efficiency of WEEE plastics recycling.**

2 WEEE Plastics
Composition and Fate

2.1 Share of polymers

A **wide range of polymers** can be found in WEEE plastic fractions. Within the framework of the previous study, a large database on WEEE plastics composition at the WEEE category level[6] 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%[7]), 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[8,9,10,11,12] as well as process data provided by WEEE recyclers and/or 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 a 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[13], are displayed in Figure 2.

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%).
- 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%).
- 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%).
- Large equipment contains only 15% plastics, mainly PP (57%), ABS (12%), PA (3%), PE (2%) and PC/PC-ABS (2%).
- Small equipment (non-ICT) consists of 31% plastics, mainly ABS (30%), PP (14%), HIPS (11%) and PC-ABS (7%).
- Small ICT equipment has 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.

2.2 BFR levels

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

Share and composition of plastics in WEEE

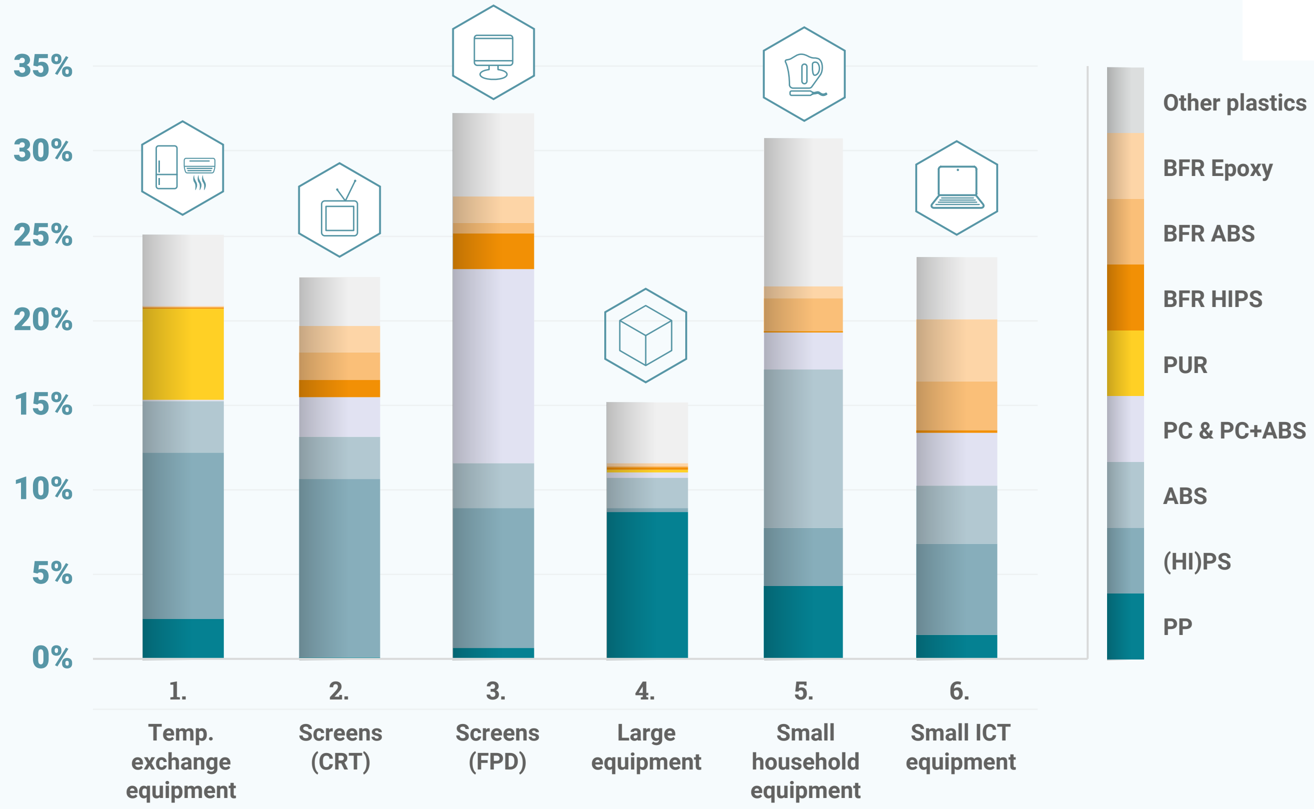


Figure 2: Share and composition of plastics in WEEE, per category. FPD refers to flat panel displays monitors and TVs but also, in the scope of this study, laptops and tablets. The total for each category represents the total proportion of plastics. The remainder consists mainly of ferrous and non-ferrous metals.

grouped into the following main groups:

- **Halogenated** flame retardants, either **brominated** (accounting in 2018 for 55% of global use of flame retardants in EEE[14]) or **chlorinated** (1%). Brominated flame retardants are usually used in combination with antimony trioxide as synergist (11% of global FR use in EEE1), typically in concentrations equivalent to a 1/3-1/2 of the Br content[15].
- **Organophosphorus** compounds (27% global FR use in EEE), 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. 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, **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[16]:

- **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 now classified as POP substances under the Stockholm Convention due to their persistent, bioaccumulative and toxic (PBT) and long-range transport (LRT) properties, see also Chapter 3.2. However, it is worth noting that the majority of BFRs found in WEEE today are permitted substances.

- **Reactive BFRs:** chemically bound to the polymeric structure. One of the main reactive BFRs is tetrabromobisphenol A (TBBPA), used reactively in epoxy resins for circuit boards.
- **Oligomeric and polymeric BFRs:** bromine atoms are incorporated directly into the polymeric structure itself. They can also be considered additive BFRs, as they are also physically incorporated into the polymer matrix, but they are much larger molecules with much lower migration potential and no potential for bioaccumulation. Polymeric BFRs include brominated polystyrene (BrPS), brominated epoxy resin (BEO), brominated polyacrylate (BrPA) and butadiene styrene brominated copolymer (Poly-Bu-St).

2.2.1 Functional BFR loadings

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 to reach the desired flame-retardancy depend on several factors such as:

- Required **flame-retardancy**: commonly tested and expressed using the standardised UL 94[17] 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). Examples of formulations are given in Table 1.
- **The potency of BFR compound** used: some compounds are more reactive or have a higher bromine content 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).
- **Polymers** considered: 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 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

Polymer	UL 94 Rating	BFR content	Br content	Sb Content
HIPS	V2	8.9%	6.0%	2.0%
HIPS	V0	14.9%	10.0%	3.0%
ABS	V2	8.6%	6.0%	3.0%
ABS	V0	14.3%	10.0%	5.0%

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

Component		Connectors			External Casings			Foams			PWB		
Polymer		PA6	PA66	PBT	PC	ABS	HIP S	PC ABS	PE	PP	EPS	XPS	Epoxy
OctaBDE*	V2					15%							
DecaBDE	V0					10%			27%	26%			
BCO	V2			13%	13%								
BEO	V0	21%	21%	16%	21%	22%	14%						
BrPA	V2			11%									
BrPS	V0	21%	21%	13%									
BTBPE	V2					18%	16%						
EBP	V0			11%		15%	11%		25%	20%			
EBTBP	V2			13%			13%						
HBCD*	V0						4%				<1%	<3%	
Poly-Bu-St	V2										<1%	<3%	
TBBPA	V0					20%		14.3%					25%
TBBPA-DBPE	V2						3%			7%			
TBNPP	V0									3%			
TBPT	V2					15%	15%						
TTBPT	V0					17%	13%						

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).

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

Table 3: Range of BFR and Br content in polymers when brominated. The 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.

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

2.2.2 BFR Levels in WEEE Plastics

Mixed 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 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**, resulting from the pre-processing of WEEE, are substantially below these "functional Br levels".

Several studies have been conducted to determine the levels of BFRs in mixed WEEE plastic fractions. These studies, if based on scientifically robust sampling and analysis methods, can provide a sound basis for policymaking, standards setting, and operational decisions. For example, they can help identify WEEE categories that require specific treatment due to elevated levels of restricted BFRs. The composition of those mixed WEEE plastic fractions is also decisive for their classification as "special" waste (hazardous waste, POP waste, etc.).

The previous study involved building a **comprehensive database on the levels of BFRs in mixed WEEE plastic fractions**. This database relied on several scientific papers, containing data up to 2017[19]. In the current study, this database could be considerably expanded by acquiring and consolidating additional data obtained from tests conducted by a European Producer Responsibility Organisation (PRO) between 2014 and 2023 to assess the BFR sorting efficiency of WEEE plastic sorting companies, following a methodology based on the standard TS 50625-3-1.

In total, data from 138 unsorted WEEE plastic samples were consolidated. All were obtained following standard sampling and analysis procedures designed to ensure representativeness and accuracy. Detailed results are given in Table 4. Furthermore, the temporal evolution of average PBDE and Br levels is illustrated in Figure 3.

Several observations can be made from these results:

- Across WEEE categories, BFR levels are highest in **screens** (Br levels ranging between 6,000-13,000 ppm in 2020-2023), followed by **small equipment** (2,000-7,000 ppm Br in 2020-2023). Large household appliances contain relatively little (1,500 ppm Br in 2017), and temperature exchange equipment almost none (350 ppm Br in 2017).
- Over the period considered (2010-2022), **total BFR levels tend to decrease in screens**. This could be due to a change in the type and age of appliances[20], or indicate a growing use of other flame retardants such as mineral FRs and organophosphorus compounds. **BFR levels in small equipment and large equipment appear relatively stable**.
- **PBDEs account for a minor and declining share of the total bromine content**. In recent samples (2020-2021), PBDE levels reached up to 2,237 ppm in plastics from screens and up to 644 ppm in plastics from small appliances. However, in other recent samples (from screens), PBDEs were not found above the detection limits. **Across all recent samples, average PBDE levels reached 239 ppm in plastics from small appliances and 805 ppm in plastics from screens**[21].
- As for the **other POP-BFRs**, in recent years HBCD was found at up to 468 ppm in plastics from small equipment, and PBBs were not found above the detection limits.

It should be noted that for some years and WEEE categories, the number of samples tested is very small, and therefore figures should be considered with care. For instance, the elevated levels found in plastics from screens in 2022 may not be representative and be due to higher-than-average levels in the individual sample tested that year. It should also be noted that plastics from screens often have a larger size that for other WEEE categories (as they usually come from manual dismantling), and are therefore particularly difficult to sample representatively. Generally, **there is a lack of data on BFR levels in mixed WEEE plastics**.

Category	Year of sampling	Number of samples	Total Br		PBBs		HBCD		ΣPBDEs		TBBPA		Source
			mean	max	mean	max	mean	max	mean	max	mean	max	
1. Temperature exchange equipment	2010	12	245	580	BDL	BDL	BDL	BDL	92	500	5	30	*Wäger et al. 2011*
1. *Temperature exchange equipment*	2017	15	353	810	BDL	BDL	BDL	BDL	103	382	102	652	*Bill et al. 2022*
4. *Large equipment*	2010	6	1,083	2,100	BDL	BDL	BDL	BDL	450	1,600	18	60	*Wäger et al. 2011*
4. *Large equipment*	2017	21	1,541	4,283	BDL	BDL	8	63	201	474	222	1,000	*Bill et al. 2022*
5-6. *Small equipment (including ICT)*	2010	17	5,594	15,000	BDL	BDL	BDL	BDL	812	2,100	1,537	6,390	*Wäger et al. 2011*
5-6. *Small equipment (including ICT)*	2014	5	3,564	4,373	BDL	BDL	/	/	525	737	/	/	*Hennebert et al. 2018, European PRO*
5-6. *Small equipment (including ICT)*	2015	5	3,510	5,670	BDL	BDL	155	468	402	562	843	1,130	*Hennebert et al. 2018, European PRO*
5-6. *Small equipment (including ICT)*	2020	1	2,020	2,020	BDL	BDL	157	157	71	71	1,267	1,267	*European PRO*
5-6. *Small equipment (including ICT)*	2021	1	7,317	7,317	BDL	BDL	152	468	330	330	1,863	1,863	*European PRO*
5-6. *Small equipment (including ICT)*	2022	4	4,238	6,573	BDL	BDL	BDL	BDL	314	644	1,547	3,363	*European PRO*
2. *Screens (CRT)*	2010	14	23,571	55,000	BDL	BDL	BDL	BDL	5,186	18,400	16,964	63,000	*Wäger et al. 2011*
2. *Screens (CRT)*	2011	6	19,167	28,000	BDL	BDL	BDL	BDL	3,574	5,120	7,553	15,000	*Taverna et al. 2017*
2. *Screens (CRT)*	2014	5	11,727	17,968	28	96	/	/	1,663	3,936	/	/	*Hennebert et al. 2018, European PRO*
2. *Screens (CRT)*	2015	3	9,380	11,545	46	92	490	745	3,590	4,453	3,405	4,180	*Hennebert et al. 2018, European PRO*
2. *Screens (CRT)*	2020	1	7,568	7,568	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	*European PRO*
2. *Screens (FPD)*	2010	6	8,950	17,000	BDL	BDL	BDL	BDL	98	490	1,253	4,120	*Wäger et al. 2011*
2. *Screens (FPD)*	2011	9	7,522	12,000	BDL	BDL	BDL	BDL	1,183	3,913	2,202	4,380	*Taverna et al. 2017*
2. *Screens (FPD)*	2014	1	13,143	13,143	BDL	BDL	15	15	4,310	4,310	/	/	*Hennebert et al. 2018*
2. *Screens (FPD)*	2015	3	6,885	8,060	BDL	BDL	8	15	1,179	1,841	2,100	2,160	*Hennebert et al. 2018, European PRO*
2. *Screens (FPD)*	2020	1	5,157	5,157	BDL	BDL	BDL	BDL	BDL	BDL	253	253	*European PRO*
2. *Screens (CRT & FPD)*	2022	1	13,307	13,307	/	/	97	97	2,237	2,237	4,123	4,123	*European PRO*
2. *Screens (CRT & FPD)*	2023	1	5,360	5,360	BDL	BDL	BDL	BDL	983	983	603	603	*European PRO*

Table 4: *Average and max levels of Br, PBB, HBCD, PBDE and TBBPA (in ppm) in unsorted WEEE plastics. "BDL": below detection limit; "-": not measured/reported. Note that TBBPA is not a POP-BFR, however it is one of the most frequently used BFR compounds and accounts for a significant portion of total bromine levels found in WEEE plastics.*

Remark: the above data is for waste plastics before sorting. In practice, BFR-containing plastics are sorted out, so that actual BFR levels in recycled fractions are much lower.

The same database can be used to estimate the proportion of brominated plastics in unsorted WEEE plastics. This estimation assumes an average functional bromine (Br) content of 10%. It

Breakdown of total bromine content (ppm) in unsorted WEEE plastics

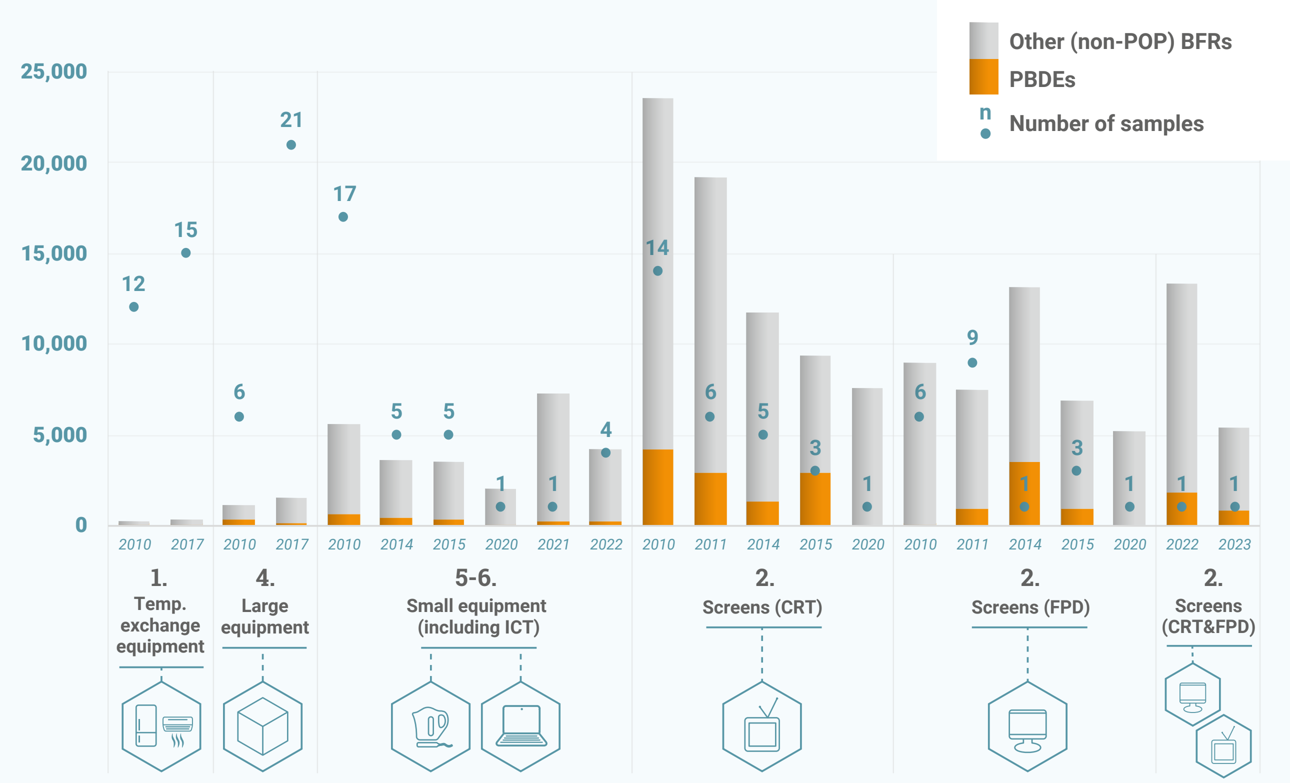


Figure 3: *Breakdown of total bromine content (ppm) in unsorted WEEE plastic samples, per WEEE category. In the case of screens, some data are representative of CRT screens only, some of FPD screens only, and others of a mixture of both.*

Estimated share of intentionally added brominated plastics in unsorted WEEE plastics (assuming functional Br content of 10%)

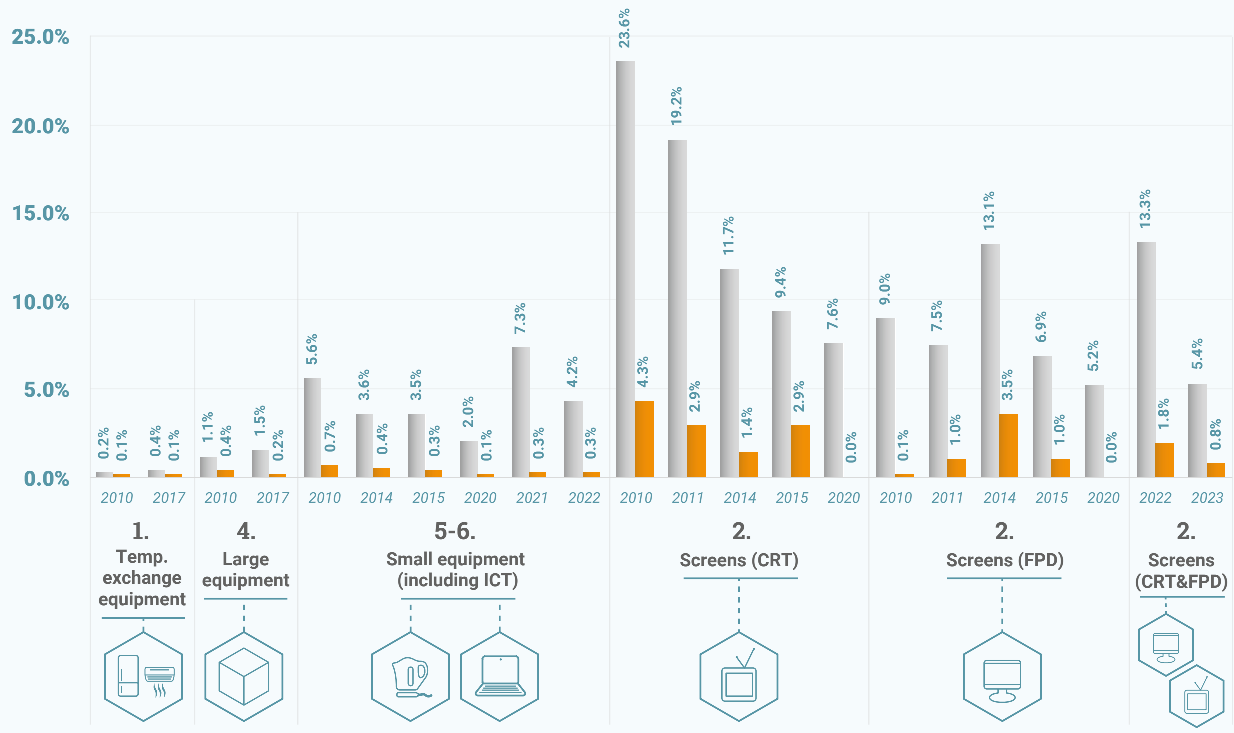


Figure 4: *Estimated share of intentionally brominated plastics in unsorted WEEE plastics.*

means that plastic pieces intentionally treated with brominated flame retardants (BFRs) contain an average of 10% Br. The results depicted in Figure 4 indicate that currently, **mixed plastics from screens and small equipment comprise up to about 7-8% brominated plastics**. For large equipment and cooling appliances, this share is much lower (respectively 1.5% and 0.4%). Regarding PBDEs, the data indicates that **mixed plastics from screens and small equipment contain less than 1% of plastics with intentionally added PBDEs**, while plastics from large equipment and cooling appliances contain less than 0.2% and 0.1% respectively.

Average composition of unsorted WEEE plastics

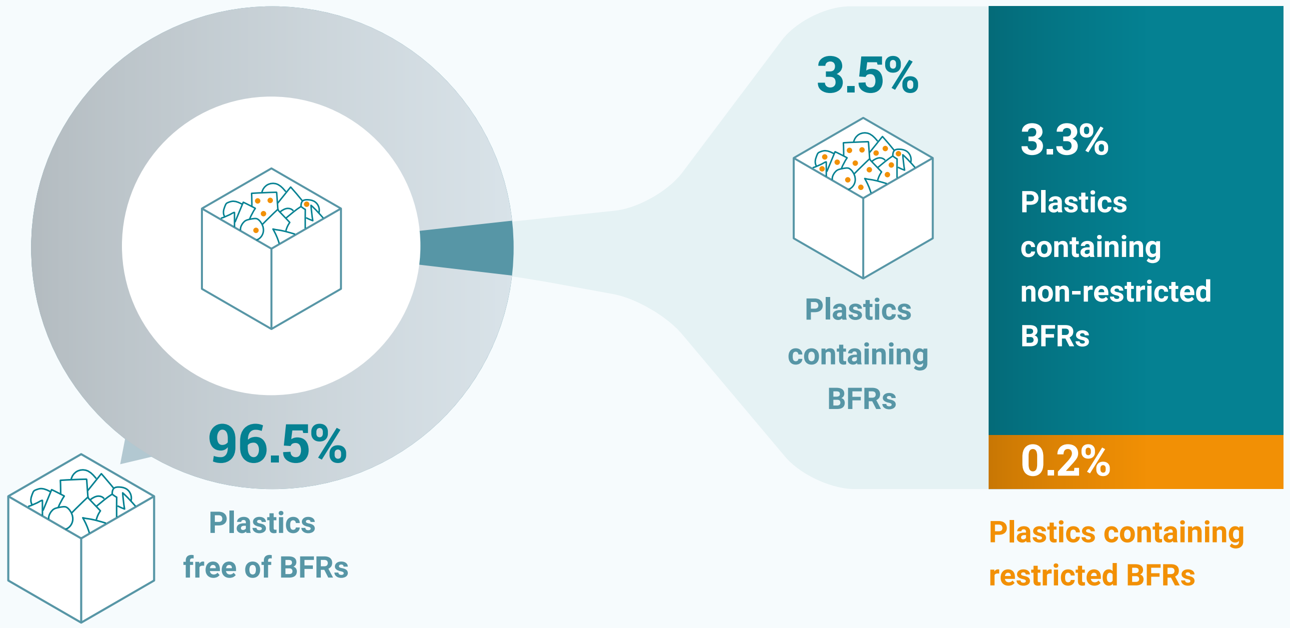


***Figure 5:** Average share of brominated versus non-brominated plastics in WEEE.*

Category	Share of total WEEE plastics generated	Average share of plastics containing BFRs	Average share of plastics containing PBDEs
Screens	11%	7.8%	0.7%
Small appliances	49%	4.5%	0.2%
Large appliances	22%	1.5%	0.2%
Cooling appliances	18%	0.4%	0.1%
Total WEEE	**100%**	**3.5%**	**0.2%**

***Table 5:** Data used to create Figure 5.*

Average Br and PBDE content based on samples from recent years (since 2017) were consolidated and combined with data on the total amounts of WEEE plastics generated by the WEEE category (compiled as part of the previous study) to create a simplified picture of the average share of brominated plastics in WEEE plastics arising nowadays (Figure 5).

Breakdown of Total Bromine Content

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 data sources referred to above as well as 5 additional data sources not included in the previous chapter, either because they applied a biased methodology including XRF-screening to select high-Br samples for BFR analysis , or because the sampled material didn't correspond to unsorted WEEE plastic mixtures but rather WEEE plastic fractions after sorting/ reprocessing[23,24,25] or articles presumably made of WEEE plastic recyclates[26]. It was assumed that these methodological variations didn't affect the relative share of PBDEs in the total BFR content. The resulting dataset, representing a total of 475 samples, is illustrated in Figure 6.

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 downward trend is visible from 2015 onwards, indicating a phasing out of PBDEs in waste streams. The **average share of PBDEs in the total Br content decreased from above 20% in 2015-2016 to below 10% in 2021-2022. Outliers** however exist, due to the highly heterogeneous nature of WEEE streams and the possible presence of very old appliances (containing legacy substances such as PBDEs). The median share of PBDEs in the total Br content reached 0% in 2022 (56 samples), meaning that **PBDEs were not found above detection/ quantification limits in half of the samples** tested.

Share of total Br attributable to PBDEs

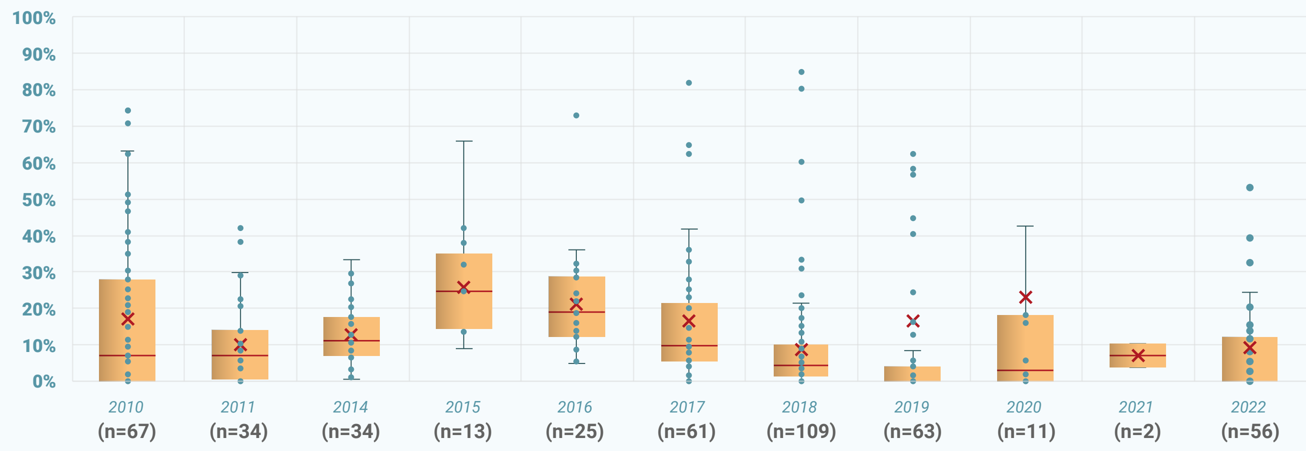


***Figure 6:** Share of total Br attributable to PBDEs. Data for 475 samples from 10 data sources (see references above). The boxes show the range from first to third quartiles, with the median dividing the box. Crosses show the average values. Values below the detection limit were considered null for this representation. "n": number of samples.*

In summary, the analysis carried out above indicates that the **levels of PBDEs in WEEE plastics have decreased significantly over the last ten years**, showing that regulatory restrictions introduced more than 15 years ago are now manifesting themselves in WEEE streams across the board.

High levels of PBDEs may still be found occasionally because some electronic devices that are now considered waste were manufactured before the regulations limiting the use of PBDEs were put in place. These regulations include the Marketing & Use Directive and the RoHS Directive, which came into effect in 2003 for Penta- and OctaBDE and in 2008 for DecaBDE. As a point of reference, electrical and electronic equipment typically remains in use (or in storage) for more than 10 years (on average 12 years for all categories according to data collected in France[27]). It is therefore likely that the **waste generated today includes some items produced before 2008 or even 2005**. In addition, some of the equipment that is now becoming waste was imported from outside the EU, where different rules apply.

To put things into perspective, **just one "old" plastic flake** with a functional PBDE content of around 150,000 ppm (15%) is enough to increase the average PBDE level to 500 ppm in a batch of 300 flakes. This shows the fine sorting that WEEE plastic recyclers must do to prevent individual particles containing high levels of PBDEs from "going the wrong way." This also shows the importance of developing and implementing statistically robust sampling and sample preparation methods, to ensure representativeness (see Section 3.2.2).

BFR Levels in Low-Br Fraction

As part of the current study, data on BFR levels in the "clean" fraction resulting from the separation of BFRs were collected from various sources[28]. As with all waste material sorting processes, BFR separation technologies are not 100% effective, so the "BFR-free" fraction may still contain residual levels of BFRs (see chapter 4.1.2 for more information on the BFR separation technologies). In addition, there is evidence that some plastics in WEEE contain BFRs well below the functional level (typically around 10,000 ppm), which could be due to cross-contamination from poor recycling practices that do not separate out BFRs. Where manual sorting of plastics is common, such as in lower-income countries, such cross-contamination is widespread[29].

The gathered data is displayed in Figure 7 for plastics from screens and in Figure 8 for plastics from small equipment. Measured Br and PBDE levels for each sample are shown, as well as the type of polymer and year of sampling.

The following observations can be made:

- **In plastics from screens, residual BFR levels seem to have decreased between 2014-2016 and 2020-2023**, both in terms of total Br content as well as PBDE levels. **In plastics from small equipment, such a decrease is not evident**. This can be linked to the observation made previously that BFR levels in unsorted plastics seem to have declined in screens and remained relatively stable in small equipment.
- **Total Br levels** reached **up to 1,880 ppm** in "low-Br" plastics from **screens** and **up to 2,433 ppm** in "low-Br" plastics from **small equipment** in recent samples (since 2017).
- **PBDE levels** reached **up to 486 ppm** in "low-Br" plastics from **screens** and **up to 553 ppm** in "low-Br" plastics from **small equipment** in recent samples (since 2017).
- In many samples, PBDEs were not found above the **detection/quantification limit** reported by the laboratories. In some cases, this limit was **as high as 400 ppm**.

Given the **current discussions regarding the UTC level** for PBDEs in recycled WEEE plastics, the available data has several implications:

- A UTC level of **500 ppm** PBDEs seems to be at the limit of the level of purity currently achievable for recycled plastics from small equipment and screens.
- A potential UTC level of **350 ppm** PBDEs may already pose challenges including:
  - It lies below the quantification limit reported for some samples (which depends on the laboratory performing the analysis as well as the heterogeneity of the analysed sample);
  - It is exceeded in several recent samples from both screen and small appliance plastics.
- A potential UTC level of **200 ppm** PBDEs doesn't seem attainable given reported quantification limits as well as measured levels in plastics from both screens and small appliances.

It is possible that the "attainable degree of purity" could decrease in the future due to the natural decline in PBDE levels and advancements in separation techniques. However, the available data prevents strong claims about when this might occur. If anything, the existing data indicates that residual PBDE levels in "low-Br" plastics from screens and small appliances have remained relatively stable, or rather, "stable in their variability." Furthermore, technical limitations in sampling and analysis methods mean that measuring PBDEs in WEEE plastics at such low levels is particularly uncertain (see Section 3.2.2).

2.3 Fate of WEEE Plastics in Europe

As part of the previous study, a mass flow model was built to estimate the whereabouts of WEEE plastics generated in Europe, using available data on WEEE flows, composition data on WEEE plastics as well as data on WEEE plastics recycling processes.

In the current study, this model for Europe is updated based on the latest available information and data (Chapter 2.2.1.1). A mapping of European WEEE plastic recyclers was also developed (Chapter 2.2.1.2). Furthermore, a closer look at the situation in Japan is given in Chapter 2.2.2.

2.3.1 WEEE Plastic Flows in 2021

The updated figures on the quantities and fate of WEEE plastics in Europe provide valuable insights into the current situation. The data used to compile these figures was obtained from various sources, including the 2022 UNITAR study on WEEE collection rates[30], estimates from Plastics Recyclers Europe regarding

PBDE levels in low-Br fraction from screens, per polymer type

(in orange: limit of dtection or quantification)

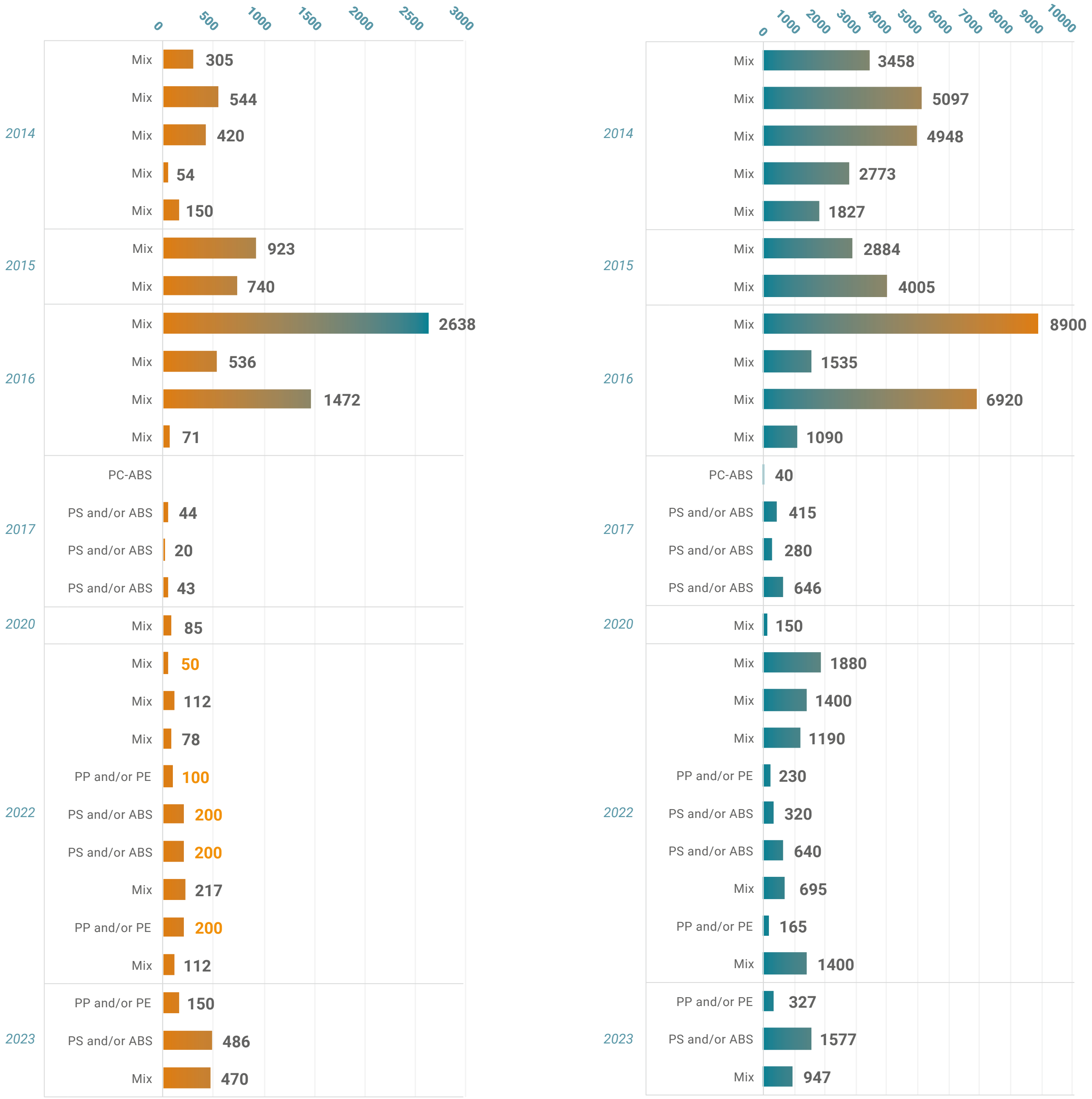


Figure 7: Bromine levels in the low-Br fraction after the BFR separation process of plastics from screens.

the quantity of WEEE plastics received by European recyclers[31], as well as data and estimates generated as part of the previous study (e.g., on outputs of WEEE plastic recyclers, fate of WEEE is residual waste). Results are illustrated in Figure 9.

According to these findings, Europe[32] generates a significant amount of WEEE plastics, approximately **2.6 million tonnes** annually. However, it is observed that only **54%** of these plastics, amounting to 1.4 million tonnes, are directed towards **official WEEE collection streams**.

PBDE levels in low-Br fraction from small equipment(incl. ICT) , per polymer type

(in orange: limit of dtection or quantification)

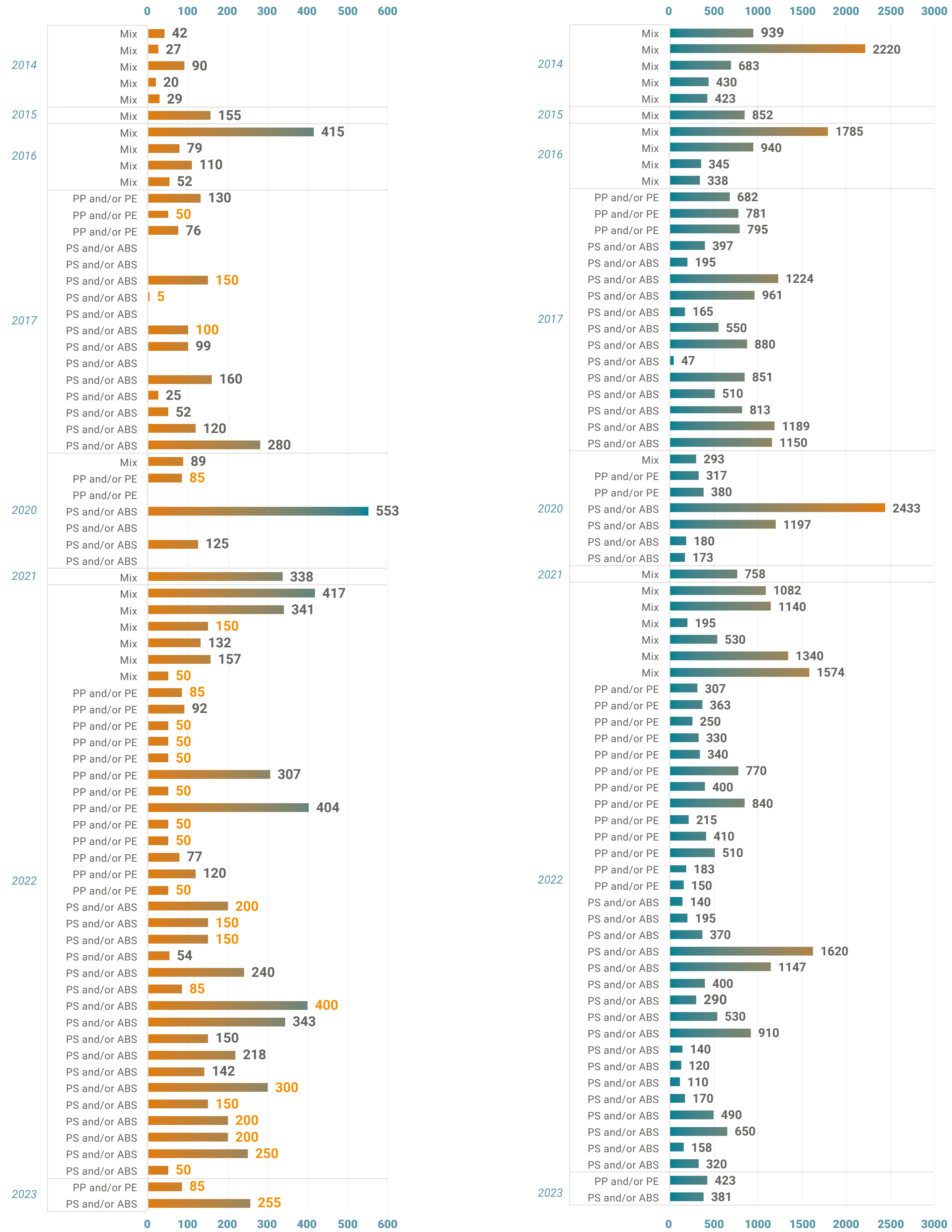


Figure 8: Bromine levels in the low-Br fraction after the BFR separation process of plastics from small equipment.

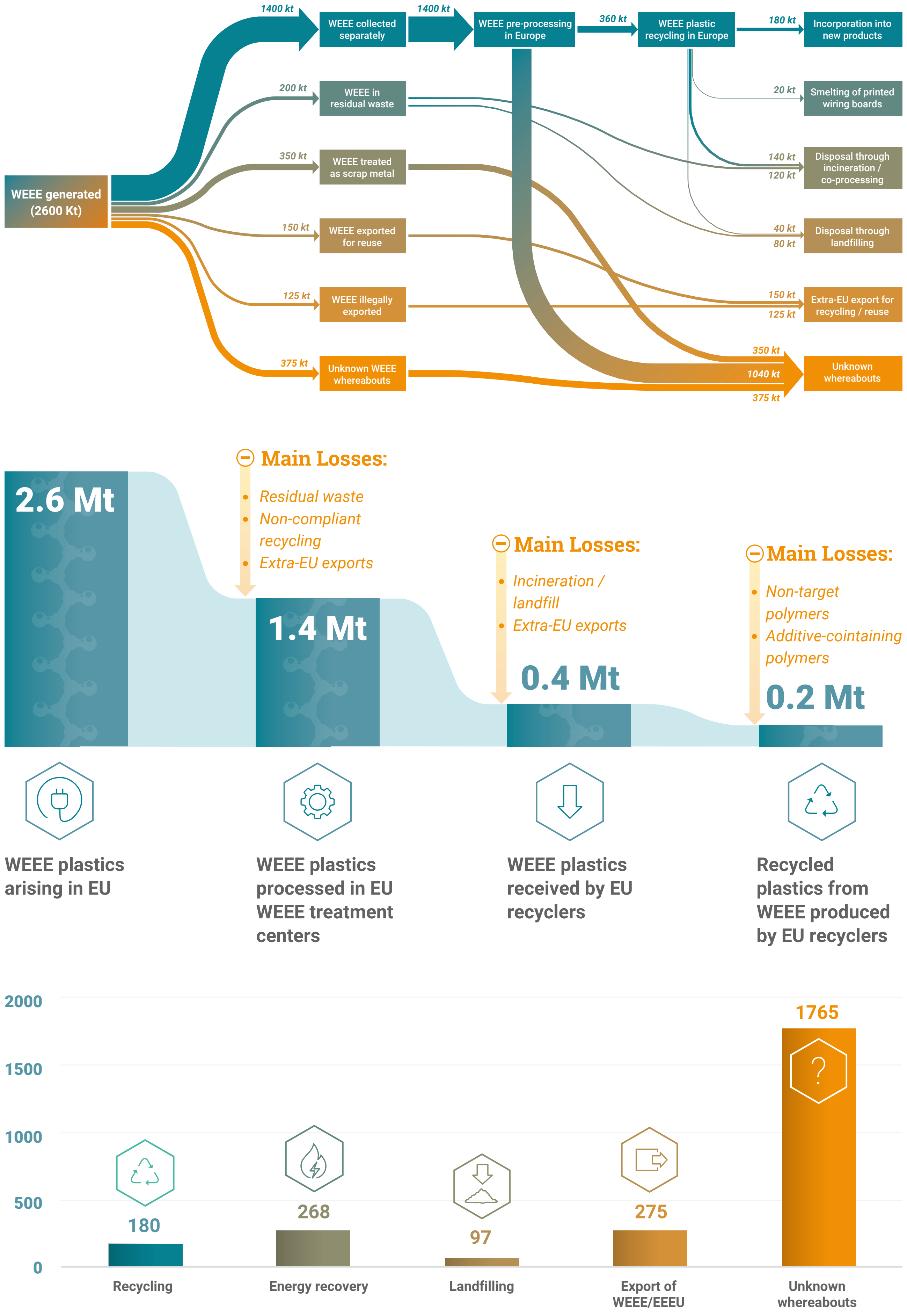


Figure 9: Estimated fate of WEEE plastics in Europe.

Within these streams, WEEE undergoes separation processes to extract different fractions, including plastics. Ideally, these plastics should be sent to WEEE plastic recycling companies. However, the available information suggests that **only 0.4 million tonnes** actually reach such companies in Europe. The **remaining 1 million tonnes** of WEEE plastics are either disposed of through **incineration or landfilling, or exported outside of Europe** for recycling. Landfilling of high calorific waste, such as plastic waste, is banned in most EU Member States however not in all. According to figures from Plastics Europe, 23% of all post-consumer plastics waste generated in Europe in 2020 was landfilled[33].

It is also worth noting that **46% of all WEEE plastics manage to evade official WEEE collection**. Among this fraction, 13% is channelled into complementary recycling routes where WEEE is treated as scrap metal, and the fate of the plastics is uncertain. Additionally, **8%** of the WEEE plastics are estimated to be disposed of with **mixed residual waste**, leading to their incineration or deposition in landfills. Furthermore, **6%** of the WEEE plastics are believed to be found in **exported EEE beyond Europe for reuse abroad**. **Illegal WEEE exports** account for **5%** of the escaping plastics, while the remaining **14%** are present in **WEEE with an unknown fate**.

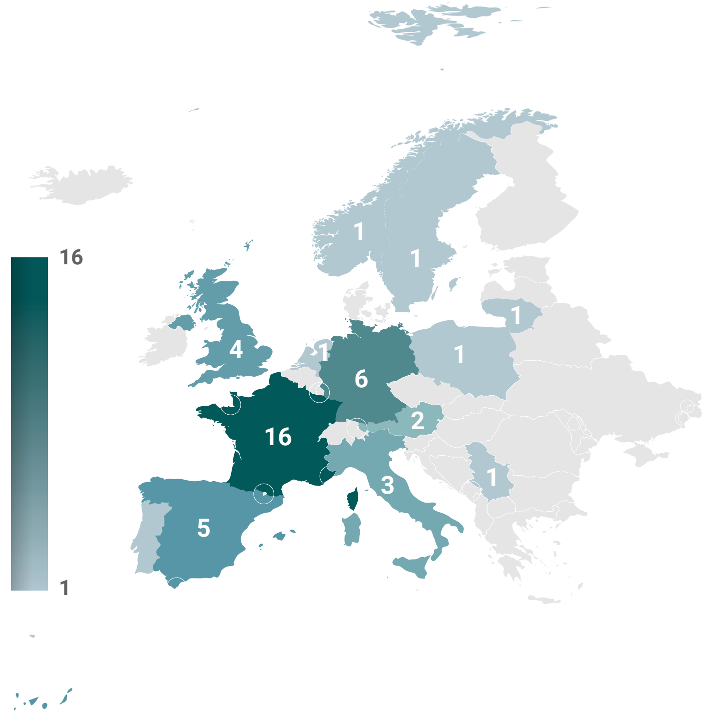
When considering the **final destinations of all WEEE plastics** arising in Europe, it is concerning to observe that over **two-thirds**, amounting to 1.8 million tonnes (68%), **have an unknown fate**. This includes WEEE plastics escaping formal WEEE collection, as well as leakages in official WEEE treatment channels. This raises concerns about potential unsafe recycling practices, burning, or dumping. Furthermore, 11% (0.3 million tonnes) of the WEEE plastics are presumed to be found in exports of WEEE and/or used EEE. An additional 10% (0.3 million tonnes) are estimated to be incinerated within Europe, while 4% (0.1 million tonnes) are estimated to be landfilled within Europe. **Only 7% (0.2 million tonnes) of all WEEE plastics generated in Europe are actually recycled within Europe**, contributing to the production of new products through the utilisation of secondary raw materials.

These results emphasise the importance of implementing more effective management and recycling practices for WEEE plastics in Europe. It is crucial to **improve collection rates, prevent illegal exports**, and **ensure proper recycling processes** to maximise the utilisation of these valuable resources while minimising their environmental impact.

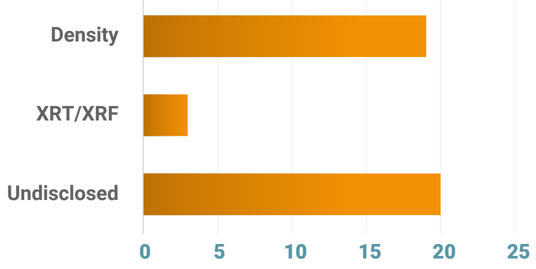
2.3.2 Mapping of WEEE Plastics Sorting/Recycling Companies in Europe

As part of the current study, a **mapping exercise** was conducted to identify **WEEE plastic sorting and recycling companies existing in Europe**. Information on treatment capacities, BFR sorting technologies, and target polymers was collected from publicly available sources as well as information provided by industry experts. The result of this exercise is illustrated in Figure 10. Our research suggests that **Europe hosts more than 40 companies specialising in WEEE plastics sorting and/or recycling**. Their **combined capacity** may reach as much as **800'000 tonnes per year** (relative to the input of WEEE plastics),

Number of European WEEE plastic recyclers



BFR sorting technology applied by European WEEE plastic recyclers



WEEE plastics recycling capacity of European WEEE plastic recyclers (t/y)

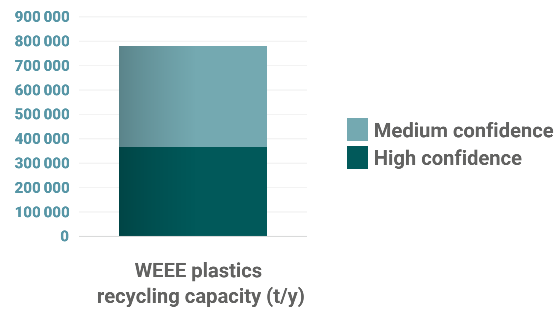


Figure 10: Mapping of European WEEE plastics recyclers

however, this figure is **uncertain** due to the lack of information on the installed capacities and/or actual production of many companies. Furthermore, it may include some double counting as different companies may be involved in different steps of the supply chain, e.g. some companies may only carry out pre-sorting, others only final sorting and compounding.

The above figure can be compared to the estimated **360'000 tonnes of WEEE plastics received by WEEE plastics recyclers**, based on data gathered by Plastics Recyclers Europe (PRE)[34]. This estimate is based on the estimated outputs of the recycling process and was made to avoid the risk of double counting mentioned above. The same PRE market study estimated installed capacity at 442,000 tonnes, giving a capacity utilisation rate of around 80%.

2.4 Fate of WEEE Plastics in Japan

2.4.1 WEEE Management in Japan

The WEEE management system in Japan operates under two main Acts: the **Act on Recycling of Specified Kinds of Home Appliances** and the **Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment**. Japan was an early adopter of an **EPR-based system for e-waste management**, which relies on a robust legal framework, an advanced collection system, and a well-developed processing infrastructure.

The **Home Appliance Recycling Law**, implemented in April 2001, mandates the recycling of four types of waste home appliances: air conditioners, televisions (cathode-ray tube and liquid crystal/plasma), electric refrigerators/freezers, and electric washing machines/clothes dryers. This law introduced **new responsibilities** for stakeholders, **requiring manufacturers to recycle these items and consumers to bear the associated costs**.

To **extend the coverage** of the home appliance recycling law to other electronics, the **Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment** was implemented in 2013. Unlike the previous law, this legislation covers a wide range of electric/electronic appliances, excluding the four items mentioned earlier. The decision to participate in the program and the items to be collected are determined by each municipality. Consequently, this new law is often described as a program to **encourage voluntary participation**, in contrast to the Home Appliance Recycling Law that imposes obligations on involved parties. Under the Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment, manufacturers are only responsible for making efforts to reduce the cost of recycling small home appliances by improving product designs and utilising recycled materials. They have **no obligation to physically or financially recycle their products**.

The **Association for Electric Home Appliances** has developed the **home appliance recycling ticket system**, which serves as the foundation for e-waste recycling and treatment. This ticketing system ensures smoother home appliance recycling activities under the Home Appliance Recycling Law. It operates in two types: consumers either pay recycling and transportation fees to the retailer or pay recycling fees through postal transfer. Consumers are responsible for the cost of transportation and recycling fees, typically ranging from 2,500 to 5,000 yen (about 17-34 euros). Manufacturers, on the other hand, are responsible for establishing their own recycling facilities. Japan currently has **approximately 50 WEEE recycling facilities**, divided into two groups of producers: **Group A** (including Panasonic, Toshiba, JVC, and Daikin) and **Group B** (including Hitachi, Mitsubishi, Sony, Sharp, and Fujitsu). These two groups were formed to promote competition, and each group implements its own collection and recycling infrastructure. Generally speaking, Group A developed a recycling system utilizing existing waste management infrastructure, while Group B created a system with new facilities and logistics partnerships. Both groups collect a similar volume of equipment.

According to the latest figures published in 2022 under the Law for Recycling of Specified Home Appliances in Japan, designated collection points nationwide gathered a total of 15 million units of the four types of waste home appliances. These appliances included 0.8 million CRT screens weighing 19 kilotonnes, 2.1 million FPD screens weighing 53 kilotonnes, 3.5 million refrigerators/freezers weighing 219 kilotonnes, 4.3 million washing machines/dryers weighing 174 kilotonnes, and 3.5 million AC units weighing 144 kilotonnes. **In total, the weight of collected appliances reached 610 kilotonnes.**

According to the Global E-waste Monitor[35], **Japan generated 2,569 kt** of e-waste in 2019, equivalent to 20.4 kg per capita. This is slightly higher than the European average of 16.2 kg per capita and **comparable to Western Europe's 20.3**

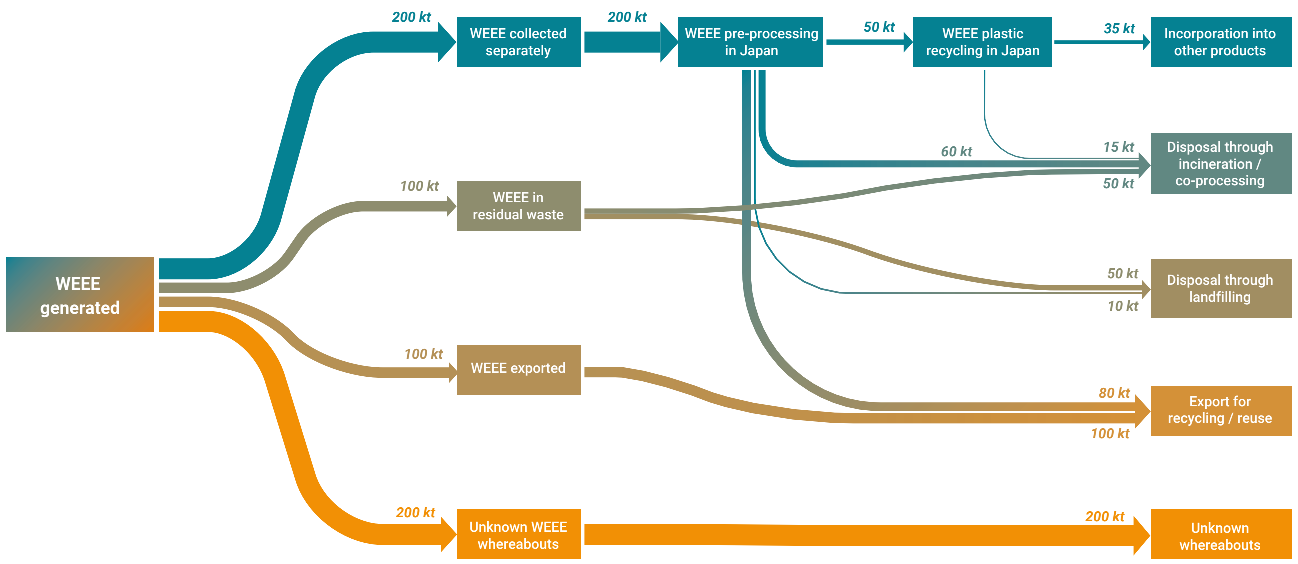


Figure 11: *Estimated fate of WEEE plastics in Japan*

kg per capita. However, as mentioned above, in 2021 Japan's official collection channels managed to collect only 610 kt of e-waste, equivalent to 4.8 kg per capita. In comparison, WEEE collection in Western Europe was reported to be around 11 kg per capita in 2022[36]. Based on these figures, **Japan's WEEE collection rate is calculated to be 24%, compared to 54% in Europe**.

Despite having a similar e-waste generation rate to Western Europe, Japan's per-capita collection rate is significantly lower. The WEEE management system in Japan still faces **challenges** such as the presence of **unlicensed collectors and illegal e-waste exports**, which pose potential risks to the environment and human health. Furthermore, the **current legal obligations** to collect and recycle WEEE only apply to four types of appliances: air conditioners, televisions (cathode-ray tube and liquid crystal/plasma), electric refrigerators/freezers, and electric washing machines/clothes dryers. For other types of WEEE, the law promotes recycling rather than requiring it. As the current WEEE collection system focuses on four large household WEEE categories, **small WEEE suffers from low collection rates, and often ends up in residual waste**.

2.4.2 WEEE Plastics Management in Japan

Little information is available on the fate of WEEE plastics in Japan. As part of the current study, the available information was used to generate the figure below for **WEEE plastics flows in Japan**. The estimated total WEEE plastic generation of 600 kt is based on an assumed 25% plastic content in the 2,569 kt WEEE generation from the Global E-waste Monitor. As for the estimates on the fate of the generated WEEE plastics, estimates are based on a study by Oguchi et al.[37].

According to these estimates, **less than 10% of all WEEE plastics generated in Japan are recycled in Japan**. A large proportion (about **30%**) of all WEEE plastics are **exported**, either as part of WEEE exported for recycling/reuse or as mixed WEEE plastics for recycling abroad. About **20%** of all WEEE plastics are **incinerated** in Japan and about **10%** are **landfilled** in Japan. The fate of the remaining **30%** is **unknown**.

There are **two main WEEE plastic recycling companies** in Japan:

- **Green Cycle Systems** (GCS), part of Mitsubishi Electric Corporation, has been in operation since 1999. GCS receives plastics mainly from air conditioners, refrigerators and washing machines, as well as plastics from office and ICT equipment. They report an annual input of 15 kt of mixed WEEE plastics and an output of 12 kt of recycled granules[38], representing a **recycling yield of around 80%**, which is significantly higher than that achieved by European WEEE plastics recyclers (around 50%). This high yield is probably due to the fact that they mainly receive high-quality, often manually pre-sorted, plastics from large household appliances, which contain a relatively high proportion of recyclable low- and medium- density plastics (PP, ABS and PS with low additive content). Their process can be summarised as follows:

  1. Density separation to produce low-, medium- and high-density fractions;

  2. Electrostatic separation to separate between ABS and PS in the medium density fraction;

  3. XRF separation to remove plastics containing BFRs from ABS and PS, and glass fibre from PP.

- **Planic**, a joint venture between Toyota Tsusho, Veolia Japan and Kojima Sangyo, whose facility opened in 2022, becoming Japan's largest WEEE plastics recycling company with an annual treatment capacity of 40 kt[39]. They receive plastics from various sources, including WEEE and end-of-life vehicles (ELV). Their process can be summarised as follows:

  1. Density separation @ 1.09 (using patented pH-neutral agent) to sort out the heavy fraction;

  2. Density separation @ 1.00 between PE/PP and PS/ABS;

  3. Electrostatic separation between PS and ABS;

  4. Proprietary technology to separate PE from PP.

There are also **many smaller companies** that shred WEEE plastics, sometimes followed by a simple density sorting process. These companies **usually export shredded WEEE plastics** (sorted or not) for recycling abroad. Until 2019, China was the main destination for such mixed WEEE plastics, but since China's decision to ban such imports, shipments have been redirected to other Asian countries.

There is **no specific law in Japan governing the management of plastics containing BFRs**. When handled by WEEE plastics recycling facilities in Japan, this fraction is generally separated by density-based sorting processes and sent for energy recovery. **The fate of exported WEEE plastics containing BFRs is largely unknown**. If treated by density-based mechanical sorting, these plastics are most likely to be separated and disposed of (although this may be by open landfill or open burning). If treated by manual sorting processes, which are common in low-income countries, plastics containing BFRs are likely to end up in products in an uncontrolled way.

3 Regulatory Framework

3.1 Introduction

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).

Regulations relating to chemicals and products 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 has been reached**. 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[40]. More recently, the Commission and its Joint Research Center have commenced the work on the development of end-of-waste criteria for plastic waste, with finalization of technical assessment expected by Q1 2024.

Given the uncertainty of the application of product and chemical regulation, this study focused on requirements from **waste regulations** and **waste shipment 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. Wastes can be classified as 'green' listed (not hazardous not notifiable), 'amber' (not hazardous and notifiable) and 'red' (hazardous and notifiable);
- **WEEE Directive** that sets rules for the collection, treatment and recovery of waste electrical and electronic equipment;
- **WEEE treatment standards** that outline 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.

3.2 POP Regulation

3.2.1 POPs in Wastes

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 are restricted at the international level by the Stockholm Convention on Persistent Organic Pollutants. Currently, 28 compounds or groups of compounds are listed as POPs under the J either in its Annex I part A (Elimination), B (Restriction) or C (Unintentional production). Annex I part A includes 5 BFR compounds, referred to as **POP-BFRs**:

- Hexabromobiphenyl (hexaBB), listed in 2009;
- Commercial pentabromodiphenyl (PBDE) 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 transposed 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 content limit" (**LPCL**), Annex IV). Currently, a LPCL of **50 ppm** is set for hexaBB, while the LPCL for HBCD and PBDEs, have recently been reviewed by the European Commission with Regulation 2022/2400 which amends Annexes IV and V of the POP Regulation. Specifically, from June 10th, 2023, for HBCD the limit value is lowered from 1,000 ppm to **500 ppm**, with the possibility for the Commission to adopt a legislative proposal to further lower this value to 200 ppm no later than December 2027. For PBDEs (sum of c-pentaBDE, c-octaBDE and c-decaBDE), the threshold from June 10th is reduced from 1,000 ppm to **500 ppm** until December 2025, to **350 ppm** by 2027 and to **200 ppm** from December 2027. The Regulation specifies that in the instances where the limit values for PBDEs to place this substance on the market as per Annex I are higher than the limit values of 350 ppm and 200 ppm, those should be considered as the LPCL.

Waste whose concentration exceeds the limits must be destroyed of or recovered in 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 are prohibited. The following disposal and recovery operations for waste that exceeds the lower limit value are permitted (Annex V):

- Physico-chemical treatment (D9), e.g. solvent-based purification processes;
- Incineration without energy recovery (D10), e.g. hazardous waste incinerators;
- Incineration, using the waste to generate energy (R1), e.g. municipal solid waste Incinerators, co-processing in cement kilns;
- Recycling and reclamation of metals

(R4), e.g. smelters handling PWB with precious metal recovery.

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

3.2.2 Implications of Lower LPCL Values: Addressing Enforcement and Analytical Methods

The latest LPCL for HBCD and PBDEs introduced by amendments to Annex IV has several implications. First, as highlighted by industry associations and interviews with stakeholders, **accurate measurement of bromine concentration is complex** using current laboratory technologies due to the **lack of verified methods and standards** at concentrations below 1,000 ppm. This has led to large variations in results of measured recycled WEEE plastics, with sample preparation (size, storage) and pre-treatment (type of comminution and time) before analysis already having a significant impact on the measurements[41]. Second, as reported by Grob (1993)[42], the commonly used gas chromatography with mass spectroscopy (GC/MS) analysis of heavy components is sensitive to discrimination by contamination of the injector and start of the GC column, resulting in lower measured concentrations than present in the sample. Thirdly, **measurement accuracy does not currently allow plastics recyclers to obtain accurate results** when substances to be analysed are found in the range of 100 to 1000 ppm. Work carried out as part of the CREAToR and PRIUMUS projects indicates that in the case of HBCD in mixed WEEE plastics, the measurement accuracy does not allow for plastics recyclers to obtain results with high confidence that the HDCB concentration would be below 500 ppm in the recycled output[43]. Furthermore, for the 200 ppm limit value, it was calculated that 1,000 kg of the low-Br fraction should be sampled to be statistically relevant (assuming an average particle mass of 10 grams in the sample). In practice, this 1,000 kg sample should then be finely shredded and sub-sampled before being sent to a laboratory, which is rarely done due to the limited capacity of WEEE plastics recyclers[44].

Similarly, **the standardised methods for measuring the sum of PBDEs in WEEE** (IEC EN 62321-3-1) **are validated for concentrations at and above 1,000 mg/kg**. This method, based on X-Ray Fluorescence (XRF) has already proven its efficacy and logistical feasibility in the working environment. As no validated methods are available for the assessment of concentrations in the levels of 50 mg/kg and 500 mg/kg, considering also sampling uncertainties, conformity with specified concentration limits cannot be guaranteed by operators and would not be enforceable.

Overall, while recyclers interviewed suggested that lower LPCL for PBDEs such as 200 ppm might not necessarily pose a problem today, **the lack of validated and standardised analytical methods and the inaccuracy of results make sampling and analysis of these thresholds difficult**. In fact, it may be that the available analytical results are inaccurate and under- or over-estimate the real concentrations, due to the sampling and analytical uncertainties discussed above.

Lower LPCL limits, coupled with the lack of standardisation and precise sampling and testing results, may **hinder the availability of compliant secondary plastic materials in the EU**, the achievement of recycling/recovery targets, and lead recyclers to adopt a precautionary approach by diverting materials to incineration or landfill, both of which are very limited in capacity today, with some Member States having no capacity at all. In addition, by lowering the LPCL limits, more sorting residues will be considered as hazardous waste, a practice already common in many Member States which assimilate POP wastes to hazardous wastes. Should this happen, huge amounts of plastic residues will have to be diverted from incineration or landfill towards hazardous waste incineration, for which there is no capacity at all. The feasibility and validity of an automatic classification as hazardous waste for all waste exceeding LPCL is currently being investigated by the Commission, set to launch a call for tender on this. Lastly, any reduction below 1,000 mg/kg would lead to more complex requirements for treatment and increase the risk of **diverting significant volumes of WEEE wastes to undocumented channels** as many countries do not possess advanced techniques for the identification of POPs in wastes.

3.2.3 POPs in Products

Different limit values apply to POPs in products, corresponding to the "unintentional trace contaminant" threshold (**UTC**) set by Annex I of the Regulation.

- For HBCD, the current UTC level is 100 ppm. After discussion of potential lowering of the limit, the Commission confirmed during the 28th POPCA meeting on June 14th, the intention to maintain the UTC limit at 100 mg/kg for buildings and construction. This means that wastes containing up to 500 ppm / LPCL) HBCD may be sent for recycling, however products from recycling should contain less than 100 ppm of HBCD.
- For (the sum of) PBDEs, the current UTC level is 500 ppm. This threshold is currently under review by the European Commission, with a proposal for the PBDE group of substances to lower it to 350 mg/kg initially, and to 200 mg/kg after 2 years of the revision's entry into force. If this lower limit was to be confirmed, wastes containing up to 500 ppm (LPCL) PBDEs could be sent for recycling, however products from recycling should contain less than 350 ppm or 200 ppm.

It should be noted that the current limit values of PBDEs as per the **RoHS Directive** (Annex II limit) are currently at **1,000 ppm**. This **inconsistency** in the limit values between the POP regulation and the RoHS Directive implies that **European plastic recyclers must comply with a 500 ppm UTC level, or even a 200 ppm one**, if the lower limit was to be confirmed, while **goods containing up to 1,000 ppm PBDEs as per RoHS are still sometimes imported into the EU**. In fact, while imported products also have to comply with the POP legislation, in practice due to a lack of enforcement and knowledge of EU regulations, these products have sometimes contents above UTC levels. The Impact Assessment study issued by the Commission laying down the assessment of impacts associated with potential options for the revision of the RoHS Directive highlights the need "to align the RoHS Annex II limit values with regards to substance restrictions for PBDEs to those of the POPs Regulation in order to ensure consistency in the EU Regulatory Framework"[45]. Moreover, the study advocates against lowering the RoHS limit value to 500 ppm due to the lack of environmental and social impacts and because it would lead to an amendment of the Directive, causing negative impacts to the EEE industry and Member States.

Lowering the UTC thresholds in Annex I would present **several risks** for the plastic recycling industry as highlighted by industry associations. First, changing legal thresholds creates **uncertainty**, which could **discourage investments** in increased recycling capacity and render recycling in Europe uncompetitive. Second, with UTC levels lower than LPCL, large quantities of plastics will have to be incinerated or sent for disposal instead of recycling or will enter undocumented channels such as illegal exports. Reduced UTC levels may therefore further reduce the quantities of WEEE plastics treated by specialised WEEE plastics recyclers, and lead to additional environmental burdens due to inadequate management of these problematic waste streams.

Even at today's state-of-the-art installations, lowering the threshold limit for POPs - both as Low POP Content and Unintentional Trace Contaminants - will increase the percentage of plastics incinerated /landfilled. Even if increased separate collection and compliant treatment of WEEE helps towards environmental and human protection, European thresholds – whatever the limits - will have little impact on the global environment, unless the export of waste plastics to non-compliant overseas facilities that do not have the capacity or capability to work to the same environmentally sound standards are halted.

As such, industry associations urge for an alignment between Annex I and Annex IV values at pragmatic levels, to ensure that the recycling industry in Europe could develop further capacity and continue innovating while upholding the principles of the circular economy and ensuring that secondary plastics are recycled and reused in new products.

3.3 Waste Classification

Waste classification is internationally regulated by several different frameworks. Specifically, waste needs to be classified based on the Basel Convention Annex VIII or IX if applicable as well as by Y and H-codes under Annex I and Annex III, by the OECD list, the European list of waste, the UN class, UN number, UN shipping name and customs codes. In addition, many countries have their own national waste codes in the country of export and import.

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). Commis¬sion Regulation (EU) No 1357/2014 defines limit values for different hazardous properties. In the context of waste classification, Article 7 WFD set out further provisions for the assessment of hazardous properties and waste classification in the so-called List of Waste (LoW). The LoW was established by Commission Decision 2000/532/EC, which requires that each waste is to be classified by a six-digit number. In the context of POPs, waste containing certain POPs as indicated in the Annex to the LoW (point 2, indent 3)[46], above relevant thresholds of POPs Regulation, **are considered hazardous** without further consideration. Hexabromobiphenyl, a type of POP BFR, is included in the LoW and therefore is considered hazardous waste if its concentration exceeds the LPCL of 50 ppm. It's important to note that the presence of POPs listed in the Annexes of the POP Regulation other than those specifically mentioned in the Annex to the LoW (point 2, indent 3), even in concentrations exceeding the limit values established in Annex IV to the POP Regulation, **does not automatically lead to a classification of waste as hazardous**. Classification would depend on the hazard classification of the substance and must be assessed by applying the general rules of Annex III to the WFD applicable to HP1 to HP15[47].

National legislations prescribe how the classification of waste as hazardous or non-hazardous affects requirements regarding accepted treatment methods, required authorisations for treatment facilities 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, while 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 not[27]. For instance, Br-rich fractions resulting from Sink/Float or XRT sorting (see 4.1.2) are classified as hazardous waste if they originate from CRT screens, but as non-hazardous if they originate from FPD screens. Other countries like Ireland, adopt a precautionary approach and always classify plastics containing BFRs as hazardous.

It should be noted that, according to the Waste Shipment Correspondents' Guidance No 12 from November 2021[48], Member States have agreed that "plastic waste containing POPs, such as POP-BDEs, in quantities meeting or exceeding the concentration limits indicated in Annex IV of the POP Regulation (i.e. LPCL) should be classified under the Basel Convention as entry Y48 for exports from the EU and imports into the EU, or under entry EU48 for shipments within the EU. However, such waste is to be classified as hazardous if the waste exhibits a hazard characteristic listed in Annex III to the Basel Convention or Annex III to Directive 2008/98/EC". Both Y48 and EU48 codes refer to "non-hazardous mixed plastic waste", and require the prior notification and consent procedure.

Under the Basel Convention, the current **Swiss-Ghana proposal** to re-classify e-waste could drastically change how plastic containing BFRs would be classified, mandating that plastic components containing a brominated flame retardant should be classified as hazardous (see 3.4.1). Most WEEE plastic recycling facilities have no license to receive and treat hazardous waste so the classification of WEEE plastic fractions as hazardous could lead to facility shutdowns and further reductions in volumes recycled in Europe.

Waste classification as hazardous or non-hazardous has a direct consequence on, among others, transboundary shipment procedures.

3.4 Transboundary Shipments

According to the Global Transboundary E-waste Flows Monitor 2022[49] of the total amount of global e-waste 53.6 Mt, 5.1 Mt crossed country borders in 2019, of which 35% was shipped in a controlled manner and 65% in an uncontrolled manner. With e-waste generation expected to increase by an average of 2 Mt annually to 74.7 Mt in 2030, transboundary movement of this waste, including illegal import

and export, is also expected to increase. Several legislations have been put in place to control the transboundary movements of hazardous and other wastes, including e-waste and ensure their environmentally sound management. Specifically, this chapter will look at rules set by the Basel Convention, the OECD Waste Shipment Framework, and the EU Waste Shipment Regulation.

3.4.1 Basel Convention

The Basel Convention on the Control of Transboundary Movements of Hazardous Waste and their disposal (hereafter the **Basel Convention**), adopted in 1989 and entered into force in 1992, is the main international regulatory instrument for controlling the transboundary movements of waste characterised as hazardous under the Convention. This multilateral treaty, ratified by 190 countries/parties, is focused on preventing environmentally and socially detrimental hazardous waste-trading patterns, including those relating to e-waste, which, due to its constitution, often contains hazardous elements. To achieve this goal, the Convention strictly controls transboundary movements of covered wastes and requires obligations on minimising waste generation and ensuring their environmentally sound management.

In the Basel Convention, hazardous wastes are defined by Article 1[50], in terms of the substances in the waste materials exhibiting a hazardous characteristic (e.g., toxic, or eco-toxic) listed in Annex III, and if they belong to any category contained in Annex I. To facilitate the application of the Convention, **wastes listed in Annex VIII are characterized as hazardous** under Article 1 and **wastes listed in Annex IX are not covered by Article 1**. However, in no circumstances do Annexes VIII and IX affect the application of Article 1, par. 1 (a).

In the case of e-waste, more criteria for better distinguishing between hazardous waste and non-hazardous waste are available in the "Technical guidelines on transboundary movements of e-waste and used-EEE", with the main distinction between entry **A1180 and B1110**.

Wastes considered hazardous and "other wastes" requiring special consideration as per Annex II under the Convention are subject to the **Prior Informed Consent (PIC) procedure**, requiring the exporter of hazardous or other wastes to notify the authorities of the prospective States of import and transit with detailed information on the intended movement and obtaining written permission from the importing country before any shipment takes place. Wastes listed in Annex IX are presumed to not be hazardous and, as such, not subject to the PIC procedure.

The text of the Basel Convention was modified by the so-called **Basel Ban Amendment**, an agreement by Parties to prohibit the member states of the OECD, the EU, and Liechtenstein from exporting hazardous wastes - as defined by the Convention – to other countries, primarily developing countries[51]. The ban amendment entered into force on December 5th, 2019, and rules that Annex VII country (OECD, EU, Liechtenstein) regardless of whether they have ratified the Ban Amendment or not, cannot export hazardous wastes to a non-Annex VII Party that has ratified the Ban Amendment as their ratification automatically reflects their national import prohibition. Likewise, a developing country (non-Annex VII Basel Party), regardless of whether they have ratified the Ban Amendment, will not be able to accept hazardous wastes from an Annex VII Party that has ratified the Ban Amendment because that Party is prohibited from exporting hazardous waste to a non-Annex VII country under the Ban Amendment. However, if neither importing Parties nor exporting Parties in a transboundary movement have ratified the Ban Amendment, then the Amendment will not apply. To note that the Ban Amendment is already implemented in the EU under the Waste Shipment Regulation (see 3.4.3).

During the fourteenth and fifteenth meetings of the Conferences of the Parties to the Basel Convention (COP 2017 and 2022), two major proposals were discussed: the Norwegian proposal and the Swiss Ghana proposal respectively. The first, resulted in 2019 in adopted **amendments** to Annexes II, VIII and IX to enhance the control of the transboundary **movements of plastic waste and clarify the scope of the convention as it applies to such waste**. The amendments became effective as of January 1, 2021, with key changes including:

- An amendment to Annex II and VIII, which clarifies the scope of plastic wastes presumed to be hazardous and therefore subject to PIC procedures. This includes **plastic waste containing brominated flame retardants that exhibit hazardous characteristics** and fall under the new entry A3210 of Annex VIII.
- A strengthened control system, whereby Parties must ensure that all plastic waste is included in the list of controlled wastes and must provide specific information on the types and quantities of plastic waste that are subject to control.
- The promotion of plastic waste management, calling for greater cooperation between parties to promote the environmentally sound management of plastic waste and encouraging Parties to take measures to minimise the generation of plastic waste and to promote the use of sustainable alternatives to plastic.

Therefore, in the case of plastic waste containing BFRs, the Basel Convention does not set specific thresholds for considering such waste hazardous. The hazardous properties of plastic waste containing brominated flame retardants are evaluated on a case-by-case basis, considering the characteristics set out in Annex III and II of the Convention. This includes factors such as toxicity, persistence and potential to bioaccumulate, among others.

The second major debate, which is still being discussed, is the Swiss-Ghana proposal to re-classify e-waste. This proposal was discussed in 2022 with the objective to direct all WEEE to environmentally sound management and treatment by state-of-the-art recovery technologies. The following changes were adopted to Annexes II, VIII and IX of the Convention:

- Annex II (waste that requires special consideration: subject to the PIC procedure): addition of new **entry Y49** covering all e-wastes **replacing Basel codes B1110** and B4030, its components and wastes from the processing of e-waste (e.g., fractions from shredding); except for e-waste covered by entry A1181 (in Annex VIII);

- Annex VIII (waste presumed to be hazardous: subject to the PIC procedure): **addition of new entry A1181** covering hazardous e-wastes, its components and wastes from the processing of e-waste (e.g., fractions from shredding) and deletion of existing entry A1180;
- Annex IX (waste presumed not to be hazardous: not subject to the PIC procedure): **deletion** of the existing e-waste **entries B1110** (e-wastes) and B4030 (single-use cameras).

Concerning plastic wastes containing BFRs, the new entry A1181, defines waste electrical and electronic equipment, including scrap as follows:

a) Containing or contaminated with cadmium, lead, mercury, organohalogen compounds or other Annex I constituents to an extent that the waste exhibits an Annex III characteristic, or

b) with a component containing or contaminated with Annex I constituents to an extent that the component exhibits an Annex III characteristic, including but not limited to any of the following components:

- glass from cathode ray tubes included on list A
- a battery included on list A
- a switch, lamp, fluorescent tube or a display device backlight which contains mercury
- a capacitor containing PCBs
- a component containing asbestos
- certain circuit boards
- certain display devices
- **certain plastic components containing a brominated flame retardant**

In summary, with no further changes, the amendments will become effective on 1 January 2025, defining all plastics that may have brominated flame retardant as "hazardous waste", even though of all BFRs, only a small fraction are currently restricted. In other words, all transboundary movements of **e-waste and fractions, both hazardous and non-hazardous, will be subject to the PIC procedures**, and if hazardous it will also have to be diverted from incineration or landfill towards **hazardous waste incineration**, for which recyclers have no permits and capacity currently.

The recycling industry has raised concerns about whether waste containing POPs levels above the Low POP Content Threshold should be classified as hazardous. In fact, there are major differences between various types of POPs. For instance, PBDEs are immobilised additives in the polymer matrix and therefore, WEEE plastics are not considered hazardous, meaning WEEE plastics facilities do not have permits to take in hazardous wastes.

Moreover, as the industry argues, the transboundary movement of hazardous waste is incredibly complicated and expensive, making it increasingly difficult to transfer WEEE plastics to proper recycling facilities within the EU. Lastly, there is a lack of capacity to incinerate plastic containing BFRs in hazardous waste incinerators, with the conventional advanced solid waste incinerators already at capacity limits.

3.4.2 OECD Waste Shipment Framework

Following the Basel Convention, in 19992, the OECD adopted a **Council Decision [OECD/LEGAL/0266] on the Control of Transboundary Movements of Wastes Destined for Recovery Operations** (hereafter the OECD Control System). The Decision aimed to create a workable set of rules, based upon the Basel Convention, with a simplified procedure and more explicit means of control, facilitating trade of recyclables in an environmentally sound and economically efficient manner, also allowing non-Basel signatories to join (such as the USA). Wastes exported outside the OECD area, whether for recovery or final disposal, do not benefit from this simplified control procedure.

A two-tiered system serves to delineate controls to be applied to such transboundary movements of wastes:

- **Green** control procedure: for wastes falling under Appendix 3 of the Decision, presenting a low risk for human health and the environment and, therefore, are not subject to any other controls than those normally applied in commercial transactions. Appendix 3 contains the wastes in Annex IX of the Basel Convention (Part I) and additional wastes that the OECD Member countries agreed to be subject to the Green control procedures (Part II).
- **Amber** control procedure: for wastes presenting a sufficient risk to justify their control, falling under Appendix 4 of the Decision. These correspond to wastes in Annexes II and VIII of the Basel Convention (Part I), as well as additional wastes agreed by OECD Members (Part II) and are subject to **PIC procedures** (notification and written consent) before their transboundary movement.

Normally, amendments made to Annex IX under the Basel Convention are automatically incorporated into Part I of Appendix 3 to the Decision and amendments made to Annexes II and VIII under the Basel Convention are incorporated into Part I of Appendix 4 to the Decision unless an objection is made by Member countries. On August 2022, an **objection was raised** by Japan on the automatic incorporation of the amendments to the Basel Convention about e-waste (the Swiss Ghana proposal) into the OECD Decision. A process is currently underway to work towards an alternative proposal on how to control transboundary movements of e-wastes under the OECD Decision.

3.4.3 EU Waste Shipment Regulation

The Waste Shipment Regulation (WSR), also known as Regulation (EC) No 1013/2006, is an EU law that implements the obligations of the Basel Convention and it further transposes the provisions of the OECD Decision. The WSR transposes the procedural rules of both regulations into directly applicable European legislation, which aims to:

i) ensure that waste shipped between EU Member States is managed in an environmentally sound manner during shipment and transported to a suitable destination for treatment, in accordance with the relevant EU waste legislation, including the principles of proximity and self-sufficiency and giving priority to recovery;

ii) ensure that waste exported outside the EU does not create adverse effects on the environment or public health in the countries of destination, by

prohibiting the export of hazardous waste to non-OECD Decision countries and waste destined for disposal operations outside the EU or the European Free Trade Association (EFTA) area and using specific provisions on the export of other waste;

iii) ensure the implementation in EU law of the provisions of the Basel Convention and the OECD Decision.

Under this regulation, wastes are classified under the following list:

• **Green**-listed wastes: for shipments of non-hazardous wastes, based on Annex IX of the Basel Convention. Shipments of these wastes within the EU and the OECD must comply with the **general information requirement** outlined under Article 18 (e.g., information on quantity, recovery facility, waste identification, contact details of the person arranging the shipment, etc.).

• **Amber**-listed wastes: notifiable waste (as per Annex II and VIII of the Basel Convention), household waste and residues from the incineration of household waste or waste for disposal (for example by landfill). For shipments of these wastes, **prior written notification and consent procedures are required by all countries concerned by the shipment** (i.e., the countries of dispatch, destination and transit). To note that to speed up the procedure, Member States can designate 'pre-consented recovery facilities for which more lenient procedures apply and for which they will normally not raise objections as competent authority of destination.

In the context of the identification of waste for the purpose of correct procedure and documentation, the classification according to green or amber-listed wastes applies. These lists provide for a classification approach different to the one of the LoW (see the chapter on waste classification). However, classification according to WFD and LoW is also relevant in the context of the WSR, for instance as a criterion for whether the waste may be exported for certain non-EU non-OECD countries. Indeed, the classification of waste in accordance with the list of the Basel Convention and OECD codes as well as the entries of the LoW is to be indicated on the notification and movement document used in the framework of the notification procedure.

As regards to **trade restrictions** (Table 6) the WSR contains several provisions prohibiting the following waste shipments: **exports of waste for disposal to third countries**, except to EFTA countries that are parties to the Basel Convention; **exports for recovery of hazardous waste and 'other waste'** under Annex II of the Basel Convention (mixed household waste and from 2021 also certain plastic waste) **to third countries, except those directed to countries covered by the OECD Decision**; imports of waste for disposal or recovery from third countries that are not party to the Basel Convention nor belong to the OECD and have no bilateral agreement with the EU or Member States. The EU therefore **already implemented the provisions of the Basel Ban Amendment**, prohibiting the export of hazardous waste from EU countries to other primarily developing countries (i.e., parties that are not part of the OECD, the EU or Lichtenstein and that have not ratified the Ban Amendment).

	Between EU members states	Import into the EU	Transit through the EU	Export out of the EU
Waste for disposal	Consent required	Consent required	Consent required	Prohibited
"Green wastes" for recovery (Annex III, IIIA and IIIB of WSR) that do not contain any hazardous components	Information requirements	Information requirements	Information requirements	Information requirements or special provisions
All other waste	Consent required	Consent required	Consent required	Prohibited

Table 6: *Simplified overview of permissible transboundary waste shipments under the WSR*

In 2020, this regulation was amended with regulation 2020/2174, which addresses amendments made to the Basel Convention on its fourteenth COP meeting with regards to a new entry for hazardous plastic waste and two new entries for non-hazardous plastic waste (see chapter "Basel Convention"). As a result, from 1 January 2021, the export from the Union and import into the Union of hazardous plastic waste (entry AC300) and non-hazardous mixed plastic waste (entry Y48) to and from third countries to which the OECD Decision applies, is subject to the procedure of prior written notification and consent, while export of these plastic waste to third countries which the OECD Decision does not apply is prohibited.

The WSR is proposed to be **repealed by the (proposed) EU Waste Shipment Draft Regulation**, published by the EU Commission on November 17th, 2021. The revised legislation should protect the environment and human health more effectively by reducing the shipments of problematic wastes outside of the EU, updating the shipment procedures to reflect the objectives of the circular economy and improving enforcement.

To ensure that the export of waste from the EU to third countries is managed sustainably, the following measures **are proposed**:

- For countries that are not members of the OECD, the **export of non-hazardous (green-listed) wastes destined for disposal from the EU would be made conditional on an official request from the country to import non-hazardous waste** from the EU and demonstrate that it can **recover it in a sound manner**. A list of countries authorised to import waste from the EU will be set up.
- The Commission will monitor the levels of waste exports from the EU to OECD countries. If there is a surge in waste exports to one of these countries, risking serious environmental or public health problems in that country, the Commission will seek information on the treatment of this waste in the country concerned. The Commission will suspend the export of this waste if there is no guarantee that this treatment is sustainable.
- EU exporting companies would have to carry out **independent audits** for their waste exports outside the EU.

These audits should demonstrate that the facilities treat this waste in an environmentally sound manner. EU companies would only be authorised to export to these facilities if this is the case.

- To address waste being illegally presented as "used goods", specific binding criteria will be developed to differentiate between waste and used goods for specific commodities of particular concern, such as used vehicles and batteries.

- The export of **plastic wastes to non-OECD countries would be banned** with an objective within 4 years to **phase out the export of plastic wastes also within OECD countries**.

On January 17th, 2023, the EU Parliament **adopted its negotiating position** for the new law and a general approach on the file is expected to be reached under the Swedish presidency at the Environment Council on 20 June 2023.

3.5 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 must 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.

The Commission is currently evaluating the WEEE Directive to assess whether it's still fit for purpose and determine whether a review is needed. To gather evidence from a wide range of stakeholders, a call for evidence was open for feedback until November 3rd, 2022, and an ongoing public consultation with a deadline of 22 September 2023.

3.6 EN 50625 Standards

EN 50625 series of standards developed by CENELEC (European Committee for Electrotechnical Standardisation) in response to the WEEE Directive establish requirements for the collection, transport, and treatment of WEEE in compliance with the Directive.

The EN 50625 series comprises five European Standards (EN) and six Technical Specifications (TS). These standards are **legally binding** for WEEE treatment facilities **in eight European countries**, including Belgium, the Czech Republic, Ireland, France, Lithuania, Luxembourg, the Netherlands and Slovenia. In some countries such as Switzerland, compliance with EN 50625 is part of the contractual obligations of WEEE treatment operators towards producer responsibility organisations (PROs).

Annex A of EN 50625-1 (General treatment requirements) specifies the removal of substances, mixtures, and components listed in Annex VII of the WEEE Directive from WEEE. Regarding **plastics containing BFRs**, the standard sets the following requirements:

- A.6.2: Plastic fractions resulting from the treatment of cooling appliances and large household equipment are deemed free of BFRs and can be recycled.
- A.6.3.1: Plastic fractions from other appliances are considered to contain BFRs unless there is evidence to the contrary provided by an independent body utilising accepted methods.
- A.6.3.2: Plastic fractions containing BFRs must be segregated from those that do not contain BFRs, and appropriate treatment must be applied according to legislation (POP Regulation). If not separated, the fraction is considered a BFR fraction and must be managed accordingly.

Treatment of WEEE plastics containing Brominated Flame Retardants (BFRs)

WEEE plastics

TO CHECK OR NOT TO CHECK THAT IS THE QUESTION

WEEE plastics are deemed to have restricted BFRs if no check is made showing that the WEEE plastics contain >2,000 ppm Bromine [Br].

In that case all WEEE plastics need to be delivered to specialized WEEE plastics recycling plants capable of separating BFR containing plastics.

If WEEE plastics are checked (described in the EN 50625-1 General treatment and depollution standard) and the check shows that the plastics contain less than 2,000 ppm Br, they are free of restricted BFRs.

<2,000 PPM Bromine

>2,000 PPM Bromine or not tested

SPECIALIZED RECYCLING FACILITY FOR WEEE PLASTICS

The plastic mix may contain restricted BFRs in which case the mix must be treated by specialized recyclers that separate the plastics containing BFRs from other plastics.

Only 8% of this fraction contains re- stricted BFRs. After separation 92% of the plastics can undergo further sorting and treatment.

92%

Plastics free of BFRs

8%

Plastics with restricted BFRs

POLYMER SEPARATION

The plastic mix that does not contain restricted BFRs above the threshold values can thus be used in advanced recycling processes. The first step is the separation of the individual polymers.

The processes also have non-recyclable fractions.

NON-RECYCLABLE FRACTIONS

POPs regulation applies

PLASTIC EXTRUSION & COMPOUNDING

The separated polymers from WEEE will then be extruded and if needed compounded. These plastic pellets are checked on conformity with POP legislation. For EEE products this is RoHs and For all other products this is REACH. Product legislation has clearly defined limit values for the presence of any legacy substances such as BFRs.

Plastics recycling saves large amounts of CO_2 emissions and energy compared to virgin plastics.

ELIMINATION OF PLASTICS

WEEE ptastics containing restricted BFRs must be incinerated. Non-recyclable ptastics are also incinerated. Although these substances have not been used in EEE since long, they can stilt be present in WEEE as legacy substances.

Figure 12: Management of WEEE plastics according to EN 50625 standard[55]

Normative requirements for the separation of plastics containing BFRs are further detailed in TS 50625-3-1 for specific categories of WEEE, such as screens and small appliances. It establishes that treatment operators must ensure the segregation of BFRs if the total bromine concentration is known or assumed to be above **2,000 ppm**. Plastic fractions containing BFRs should be treated according to legislation, while fractions below the threshold are considered to comply with the de-pollution requirement for BFRs.

Sampling and analysis of plastic fractions are described in Annex B of TS 50625-3-1, which provides guidelines for demonstrating that the fractions are free of BFRs. The analysis is conducted using either total bromine concentration or restricted BFRs, as per POP Regulation.

In summary, the EN 50625 standard series requires the separation of BFR-containing plastics in specific categories of WEEE, such as screens and small appliances. It introduces a threshold of 2,000 ppm Br to distinguish between BFR-containing and BFR-free fractions. Alternatively, an analysis of restricted BFRs can be performed. BFR-free fractions may be recycled, while BFR-containing fractions must be treated in accordance with the POP Regulation, which sets requirements for the treatment of plastics containing POP-BFRs above the LPCL (PBB, HBCD, PBDEs) (see chapter 3.2).

The 2,000 ppm Br separation threshold facilitates the separation and monitoring of BFR-containing plastic fractions in operational settings, as plastic sorting technologies such as the Sink/Float method cannot distinguish between restricted and non-restricted BFRs.

At the time it was set, the 2,000 ppm threshold represented a "safe total Br level" below which the LPCL for POP-BFRs, then set at 1,000 ppm (for the sum of PBDEs excluding DecaBDE), was statistically unlikely to be exceeded, as POP-BFRs represented only a small proportion of the total Br content. As described in chapter 2.1.2.3, this share has decreased over the last decade due to restrictions on the use of POP-BFRs. In fact, around 2010, PBDEs (including DecaBDE) still accounted for up to 50% of the total Br content found in WEEE plastics, meaning that plastics containing less than 2,000 ppm of total Br would very likely contain less than 1,000 ppm of PBDEs. As DecaBDE was not yet restricted under the POPs Regulation, this "safe limit" was already very conservative.

In light of recent data on BFR levels and the reduced LPCL of 500 ppm for PBDEs (valid from 10 June 2023), the validity of this "safe Br level" can now be reconsidered. As shown in chapter 2.1.2, **PBDEs** currently account on average for **less than 10% of the total Br** content found in WEEE plastics. **Based on the same statistical considerations** that were used to set the 2,000 ppm threshold in EN 50625, the **"safe Br level" would now be set at 5,000 ppm**. Considering a future LPCL of 350 ppm (valid from 30 December 2025), this safe Br level would be 3,500 ppm, but by then the share of PBDEs in total Br is likely to have decreased further. Nevertheless, the **2,000 ppm Br** threshold has become a **widely accepted industry standard** and is easily achievable using state-of-the-art sorting technologies. While there is certainly no scientific justification for lowering it, there is also **no practical need to raise it**.

4 Conventional & Emerging Technologies

4.1 Conventional Technologies

4.1.1 WEEE pre-processing and WEEE Plastics Recycling

After collection, WEEE is processed to **remove hazardous substances** and **recover valuable materials** such as steel, aluminium, copper, gold, and silver. The pre-processing stage involves separating materials from each other through manual or mechanical methods, while end-processing involves recycling, incineration, or landfilling of fractions produced through pre-processing.

Plastic fractions such as external casings and printed circuit boards can arise in different forms during WEEE pre-processing, by **manual dismantling** or **mechanical WEEE pre-processing**. Printed circuit boards typically end up in non-ferrous metal fractions and are sent to integrated smelters to recover copper and other precious metals. Organic materials in printed circuit boards, such as Epoxy, serve as reducing agents in the smelting process.

Mixed plastic fractions 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. However, 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. Still, the recycling of WEEE plastics is generally required to reach the mandatory recycling targets.

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, administrative constraints, or economic reasons. Pre-sorted WEEE plastic fractions have a positive market value.

Mixed WEEE plastic fractions are usually sent for plastic recycling to 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. 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 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. **WEEE plastics containing significant loads of additives, whether fillers, flame retardants, plasticizers or others, must also be sorted out before recycling**.

Various technologies are applied to sort WEEE plastics by both type and additive content, and most commonly, mixed WEEE plastic fractions are first cleaned of their non-polymeric impurities, for instance through air classification, magnetic sorting or eddy current separation. Plastic fractions are subsequently size-reduced (shredded) to optimise the efficiency of further sorting processes. 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, three fractions are created during the density sorting process (see Figure 13). One fraction with a density lower than 1 kg/L contains additive-poor polyolefins (PP and PE), while one fraction with a density between 1 and 1.1 kg/L contains additive-poor ABS and PS, as well as PP containing 20% glass fibre, talc, or other mineral fillers. The third fraction has a density higher than 1.1 kg/L and contains a complex and highly heterogeneous mixture of polymers loaded with various additives, including BFRs, PFRs, phthalates, and heavy metals.

The first two fractions are relatively

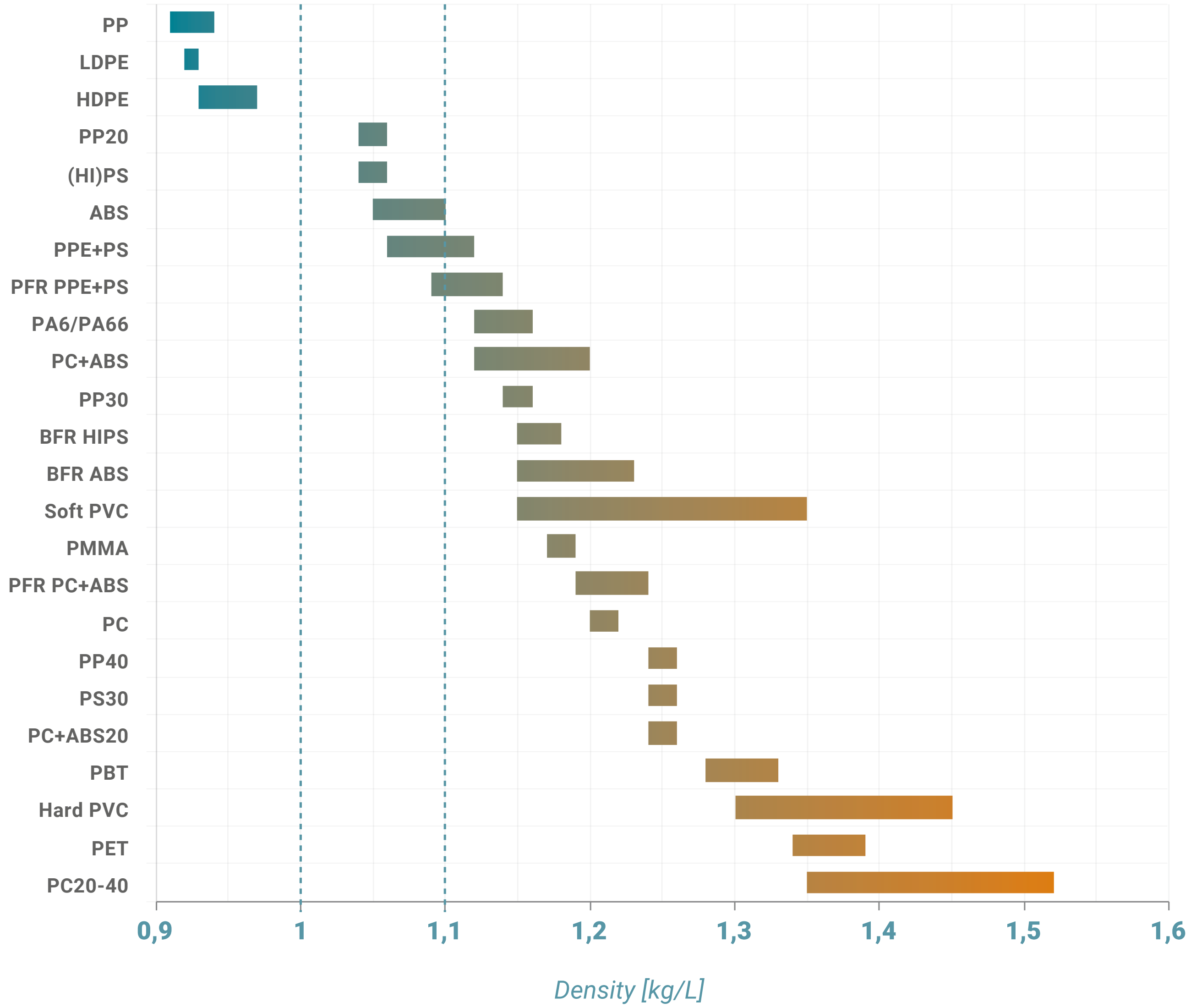


Figure 13: Density range of common WEEE plastics. PFR = organophosphorus flame retardants. BFR = brominated flame retardants. PP20/30/40/50 = PP filled with 20/30/40/50% glass fibre, talc or other mineral fillers. PS30 = PS filled with 30% glass fibre. PC20-40 = PC with 20-40% glass fibre. PC-ABS20 = PC-ABS filled with 20% glass fibre.

homogeneous and can be further sorted using **electrostatic separation** methods. These allow particles to be separated based on differences in electrical conductivity of the particles and work best with relatively homogeneous fractions, consisting of two or three plastic types. Electrostatic sorting can separate 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 then be processed into regranulates, usually with an intermediate compounding step (blending with a masterbatch of additives). It should be noted that monopolymer streams are not 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, and it's typically **disposed of** by **incineration or co-processing in cement kilns.** This fraction, which includes mostly black or dark-coloured plastics, cannot be further sorted using near-infrared technologies, as black plastics cannot be recognized by near-infrared sorting technologies.

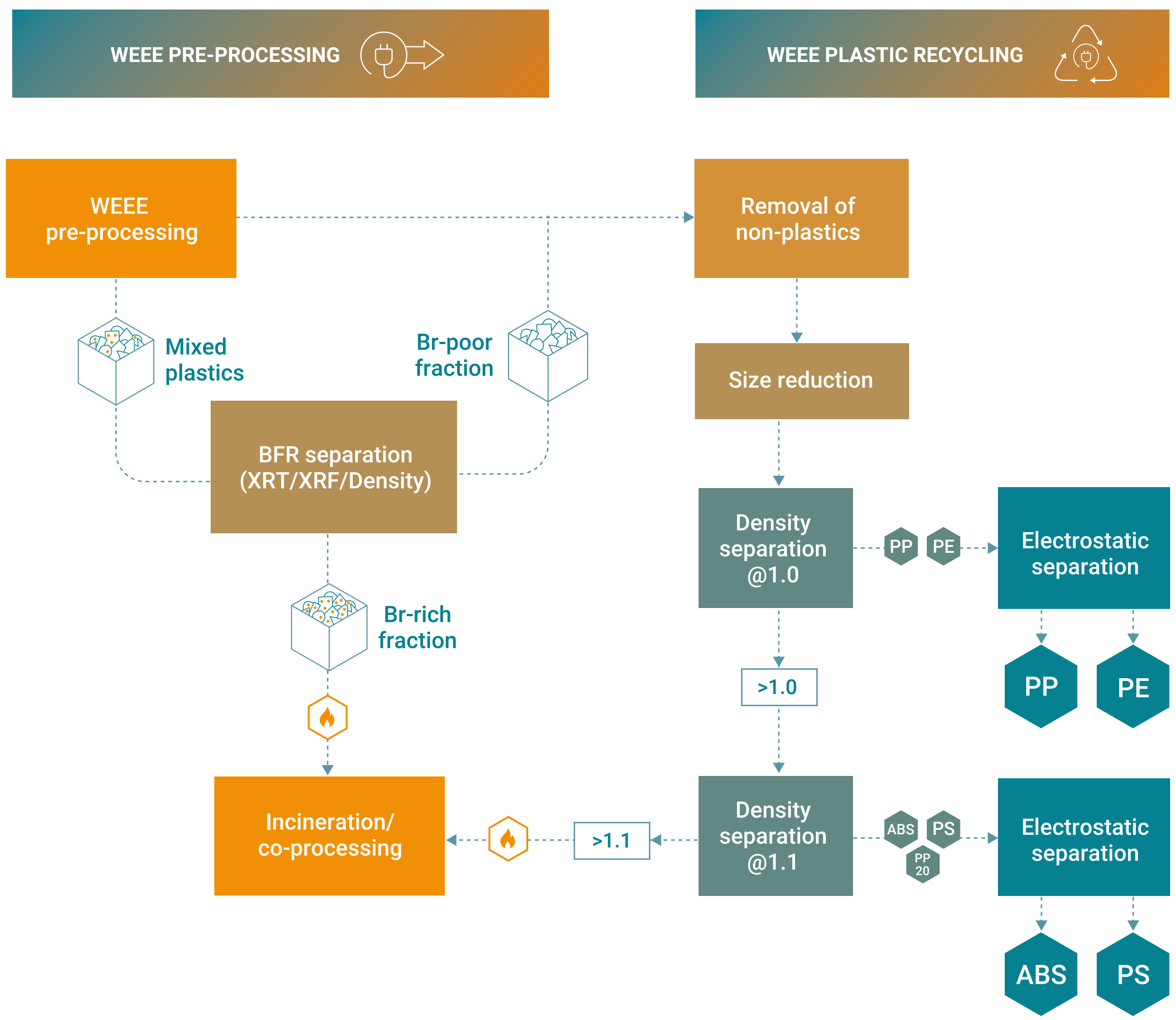


Figure 14: Conventional WEEE plastic treatment processes

One major European WEEE plastic recycling company reports being able to recover a pure PC-ABS fraction[56], 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 14.

4.1.2 Separation of Br-rich Fraction

As seen in 3.5, the WEEE Directive mandates 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 between a Br-rich fraction and a Br-poor fraction that can be treated or recycled, respectively. The segregation of BFR plastics can be achieved using manual (inspecting each plastic piece) or mechanical (in batch or continuous) methods. Six methods have been identified as potentially effective for separating BFR plastics during WEEE treatment. These methods are ISO markings, source segregation, sink/float, X-ray transmission (XRT), laser-induced breakdown spectroscopy (LIBS), and X-ray fluorescence (XRF). Each of these methods can further be assessed with respect to its **effectiveness** in segregating BFR plastic loads; its **selectivity** (ability to separate BFR plastics in a targeted manner); **technology readiness level (TRL),** an indicator of the maturity of the method; and **cost**.

Concerning **effectiveness**, ISO markings are insufficient because they are missing, incomplete, or incorrect. Source segregation requires detailed knowledge about the WEEE types, models, and components containing BFRs, which does not exist. On the other hand, Sink/float is highly effective, allowing >95% of the Br load to be sorted out into the sinking fraction. Sensor-based sorting methods, such as XRF, LIBS, and XRT, can reliably detect Br when present at functional levels (i.e., 5-15% range). However, XRT is less reliable than the other two methods, as its accuracy can be negatively impacted by the presence of interfering elements in the matrix and also by varying thickness of the analysed particles. There is insufficient information available to assess the effectiveness of LIBS.

Regarding the **selectivity** of the method, visual separation methods based on either ISO labels and/or source segregation, have poor selectivity as reliable information is missing. Sink/float has also poor selectivity because WEEE plastics often have overlapping densities, implying that the Br-rich fraction resulting from sorting also contains non-brominated materials such as relatively dense polymers as well as plastics containing non-brominated additives. 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. The XRF method has high selectivity as it separates materials based on their actual atomic composition. For LIBS there was insufficient information available to assess its selectivity.

On the **technology readiness level (TRL)** most of the considered technologies and methods are already used in WEEE pre-processing and WEEE plastics recycling operations, except on-line LIBS-based methods, which appear to only have been applied in research projects (e.g., CloseWEEE project).

Lastly, the **cost** of the methods varies as well. ISO labels and/or source segregation, as well as hand-held sensor techniques (XRF, LIBS), have high operating costs due to the relatively expensive manual labour costs, and as such are economically unfeasible. Sink/float methods are relatively inexpensive, while on-line XRF sorting machinery is on average 50% more expensive than on-line XRT sorters[57]. No information could be found on the cost of LIBS sorting technologies.

In conclusion, each method has its strengths and weaknesses, and in reality, a **combination of methods is often used**. For example, 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.

4.1.3 Treatment of Br-rich Fraction

Br-rich fractions generated during the sorting processes that POP-BFRs above the LPCL should be treated to ensure their destruction or irreversible transformation (see 3.2). Additionally, these fractions should be classified as "non-hazardous mixed plastic waste", and therefore subject to the PIC procedure for shipments within the EU (under entry 48) as well as imports to and exports from the EU (entry Y48)[58].

As can be seen from Figure 15, most of the heavy fraction is composed of plastics, with PC and PC-ABS representing a large share. While this fraction is currently being sent for disposal (mainly in municipal or hazardous waste incinerators, or in cement kilns), it could represent a high market value. Especially for PC/PC-ABS, if separation from this waste stream was possible. Several companies are already working on a technology that would allow first to separate PC and PC-ABS from the heavy fraction, and subsequently to separate the BFR containing PC/PC-ABS from the PC/PC-ABS fraction.

The commonly employed treatment technologies include **incineration**, either in municipal waste incinerators or hazardous waste incinerators (depending on waste classification), co-processing in cement kilns, or utilization as a reducing agent in non-ferrous metal smelters. Incineration plants, cement kilns, and smelters can effectively destroy or transform POP-BFRs provided they maintain a minimum temperature of 850°C for at least 2 seconds[59] . These conditions are mandated by Article 50 of the Industrial Emissions Directive (2010/75/EU) for all municipal and hazardous waste incineration plants. Cement kilns and metal smelters typically operate at temperatures exceeding 1,000°C. However, specific measures may be required in these installations due to challenges such as bromine corrosion, emission of brominated dioxins and furans, and the presence of leachable antimony in the by-products[60].

Although **landfilling** is not an permitted treatment option for waste containing POP-BFRs above the LPCL, it may still be practised in some countries. Studies have shown that BFRs and associated heavy metals can leach from non-sanitary landfills into nearby soils and water bodies. While modern landfills mitigate these risks to some extent, the drawback is that any POP-BFRs present in the waste are not destroyed or irreversibly transformed.

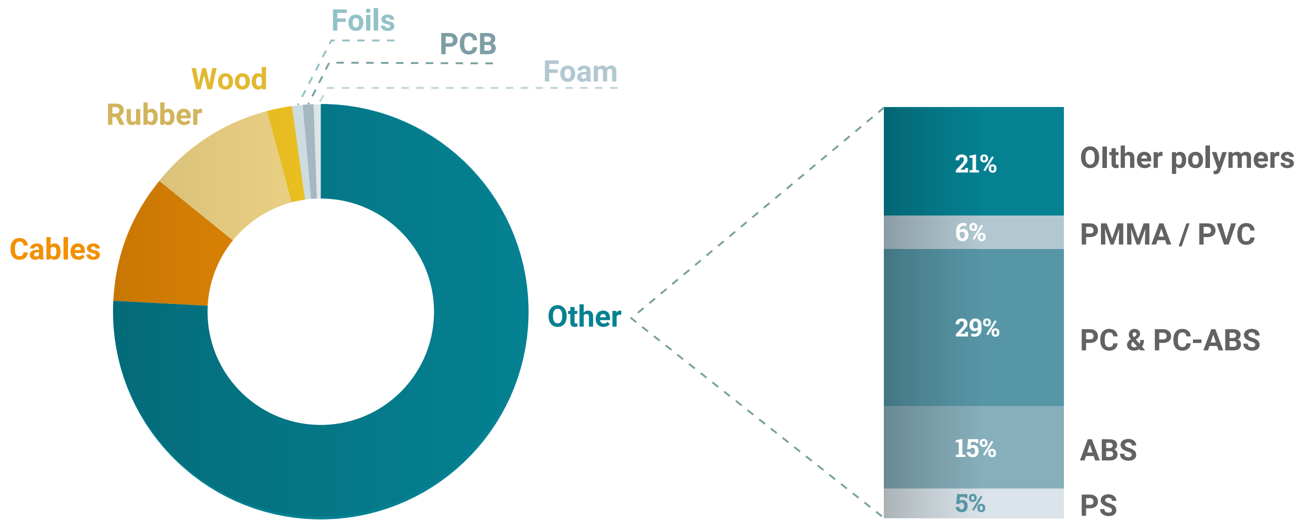


Figure 14: *Average composition of the heavy fraction (adapted from Plastics Recyclers Europe[61])*

4.2 Emerging Technologies

4.2.1 Solvent-based Recycling (Selective Dissolution)

Solvent-based recycling refers to a process that dissolves the polymer without chemically modifying it. In this process, pre-sorted shredded plastic waste is immersed in a solvent. The polymers and their additives are thereby dissolved. Additives and other impurities can be removed from the solution (e.g. by centrifugation and/or filtration) and the clean polymer can then be recovered from the solution by a process of precipitation or evaporation. Such technologies may become a suitable treatment option for Br-rich WEEE plastic fractions.

In particular, the **CreaSolv©** process, which has been under rigorous development and testing 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[62]. The CreaSolv® process consists of four main steps. First, input material (pre-sorted Br-rich ABS or PS fractions) is brought into contact with a specific solvent formulation allowing the selective dissolution of the target polymer (ABS or PS). Secondly, the residual solids are removed from the solution by fine filtration or centrifugation, leaving the target polymer in the solution along with some associated additives such as BFRs. In the third step, the target polymer is 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 or PS regranulates.

A more recent investigation into the separation of additives from dissolved WEEE plastics has been undertaken by **PLAST2bCLEANED**. They have attempted to improve the quality of separating legacy additives from WEEE plastics through an improved technically feasible and economically viable way solvent-based system[63]. After the initial dissolution of the WEEE plastic in a hot organic solvent solution, a three-step process is used to retrieve the separate fractions. This includes antimony recovery, hot cross-flow filtration and spray drying. Hot cross-flow filtration is used for the recovery of bromine flame retardants from the mixed solution. This utilises a multilayer membrane through a hot filtration process to separate molecules of different sizes and characteristics within the solution. It was found that after two hours of filtration, between 80% and 90% of Br was removed from the solution . Based on interviews with industry leaders, the PLAST2bCLEANED process has received significant backing as a scalable process for future plastic processing.

SOLVENT BASED RECYCLING	
✓ ADVANTAGES	✕ DISADVANTAGES
Can be practically adapted to all thermoplastic resins.	Purity of input material should be at least 95% of ABS or PS, require fine pre-sorting.
Tolerant to most common polymer impurities in the target material e.g. it can handle PS impurities in ABS.	Technology is not yet fully matured and still subject to continued industry development.
Technology doesn't destroy the chain polymers and weaken their form.	Solvent recycling is an added requirement in the process, resulting in excessive solvent recovery and recycling.
Produced recyclate close or equal to virgin quality.	Cost of extraction often greater than the value added from extracting additional polymers.
Relatively low carbon footprint, close to that of mechanical recycling.	

Based on the variety of available solvents, selective dissolution can be utilised for the processing of many different blends. However, due to the process's utilisation of different solvents, this requires sufficient recovery and recycling of solvents after their use. Additionally, despite the apparent benefits of the technology, **its implementation is still hampered** by economic and technical challenges, especially regarding its implementation at scale. With this being further undermined by the failure to share Intellectual property (IP) between actors, preventing industry wide innovation based on latest available knowledge.

4.2.2 Chemical Recycling

Chemical recycling includes the process of converting polymers to monomers through a chemical reaction or the production of new raw materials via chemical modification, altering the chemical structure of plastics. This is undertaken through a process of thermolysis, depolymerisation or gasification.

Chemical recycling is utilised to treat residual fractions, after the use of an initial process to recover resins of interest (PP/ABS/HIPS). Without the use of such chemical processes, these residual fractions are often lost during the sorting phase, due to being mixed with other polymers or discarded within lower-quality products. The following chapters outline three chemical recycling processes of thermolysis (pyrolysis), depolymerisation (solvolysis) and gasification.

4.2.2.1 Thermolysis (Pyrolysis)

Thermolysis is a chemical process that consists of heating plastics in a chemically inactive atmosphere (i.e., the removal of oxygen). This includes 'rapid pyrolysis' which involves the flash heating of plastics in a vacuum without oxygen. Thermolysis typically occurs at temperatures ranging from 400°C to 800°C[65]. According to operating conditions (temperature, type of the reactor, etc.), this will produce an oil (the aim of the process), a gaseous fraction (a mixture of gases such as methane, hydrogen, carbon monoxide, and carbon dioxide) and a solid fraction called char or coke.

A project undertaken by **NONTOX** has focused on increasing the recycling rate of WEEE plastic waste through a system of thermolysis conversion, to reduce contaminates in recycled plastics to meet regulatory requirements[66]. This consists of a sorting and pre-treatment stage of plastic feedstock, before then utilizing two technologies (Extruclean and CreaSolv®) to remove hazardous substances within the target plastics. It then uses a process of thermochemical conversion of non-target plastics and side streams from the main recycling processes, allowing for the extraction and processing of fractions that are normally

THERMOLYSIS (PYROLYSIS)

ADVANTAGES	DISADVANTAGES
Has been utilised within the industry for a significant period and has been supported by innovation and development.	Needs to work in fast pyrolysis.
Suitable for the utilization of polyaddition polymers.	Mixing of plastics is possible under certain conditions, if not correctly undertaken.
Allows for the possibility of processing mixed plastics.	Requires high-quality upstream sorting allows to obtain products of the best quality.
Allows for the obtaining of petroleum substitutes.	Expensive compared to traditional mechanical recycling.
Energy is provided by a fraction of the plastic.	
Large scales possible (up to 100kt/year envisaged).	
Lower carbon footprint compared to mechanical recycling.	

disposed of. It is important to highlight, however, that traditional pyrolysis or gasification processes, apart from the thermochemical conversion utilized in the NONTOX project, are generally ill-suited for handling plastics containing halogens (such as PVC and BFRs) or nitrogen (including ABS, PUR, and PA).

Thermolysis can treat an array of plastics and plastic blends. This includes a particular focus on polymers deriving from polyaddition, including polyethylenes (PE), polypropylene (PP) and styrenics (PS, HIPS, ABS, SAN, etc.)[67]. Additionally for PE/PP or blended plastics, the oil obtained through the process is equivalent to a naphtha, allowing it to be utilised as an alternative input for steam crackers.

The difficulty in this process lies in the capacity to free and capture bromine, ensuring the obtaining of quality oil. This extraction of oil is also considered a major limitation, as this oil can be utilised as the basis of fuel as well as new plastics, causing a potential overlap in final product value (material value over the value for energy recovery).

4.2.2.2 Depolymerisation

Depolymerisation is a process that involves the breakdown of polymers into their constituent monomers through chemical or biological means. Depolymerisation can occur at a range of temperatures and pressures depending on the specific polymer and the method used. Chemical depolymerisation can be done using various solvents, e.g., hydrolysis, methanolysis and glycolysis[68]. Given the selectiveness of the reaction, it is essential to have pure plastic streams for these technologies.

Depolymerisation technologies are selective, allowing for specific monomers to be recovered. Solvolysis is particularly effective towards polymers resulting from polycondensation (i.e., resins such as **PET, PA, PC or PUR**)[69]. The extracted monomers can be used as feedstocks to produce new polymers or as chemical intermediates.

Despite increased usage of depolymerisation techniques, it is still subject to industry development, with further innovation required to ensure a more sufficient recovery of polymers.

DEPOLYMERISATION

ADVANTAGES	DISADVANTAGES
Suitable for polycondensation polymers (PET, PA).	The process is not fully mature and still subject to developments.
Allows to obtain of monomers (or their precursors) in a selective way.	Requires good purity of inflowing streams.
	The monomers must then be repolymerized after.
	Requires efficient purification of obtained monomers.
	Has not been tested for halogen-containing plastics.

GASIFICATION

ADVANTAGES	DISADVANTAGES
Considered the most efficient thermolysis technologies to produce fuels from plastic.	High investment cost for required equipment.
Allows for the obtaining of petroleum substitutes.	Release of toxic gases for human and environmental health, must be controlled.

4.2.2.3 Gasification

The gasification of plastics involves plastic being subject to a chemical and thermal conversion through its reaction with a gasifying agent, these notable include oxygen, steam or air. This is undertaken at a temperature of around 500–1300 °C, resulting in the production of synthesis gas or syngas[70].

A traditional process of plastic waste gasification consists of two separate stages. Firstly, plastic waste is heated to a desired temperature, before being placed into a decomposition unit. The resulting product is then placed in the gasifier as steam is simultaneously added, with the steam being produced through the heating of water. The resulting chemical reaction provides a solid (e.g., non-volatile metals), liquid (e.g., oil and tar) and the main product of gas or syngas[71]. This gas is then used to produce fuel or combustible gas which is utilised within energy production.

4.2.3 Emerging Technologies and Bromine

Brominated plastics used in WEEE have offered additional complexity for the emergence of these new recycling technologies due to requirements regarding the removal of BFRs to meet obligations under national and international regulation.

The greatest success has arisen from solvent-based recycling methods which have reduced the level of bromine within WEEE plastics through a multi-stage filtration system. This has been demonstrated through the PLAST2bCLEANED project as it has reduced the level of BFRs in its final processed solution by between 80% and 90% after a two-hour filtration process[72]. However, this relatively high level of remaining bromine and timely filtration process reduces its current viability as a widely adoptable solution.

Additionally, chemical recycling techniques have not provided a clear and efficient process for the recovery of brominated plastics. Although thermolysis has allowed for the splitting of different polymers, its final extracted oil has still comprised undesirable levels of bromine without a clear additional process to reduce BFRs levels. Whilst depolymerisation and gasification have not offered additional routes for the successful extraction of BFRs for usable polymers.

Although these new technologies have shown the possibility for additional processing methods of brominated WEEE plastics, the current level of industry development has hampered their potential to efficiently extract bromine from WEEE plastic to the required regulatory and industry level. However, continued advancement in these technologies, particularly the development of solvent-based recycling methods, could offer a future longer-term alternative to mechanical recycling processes, supporting continued improvement in the efficiency of BFRs extraction.

5 Recycled Content

Sourcing and use of recycled plastics in EEE is nowadays a priority for most Original Equipment Manufacturers (OEMs). **Internal, voluntary targets** are for most OEMs the main reason for sourcing recycled plastics, coupled with an ambition to reduce demand on resources and particularly to curb CO2 emissions. Other factors influencing the willingness to source recycled are upcoming regulatory and compliance requirements, consumer perception, and resilience to supply chain disruptions among others.

In the consumer electronics industry, for example, Dell Technologies has committed to more than half of its product contents to be made from recycled or renewable material by 2030. By 2025/26, the Lenovo Group aims at having 100% of their PC products containing post-consumer recycled content materials and use 300 million pounds of post-consumer recycled plastics. Other OEMs such as Microsoft committed to using more and more post-consumer recycled plastics in their products, and other sustainable materials innovations, such as recycled ocean plastic which was used to make Microsoft's first eco-friendly mouse shell, made with 20% recycled ocean plastics. Other examples of goals include HP's target to have 30% of PCR plastics in print and personal systems products by 2025, moving by 2030 to a target of 75% (by weight) of circular materials (recycled, renewable and re-used) in products and packaging.

From a policy point of view, the European Commission's Circular Plastics Alliance (CPA) launched in December 2018, has the objective to boost the uptake of recycled plastics and help match the voluntary pledges from the supply and demand side. The CPA has set a goal of placing **10 million tonnes (Mt) of plastic recyclates in final products** on the EU market each year **by 2025**. For EEE products, the estimated untapped potential according to the Commission's Roadmap to 10Mt is 0.29Mt of additional post-consumer recycling outputs by 2025, compared to a 2020 baseline[73]. To achieve the target by 2025, the CPA took a series of commitments related to standardisation, including to "develop, update or revise design-for-recycling guidelines" and "actively contribute to the update of CEN and industry standards on recyclability and related ones" and "adopt a work plan for the delivery of the necessary guidelines and standards[74]. The European Committee for Electrotechnical Standardisation (CENELEC) in collaboration with IEC (International Electrotechnical Commission) and other organisations, has now started this work under the Technical Committee (TC) 111, which focuses, among others on developing design-for-recycling guidelines for electronic and electrical equipment, especially on polypropylene (PP) and acrylonitrile butadiene styrene (ABS) products and parts[75].

In the EU, requirements on recycled content in products, including EEE, have also been put forward by the Proposal for a new Ecodesign for Sustainable Products Regulation, published in March 2022. The proposal is currently undergoing trilogue discussions, but if approved, specific eco-design requirements will further be elaborated by the Commission in delegated acts, mandating, among others, higher use of post-consumer recycled materials also for plastics.

However, the sourcing of recycled plastics and their use in product content poses some challenges for companies and businesses. Some of the conditions that have been expressed as a pre-requisite to deliver on companies' pledges on recycled plastic content include[76]:

- **Market conditions**: many pledgers from the demand side (e.g., plastic converters and brand owners) commit to using a certain volume of recycled plastic materials by 2025 provided the recycled plastics are available on the EU market in **sufficient quantity and suitable quality**, at competitive prices. Several brand owners indicate that their pledge could even dramatically increase if new recycled plastics become available (e.g., new colours, food grade recycled polyolefins) or if there is market acceptance for new standards (e.g., different colours and aesthetics) - without compromising hygiene and safety. Prices also play an important role, with costs for recycled plastics assumed to be higher than virgin plastics. Aesthetic requirements, especially on colours, are also a challenge, with some recycled polymers such as PC-ABS only being available in black or grey.
- **Greater collection and sorting of plastic waste**: as highlighted in 2.2.1, there is a significant gap between WEEE generated and WEEE collected by formal channels and recycled. To supply recycled plastics to the EU market in sufficient quantity and quality, recyclers and plastics producers require sufficient feedstock, hence a sufficient amount of plastic waste collected for recycling. This is a condition very frequently expressed by pledgers from both the supply and demand sides. This entails both more plastic collected and better quality of sorted plastic waste.
- **Mixed nature of the input material**: WEEE input materials for recycling often come from products that have been manufactured/sold 20-30 years ago, with a high degree of fillers and ingredients (by total mass) which makes reaching high percentages of recycled plastic often difficult.
- **Recyclable plastic materials**: some plastics fractions such as PC-ABS are currently difficult to recycle. Moreover, in the case of WEEE, stricter regulations such as the POP regulation, make it mandatory for plastics containing POPs above certain thresholds to be landfilled or incinerated, hindering the availability of plastic for recycling.
- **Greater incineration capacity**: current incineration capacity in Europe is low and represent a limiting factor for higher production of post-consumer recycled plastics from WEEE. Indeed, more plastics can be recycled only if there is capacity for the non-targeted or hazardous plastics that need incineration. This limiting factor is proving to be a constraint for several WEEE plastics recyclers in increasing their throughput.

6 Findings and Recommendations

This study set out to provide a comprehensive overview of the current state of WEEE plastics recycling in Europe and identify opportunities for improvement. In particular, this update primarily aimed to:

- Provide updated figures on the composition and fate of WEEE plastics: In particular, on trends in BFR levels as well as on the current recycling capacity of WEEE plastics in Europe.
- Discuss technological and regulatory developments regarding the handling of WEEE plastics containing BFRs.
- Assess the potential of emerging technologies such as solvent-based recycling, pyrolysis or depolymerisation to treat plastics from WEEE.
- Identify the challenges and opportunities related to the incorporation of recycled plastics into new EEE.

Key findings and recommendations are provided hereafter.

6.1 Key Findings

On BFR levels in WEEE plastics

BFR levels in mixed (unsorted) WEEE plastics:

- BFR levels in mixed (unsorted) WEEE plastics vary across different categories. Screens have the highest BFR levels, ranging between 6,000 and 13,000 ppm of Br from 2020 to 2023. Small equipment follows with BFR levels of 2,000 to 7,000 ppm Br during the same period. Large household appliances have relatively low BFR levels of 1,500 ppm Br in 2017, and temperature exchange equipment has even lower levels of 350 ppm Br in 2017.
- Over the period from 2010 to 2022, BFR levels in screens have generally decreased. BFR levels in small equipment and large equipment have remained relatively stable during this period.
- PBDEs account for a small and declining proportion of the total bromine content in recent samples. PBDE levels in plastics from screens were up to 2,237 ppm and up to 644 ppm in plastics from small appliances in 2020-2021. However, in some recent samples from screens, PBDEs were not detected above the limits of detection. On average, PBDE levels were 239 ppm in plastics from small appliances and 805 ppm in plastics from screens across all recent samples.
- The proportion of brominated plastics in mixed plastics from screens and small equipment is approximately 7-8%, while for large equipment and cooling appliances, it is much lower at 1.5% and 0.4%, respectively. Regarding PBDEs, the data indicates that mixed plastics from screens and small equipment contain less than 1% of plastics with intentionally added PBDEs, while plastics from large equipment and cooling appliances contain less than 0.2% and 0.1% respectively. Overall, WEEE plastics contain an average of 3.5% BFR-containing plastics and 0.2% POP-BFR-containing plastics.
- The average share of PBDEs in the total bromine content has decreased from above 20% in 2015-2016 to below 10% in 2021-2022. However, outliers exist due to the heterogeneous nature of WEEE streams and resulting high sampling and analytical uncertainties, and the presence of older appliances containing legacy substances like PBDEs. In 2022, half of the samples tested did not have detectable levels of PBDEs.
- Overall, the analysis shows that PBDE levels in WEEE plastics have significantly decreased over the past decade, indicating the effectiveness of regulatory restrictions implemented more than 15 years ago. However, occasional high PBDE levels may still be found in WEEE streams due to the presence of older electronic devices manufactured before the restrictions were in place, or devices produced in countries with different rules. This highlights the need for careful sorting by WEEE plastic recyclers to prevent particles with high PBDE levels from being processed incorrectly.

BFR levels in low-Br fraction:

- The analysis indicates that residual levels of brominated flame retardants (BFRs), specifically PBDEs, have decreased in plastics from screens between 2014-2016 and 2020-2023. This is likely due to the phasing-out of CRT screens, which are a known hotspot for BFRs. However, such a decrease is not evident in plastics from small equipment, suggesting here also that BFR levels have remained relatively stable in these plastics.
- Recent samples show that total bromine (Br) levels in "low-Br" plastics from screens reached up to 1,880 ppm, and in plastics from small equipment, it reached up to 2,433 ppm. PBDE levels in these "low-Br" plastics reached up to 486 ppm in screens and up to 553 ppm in small equipment.
- In many samples, PBDEs were not detected above the laboratory's detection or quantification limits, which in some cases were as high as 400 ppm.
- Considering the discussions around the maximum allowable concentration (UTC) level for PBDEs in recycled WEEE plastics, the available data has several implications. A UTC level of 500 ppm PBDEs appears to be at the limit of current achievable purity for recycled plastics from screens and small equipment. A potential UTC level of 350 ppm PBDEs may already pose challenges, as it falls below the quantification limits reported for some samples and is exceeded in several recent samples from screens and small appliances. A UTC level of 200 ppm PBDEs does not seem attainable based on reported quantification limits and measured levels in plastics from screens and small appliances.
- It is possible that the attainable degree of purity may improve in the future due to the natural decline in PBDE levels and advancements in separation techniques. However, the existing data suggests that residual PBDE levels in "low-Br" plastics from screens and small appliances have

remained relatively stable, or rather, stable in their variability.

- Accurate measurement of bromine concentration and selection of a representative sample remains complex using current laboratory technologies due to, among others, the lack of verified methods and standards at concentrations below 1,000 ppm.

On the fate of WEEE plastics in Europe

- Europe generates approximately 2.6 million tonnes of WEEE plastics annually, but only 54% (1.4 million tonnes) are collected through official WEEE channels. Out of this collected amount, only 0.4 million tonnes reach WEEE plastic recycling companies in Europe. The remaining 1 million tonnes of WEEE plastics are either incinerated, landfilled, or exported outside of Europe for recycling.
- Around 46% of all WEEE plastics manage to evade official collection. Among these, 13% are treated as scrap metal, and the fate of the plastics is uncertain. Additionally, 8% are disposed of with mixed waste and incinerated or landfilled. Another 6% are exported as used electronic equipment (EEE) beyond Europe. Illegal WEEE exports make up 5% of the escaping plastics, while 14% have an unknown fate.
- When considering the final destinations of all WEEE plastics in Europe, over two-thirds (1.8 million tonnes or 68%) have an unknown fate, raising concerns about unsafe recycling practices, burning, or dumping. Approximately 11% (0.3 million tonnes) are estimated to be found in exports of WEEE and/or used EEE. Another 10% (0.3 million tonnes) are incinerated within Europe, and 4% (0.1 million tonnes) are landfilled. Only 7% (0.2 million tonnes) of the WEEE plastics generated in Europe are actually recycled within Europe, contributing to the production of new products through the use of secondary raw materials.

- These findings highlight the need for more effective management and recycling practices for WEEE plastics in Europe. Improving collection rates, preventing illegal exports, and ensuring proper recycling processes are essential to maximize resource utilization and minimize environmental impact.
- There are more than 40 companies specializing in WEEE plastics sorting and recycling in Europe, with a combined capacity estimated to be around 800,000 tonnes per year. This capacity can be compared to the estimated 360,000 tonnes of WEEE plastics received by WEEE plastics recyclers, based on data from Plastics Recyclers Europe. However, the 800,000 tonnes may include some double counting as different companies may be involved in different steps of the supply chain, e.g. some companies may only carry out pre-sorting, others only final sorting and compounding.
- Greater incineration capacity in Europe will also be necessary to be able to increase the production of post-consumer recycled plastics from WEEE.

On the fate of WEEE plastics in Japan

- According to the Global E-waste Monitor, Japan generated 2,569 kt of WEEE in 2019, equivalent to 20.4 kg per capita. This is comparable to Western Europe's 20.3 kg per capita. However, in 2021 Japan's official collection channels managed to collect only 610 kt of WEEE, equivalent to 4.8 kg per capita. In comparison, WEEE collection in Western Europe was reported to be around 11 kg per capita in 2022. Based on these figures, Japan's WEEE collection rate is calculated to be 24%, compared to 54% in Western Europe.
- Limited information is available on the fate of WEEE plastics in Japan. The estimated total WEEE plastic generation is 600 kt, and less than 10% of WEEE plastics are recycled domestically, while around 30% are exported for recycling or reuse. Approximately 20% of WEEE plastics are incinerated, 10% are landfilled, and the fate of the remaining 30% is unknown.

On regulatory developments related to the management of WEEE plastics containing BFRs

- The European Commission reviewed the LPCL for HBCD and PBDEs, resulting in lowered limit values. From June 10th the HBCD's limit value is reduced from 1,000 ppm to 500 ppm, with the potential for further reduction to 200 ppm by December 2027. The threshold for PBDEs also decreased from June 10th from 1,000 ppm to 500 ppm until December 2025, then to 350 ppm by 2027, and ultimately to 200 ppm from December 2027.
- UTC levels for PBDEs is also under review, with a proposal to lower the PBDE group's limit to 200 ppm. The WEEE plastic recycling industry is concerned about these new limits and the potential for unrealistically low UTC values. The lack of reliable sampling, sample preparation and analytical methods for measuring bromine concentrations below 1,000 ppm in mixed WEEE plastics makes it challenging to detect compliance in current laboratory settings. Differences between LPCL and UTC thresholds may result in situations where plastic waste with PBDEs can be recycled up to 500 ppm but regranulates must contain less than 200 ppm, potentially hindering

the availability of compliant secondary plastic materials and impacting recycling/recovery targets.

- Our analysis suggests that the operational threshold of 2,000 ppm Br is still valid given the reduced levels of PBDEs in WEEE plastics, even with lower LPCL values. Interviews with WEEE plastic recyclers support the notion that BFR plastics are well-controlled and easily sorted during conventional recycling processes.
- Changes in the Basel Convention, such as the Basel Ban and the Swiss-Ghana proposal, restrict the transboundary shipment of hazardous wastes from OECD countries, the EU, and Lichtenstein to primarily developing nations. Proposed re-classification of WEEE may classify all plastics with brominated flame retardants as hazardous waste, subjecting all e-waste fractions to Basel PIC procedures. Additionally, at the EU level, the Commission is investigating the feasibility of an automatic classification as hazardous waste for all plastic waste exceeding LPCL. This is against the interpretation given by in the Waste Shipment Correspondents' Guidance No 12 which defines plastic waste with POPs above LPCL levels as non-hazardous, however subject to the PIC procedure. Lastly, the Waste Shipment Regulation is expected to be replaced by a new regulation with stricter measures to phase out the export of plastic wastes, even within OECD countries.
- These new regulatory developments pose challenges and increased costs for the movement of waste, making it increasingly difficult to transfer WEEE plastics to appropriate recycling facilities within the EU. The recycling industry has raised concerns about these complicated and expensive regulations, impacting the proper management of WEEE plastics.

On conventional technologies to handle WEEE plastics containing BFRs

- Conventional recycling of WEEE plastics involves a series of processes to create homogeneous and additive-poor plastic fractions suitable for producing plastic regranulates. Initial sorting methods, such as XRT, XRF, or density separation, aim to isolate a fraction rich in BFRs. The sorting process aims for homogeneity in polymer types and additive content as customers prefer pure plastics with minimal additives. Plastics with significant additive loads, including fillers, flame retardants, and plasticizers, must be sorted before recycling.
- Various technologies are employed to sort WEEE plastics by type and additive content. Non-polymeric impurities are removed through processes like air classification, magnetic sorting, or eddy current separation. The plastic fractions are then size-reduced through shredding to enhance the efficiency of subsequent sorting. Density-based sorting techniques, using the "Sink/Float" method, create three fractions: a lower-density fraction containing additive-poor polyolefins (PP and PE), a mid-density fraction with additive-poor ABS and PS, and a higher-density fraction with a complex mixture of polymers loaded with various additives, including BFRs, PFRs, phthalates, and heavy metals.
- The first two fractions, which are relatively homogeneous, can be further sorted using electrostatic separation. This method separates particles based on their electrical conductivity and works well with fractions consisting of two or three plastic types. Pure fractions of PP, PE, ABS, and PS can be sorted, and these can be turned into regranulates through compounding. Mono-polymer streams as well as mixtures of PP and PE or PS and ABS can be used in the plastics industry.
- The fraction with a density higher than 1.1 kg/L, often referred to as the "waste fraction," is highly heterogeneous and unsuitable for recovering pure plastic fractions. This fraction, which includes mostly black or dark-coloured plastics, cannot be sorted using near-infrared technologies. Typically, this fraction is disposed of, mainly through incineration or co-processing in cement kilns.
- Br-rich fractions generated during sorting processes that exceed the LPCL should undergo treatment for destruction or irreversible transformation. Treatment options for fractions classified as hazardous waste are limited to licensed facilities. Some companies are developing technologies to separate and recover valuable materials, such as PC (polycarbonate) and PC-ABS (a blend of polycarbonate and ABS), from the heavy fraction.
- Treatment technologies commonly employed for Br-rich fractions include incineration, co-processing in cement kilns, and utilization as a reducing agent in non-ferrous metal smelters. Incineration plants, cement kilns, and smelters can effectively destroy or transform BFRs by maintaining minimum temperatures of 850°C for at least 2 seconds. Although landfilling is not a permitted treatment option for waste containing POP-BFRs above the LPCL, it may still be practised in some countries.

On emerging technologies to handle WEEE plastics containing BFRs

- Emerging technologies for handling the Br-rich fraction from WEEE plastics include solvent-based recycling and chemical recycling. Solvent-based recycling involves dissolving the polymer in a solvent to separate it from contaminants and additives. The CreaSolv® process is one example that selectively dissolves ABS or PS polymers, allowing for their recovery. Another solvent-based system, developed as part of the PLAST2bCLEANED project, focuses on separating legacy additives from dissolved WEEE plastics. However, economic and technical challenges, with issues regarding the scaling up of the process to ensure economic viability, still hinder the implementation of solvent-based recycling.
- Chemical recycling involves converting polymers to monomers through processes like thermolysis, depolymerisation, and gasification. Thermolysis, or pyrolysis, uses heat in the absence of oxygen to break down plastics into oil, gases, and solid char. NONTOX has used thermolysis for WEEE plastic recycling to reduce contaminants and increase the recycling rate. Depolymerisation, or solvolysis, breaks down polymers into monomers using solvents, allowing for the recovery of specific monomers like PET or PA. Gasification involves subjecting plastic to thermal and chemical conversion with a gasifying

agent, resulting in the production of synthesis gas or syngas, which can be used for fuel or energy production.

- These emerging technologies show promise in handling the Br-rich fraction and recovering valuable materials from WEEE plastics. However, challenges such as solvent recovery, bromine removal and the development of efficient processes still need to be addressed for their widespread implementation.

On the incorporation of recycled plastics into new EEE

- The sourcing and use of recycled plastics in EEE is a priority for many Original Equipment Manufacturers (OEMs). OEMs are driven by internal targets, resource reduction, CO2 emission reduction, upcoming regulations, consumer perception, and supply chain resilience. Companies like Dell Technologies, Lenovo, Microsoft, and HP have all set goals to incorporate recycled plastics into their products.

- The European Commission's Circular Plastics Alliance (CPA) aims to place 10 million tonnes of plastic recyclates in EU products annually by 2025. Standardization efforts and design-for-recycling guidelines are being developed to support the use of recycled plastics in EEE. The EU's Ecodesign for Sustainable Products Regulation proposes eco-design requirements that mandate the use of post-consumer recycled materials. The Commission also intends to develop quality standards for sorted plastic waste and recycled plastics.

- However, challenges include: market conditions, availability of recycled plastics in sufficient quantity and quality, cost competitiveness, collection and sorting of plastic waste, mixed nature of input material, difficulty in recycling certain plastics, regulatory restrictions on certain plastics, and existence of incineration capacity for the disposal of sorting residues.

6.2 Recommendations

For policymakers

- Increase the quantities of WEEE plastics reaching specialized 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. This will ensure that a larger proportion of WEEE plastics is properly recycled and reduce the environmental impact related to improper treatment practices.

- Improve the knowledge basis necessary for evidence-based policies and decisions by regularly collecting and analysing representative data on levels of brominated flame retardants (BFRs) and other additives in WEEE plastic streams. Develop new, better, standards for sampling and testing methodologies, and the data should be centrally available in the form of a data repository. This will facilitate the development of targeted regulations and measures to minimize hazardous substances in WEEE plastics.

- Review the relevance of amendments to Annex I and Annex IV of the POP Regulation which further lowers LPCL and UTC values for POP-BFRs. For PBDEs, a UTC level of 500 ppm seems to be at the limit of the level of purity currently achievable for recycled plastics from small equipment and screens. A further lowering of the level to 350 and, later, 200 ppm will pose significant challenges. Balancing environmental goals with technological capabilities is crucial to ensure effective implementation.

- Align the threshold values between Annex I (UTC) and Annex IV (LPCL) to ensure that the recycling industry in Europe can develop further capacity and continue innovating while upholding the principles of the circular economy and ensuring that secondary plastics are recycled and reused in new products.

- Incentivize greater collection of WEEE and sorting of WEEE plastic waste to boost the supply of recycled plastics in the EU market. This can be achieved through financial incentives, tax benefits, or other regulatory measures that encourage the recycling industry and plastic producers to actively participate in the circular economy and increase the availability of high-quality recycled plastics.

- Establish a regulatory structure that facilitates the flow of WEEE plastics within certified recycling networks, ensuring compliance through third-party audits based on the EN 50625 standard. This framework should eliminate bureaucratic obstacles when transferring plastic waste to compliant WEEE treatment centres and WEEE plastics recyclers. Consider WEEE plastic waste containing POPs above POP Directive limits as non-hazardous for shipments within the EU as per Waste Shipment Correspondents' Guidance No 12, and avoid automatic classification as hazardous waste for all plastic waste exceeding LPCL, as this will pose issue given the limited hazardous waste incineration capacity in Europe. Additionally, reinforce regulations to restrict the movement of materials outside of these closed industrial loops, such as limiting exports of mixed WEEE plastics outside of Europe.

For recyclers

- Develop innovative sorting and recycling methods to recover a higher share of plastics, including the recovery of PC-ABS, PA, or PBT polymers. Exploring emerging technologies such as solvent-based recycling or pyrolysis in combination with conventional mechanical methods can enhance the efficiency and effectiveness of plastic recycling processes, enabling the recovery of a broader range of polymers and valuable substances from WEEE plastics.

- Seek long-lasting partnerships with producers to optimize the design for and from recycling. Collaboration with producers in the early stages of product design can help ensure that materials and additives selected for electronic devices are compatible with recycling processes. By working together, recyclers and producers can enhance the recyclability of WEEE plastics and promote the development of more sustainable products.

- Determine the feasibility of creating ranges or bands of material specifications, and how this could increase the available volume of recycled plastics. For example, understand what the range of specifications demanded by brands is and explore whether there is opportunity for harmonisation and what is the volume of plastics that would be impacted.

For producers

- Adopt and implement recycled content targets to boost the demand for WEEE plastic recyclates and decouple from virgin plastic prices. Setting specific demand targets for the incorporation of recycled plastics in electronic devices will incentivize producers to prioritize the use of recycled materials and contribute to the circular economy.

- Avoid imposing stricter purity levels than required by law, as this inhibits the use recycled materials. Be aware that "zero contamination" is not compatible with sourcing from secondary sources.

- Exchange knowledge and insights with WEEE plastics recyclers to understand how the choice of polymers and additives influences the recyclability of plastics. Engaging in open dialogues and information sharing with recyclers will help producers make informed decisions about material selection, considering the recyclability and environmental impact of different polymers and additives. This collaboration can lead to the design of more recyclable and sustainable electronic products.

- Assess opportunities and impact of design for recycling and with recycled content on the volume of the heavy fraction and its recovery rate (e.g., reducing the use of certain additives that hinder the recycling processes).

Notes

[1] EU, UK, Switzerland, Norway and Iceland

[2] Technical guidelines on the environmentally sound management of plastic wastes. UNEP/CHW.16/6/Add.3/Rev.1.

[3] C.P. Baldé., G. Iattoni, C. Xu, T. Yamamoto, Update of WEEE Collection Rates, Targets, Flows, and Hoarding – 2021 in the EU-27, United Kingdom, Norway, Switzerland, and Iceland, 2022, SCYCLE Programme, United Nations Institute for Training and Research (UNITAR), Bonn, Germany

[4] About 11% of all WEEE generated in Europe are exported according to UNITAR study referenced above - 6% as used EEE exports for reuse, 5% as illegal WEEE exports.

5 Haarman et al. 2020. Study on the Impacts of Brominated Flame Retardants on the Recycling of WEEE Plastics in Europe. Available under: https://www.bsef.com/wp-content/uploads/2020/11/Study-on-the-impact-of-Brominated-Flame-Retardants-BFRs-on-WEEE-plastics-recycling-by-Sofies-Nov-2020.pdf

[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.

[7] Huisman, J. et al. ProSUM Project - Final report. (2017).

[8] Wäger, P. A. et al. RoHS substances in mixed plastics from Waste Electrical and Electronic Equipment. Final Report. Environmental Science and Technology 46, (2010).

[9] Wang, F. E-waste: collect more, treat better. Tracking take-back system performance for eco-efficient electronics recycling. (2014).

[10] Bizzo, W. A., Figueiredo, R. A. & De Andrade, V. F. Characterization of printed circuit boards for metal and energy recovery after milling and mechanical separation. Materials (Basel). 7, 4555–4566 (2014).

[11] Peeters, J. R., Vanegas, P., Tange, L., Van Houwelingen, J. & Duflou, J. R. Closed loop recycling of plastics containing Flame Retardants. Resour. Conserv. Recycl. 84, 35–43 (2014).

[12] APPLiA. APPLiA Statistical Report 2017-2018. (2018).

[13] 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.

[14] Cersana. Market Study: Flame Retardants (6th ed.). (2019).

[15] Weil, E. D. & Levchik, S. V. Flame retardants for plastics and textiles: Practical applications. Flame Retardants for Plastics and Textiles: Practical Applications (2009). doi:10.3139/9783446430655

[16] Guerra, P., Alaee, M., Eljarrat, E. & Barcelo, D. Introduction to Brominated Flame Retardants: Commercially Products, Applications, and Physicochemical Properties. in The Handbook of Environmental Chemistry: Brominated Flame Retardants (eds. Eljarrat, E. & Barcelo, D.) 16, 1–18 (Springer, Berlin, 2011).

[17] 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.

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- Taverna, R., Gloor, R., Zennegg, M. & Birchler, E. (2017). Substance flows in Swiss e-waste - Metals, non-bimetals, flame retardants and polychlorinated biphenyls in electrical and electronic devices.

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- Bill, A., Haarman, A., Gasser, M., Böni, H., Rösslein, M., & Wäger, P. A. (2022). Characterizing plastics from large household appliances: Brominated flame retardants, other additives and density profiles. Resources, Conservation and Recycling, 177, 105956.

[20] For CRT screens specifically, the decline in BFR levels is most likely due to a change in the typology of appliances returning. In 2010, the CRT stream probably corresponded to a mix of 50% TVs and 50% monitors. The majority of BFR use in CRTs was in the monitors. In 2020 the CRT stream is almost solely composed of TVs.

[21] In this calculation, a value of zero was assumed for samples were PBDEs were not detected.

[22] Keeley-Lopez, P., Turrell, J. & Vernon, J. An assessment of the levels of persistent organic pollutants (POPs) in waste electronic and electrical equipment in England and Wales. ICER (2020).

[23] Strååt, M. & Nilsson, C. Decabromodiphenyl ether and other flame retardants in plastic waste destined for recycling. Project Report 5170721 (2018).

[24] Data provided by European PROs on BFR levels in "low-Br" fractions after BFR separation by WEEE plastic sorting/recycling companies, sampled and analysed in 2021-2022.

[25] Strobl, L., Diefenhardt, T., Schlummer, M., Leege, T., & Wagner, S. (2021). Recycling Potential for Non-Valorized Plastic Fractions from Electrical and Electronic Waste. Recycling, 6(2), 33.

[26] Straková, J., Digangi, J. & Jensen, G. K. Toxic Loopholes - Recycling Hazardous Waste into New Products. Arnika (2018).

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[30] C.P. Baldé, G. Iattoni, C. Xu, T. Yamamoto, Update of WEEE Collection Rates, Targets, Flows, and Hoarding – 2021 in the EU-27, United Kingdom, Norway, Switzerland, and Iceland, 2022, SCYCLE Programme, United Nations Institute for Training and Research (UNITAR), Bonn, Germany.

[31] Plastics Recyclers Europe. Technical Plastic recycling in Europe: a focus on plastics from ELV and WEEE. (2022). https://www.lifeplasplus.eu/wp-content/uploads/2022/02/LPP-DE-1_Plastics-Recyclers-Europe.pdf

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[33] https://plasticseurope.org/knowledge-hub/plastics-the-facts-2022/

34 Plastics Recyclers Europe. Technical Plastic recycling in Europe: a focus on plastics from ELV and WEEE. (2022). https://www.lifeplasplus.eu/wp-content/uploads/2022/02/LPP-DE-1_Plastics-Recyclers-Europe.pdf

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36 Ibid.

37 Oguchi M., Terazono J., Kajiwara N., Murakami S. Estimation of the Flow of Plastics Derived from Electrical and Electronic Devices and Flame Retardants Contained in Japan and the Impact of China's Import Regulations on Waste Plastics. 31st Research Presentation Meeting of Japan Society of Material Cycles and Waste Management. (2020)

38 https://www.mitsubishielectric.com/en/sustainability/environment/ecotopics/plastic_sp/greencycle/index.html

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45 European Commission, Directorate-General for Environment, Gustavsson, N., Bruijne, E., Berlinghof, T.et al., Study to support the assessment of impacts associated with the general review of Directive 2011/65/EU (RoHS Directive) – Final report, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2779/809625

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47 https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018XC0409(01)&rid=1

48 https://environment.ec.europa.eu/topics/waste-and-recycling/waste-shipments/waste-shipments-correspondents-guidelines_en

49 C.P. Baldé, E. D'Angelo, V. Luda O. Deubzer, and R. Kuehr (2022), Global Transboundary E-waste Flows Monitor - 2022, United Nations Institute for Training and Research (UNITAR), Bonn, Germany.

50 Article 1, par. A: 'Hazardous wastes are wastes that a) belong to any category contained in Annex I, unless they do not possess any of the characteristics contained in Annex III; and b) wastes that are not covered under paragraph (a) but are defined as, or are considered to be, hazardous wastes by the domestic legislation of the Party of export, import or transit".

51 https://ipen.org/sites/default/files/documents/ban-basel-fact-sheet-v2_1-en.pdf

52 Plastic waste, including mixtures of such waste, containing or contaminated with Annex I constituents, to an extent that it exhibits an Annex III characteristic (**note the related entries Y48 in Annex II and on list B B3011**).

53 Export to Iceland, Lichtenstein, Norway and Switzerland is permitted with prior written notification and consent

54 Further restrictions by the national law of the non-EU country in question may exist.

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Abbreviations

ABS	*Acrylonitrile Butadiene Styrene*
ATH	*Aluminium hydroxide*
ATO	*Antimony trioxide*
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*
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")*
PRO	*Producer responsibility organisation*
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*
UTC	*Unintended Trace Contaminants*
UEEE	*Used Electrical and Electronic Equipment*
WEEE	*Waste Electrical & Electronic Equipment*
XRF	*X-ray fluorescence*
XRT	*X-ray transmission*

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