



SUSTAINABLE
RECYCLING
INDUSTRIES

Processing of **WEEE** plastics

A practical handbook

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Authors

Andreas Bill, Michael Gasser, Arthur Haarman, Heinz Böni
Empa, Switzerland

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Solving the E-waste Problem (StEP) initiative, an independent multi-stakeholder platform for designing strategies that address all dimensions of electronics in an increasingly digitized world. StEP facilitates research, analysis and dialogue among its members drawn from business, international organizations, governments, NGO's and academic institutions around the world.



Sustainable Electronics Recycling International (SERI), a non-profit organization dedicated to creating a world where electronic products are reused and recycled in a way that promotes resource preservation; the well-being of the natural environment; and the health and safety of workers and communities.

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Introduction

When people discard their used Electrical and Electronic Equipment (EEE), different materials become available for recycling and reuse. Recycling companies process such Waste from Electrical and Electronic Equipment (WEEE) and sell the sorted materials to refining and manufacturing industries. In terms of volume, the most important of these materials are steel, aluminum and copper as well as plastics. Recovering these and some other metals is rather uncomplicated and local markets for metal scrap are generally abundant. Valorizing the plastic fraction, on the other hand, is more challenging because the different plastics need to be sorted by type. In addition, plastics containing hazardous additives should be removed and individual markets have to be identified. The purpose of this document is to provide practical information on how to recognize, process and market different WEEE plastics. It is specially oriented towards recycling companies in developing and emerging economies, where the potential for investments in advanced technologies is usually very limited.

Users of this handbook are encouraged to implement, adapt and further develop the methods and processes discussed throughout the document based on their own requirements. While utmost care has been taken to collect precise and up to date information, users should be aware that the conditions and the market of plastic recycling is changing very quickly and that the methods described should only be performed while using adequate safety equipment and processes. The authors, organizations and persons affiliated to this handbook and the sponsoring organization cannot be held liable for any losses and damages in connection with the use of the information contained in this document.

Handbook structure:



General information



Plastic identification & sorting



Potential customers & markets



Process design



Managing non-target plastics





General information

Plastics are very versatile materials. They can be hard or soft, rigid or flexible, transparent or opaque, light or heavy etc. These physical properties depend on the plastic type, but can also be influenced by chemicals and other additives. Because of their versatility and the fact that plastics are often cheaper and lighter than alternative materials (e.g. wood or metal), their presence in products is continuously increasing. WEEE recycling companies are experiencing this development at first hand, as the share of plastics in their input material has been increasing over the last years and is currently as high as 20% on average. Companies that are active in trading and processing of WEEE can benefit substantially from a successful valorization of plastics, simply because these materials represent a large amount of their input. In addition, the recovery and recycling of plastics also has important environmental benefits both through the substitution of virgin plastics in products¹, and because higher recycling rates result in less plastic waste ending up in the environment and in lower CO₂ emissions. However, there are two main challenges to WEEE plastic recycling that have to be addressed:

1. WEEE contains many different types of plastics. To obtain high quality products, the different plastic types need to be sorted before they can be further processed.
2. Plastics often contain additives, some of which are hazardous to human health and the environment. The most problematic plastic additives are Brominated Flame Retardants (BFRs) and additives based on heavy metals (mostly Pb and Cd). Plastics containing such hazardous substances need to be removed and disposed of in appropriate ways.

Plastic types

Two main groups of plastics can be distinguished by their reaction to heat. Thermoplastics soften and melt when heated and harden when they cool down again. Thermosets, on the contrary, become rigid when heated and also stay rigid after they cool down, which makes their recycling impossible. Fortunately, most plastics found in WEEE belong to the first group and can be recycled. However, with some few exceptions (e.g. ABS/PC), mixing these plastics in the recycling process has negative effects on material qualities like flexibility, hardness or durability. The key to WEEE plastic recycling is therefore effective sorting, which is challenging as more than 15 different types of plastics are present in WEEE and identifying and sorting them is not always easy. To simplify the task, plastics that are used most often in EEE can be targeted first.

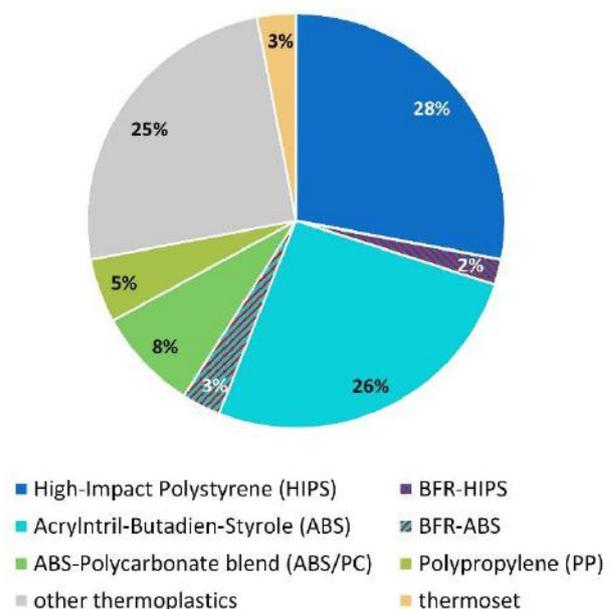


Figure 1: Main plastic types used in EEE ²

¹ A detailed life cycle assessment evaluating the environmental benefits of plastic recycling can be found in: P.A. Wäger, R. Hischer / Science of the Total Environment 529 (2015) 158-167

² Plastic composition as determined by: C. Slijkhuis, Recycling plastics from WEEE requiring a sensible and practical approach on POPs, in: Going Green Care Innovation 2018



As indicated in Figure 1, over 70% of the total mass of WEEE plastics consists of the same four plastic types, which can be collected, processed and sold in large volumes. Methods on how to identify and sort these and other plastic types will be presented throughout this document. These methods can then be further developed and adapted to target other WEEE plastics.

Plastic additives

Plastic manufacturers often use chemicals and other materials to change the properties of their products. Such additives can make plastics harder, more flexible, shinier, and heat-resistant or simply give them a certain color³. Unfortunately, the presence of some of these additives restricts the recyclability of plastics. Some of the chemicals that were used in the past, and sometimes still are today, are known to be hazardous to human health and the environment. Other additives can damage recycling equipment, or their presence reduces the quality of recycled plastics. In order to safely and successfully valorize plastics, recycling companies need to know how to detect the presence of problematic additives and how to remove and dispose of plastic fractions unsuitable for recycling.

Fillers

Plastics are mixed with low-cost filler-materials to reduce production cost. Some fillers can also make a plastic more rigid or increase its strength, toughness or heat resistance. Most of these materials are based on either minerals or glass fiber. Mineral-based fillers (e.g. calcium carbonate, talc, etc.) are, in general, unproblematic in the recycling process. Fillers based on glass fiber are used to increase the strength and resistance to bending of some plastics. Their presence can be problematic in the recycling process, especially when the glass fiber content is high.



Top: Mineral filler (CaCO_3)
Bottom: Glass fiber



Very high contents of mineral fillers can make a plastic brittle. Such brittle plastics should be sorted out as they affect product quality.



If a mechanical shredder is used to granulate plastics, it can be damaged when materials with high glass fiber content are processed.



When glass fibers are cut and shortened in the recycling process, their positive effects on strength and resistance to bending is lost, which results in reduced product quality.

Plasticizers

These chemicals increase the softness, flexibility and durability of plastics. Their main application is the production of soft PVC, which is often used as a cable insulator, but it is also possible to find them in other WEEE plastics. Some plasticizers are hazardous to human health and especially children and pregnant women should not be exposed to these chemicals.



Plasticizer used to soften PVC



Soft PVC plastics often contain high levels of potentially hazardous plasticizers and must not be used to make toys or products that come into contact with food or water.

³ For a detailed overview on plastic additives see: J.N. Hahladakis et al. / Journal of Hazardous Materials 344 (2018) 179-199



Flame-retardants

Flame-retardants are used to make plastics more resistant to fire. During their use in EEE, certain plastic parts are regularly exposed to heat, which is why WEEE plastics often contain significant amounts of flame retardants. These additives can be sorted into three main groups:

- Mineral flame retardants
- Phosphorus-based flame retardants
- Brominated Flame Retardants (BFRs)

Some flame retardants are hazardous to human health and the environment. Various chemicals belonging to the third group are persistent organic pollutants (POPs) and therefore especially problematic, which is why their use is restricted by regulatory limits (e.g. PBBs, PBDEs, HBCDD). Plastics containing BFRs therefore need to be sorted out and appropriately managed.



Flame-retardants are used to prevent plastics from catching fire when exposed to heat



High levels of BFRs can often be found in plastic housings of screens, IT-equipment and small electronic devices while BFR levels in plastics from large household appliances (e.g. fridges, freezers, washing machines, tumbling dryers etc.) are generally below legal limit values.



Different flame-retardants are used in combination with different plastic types. BFRs are mostly present in ABS and HIPS plastics. As indicated in Figure 1, around 10% of all ABS and HIPS plastics found in WEEE contain BFRs.

Pigments

The color of a plastic can be influenced by adding pigments. These are generally inorganic compounds, some of which are based on heavy metals like lead and cadmium. Heavy metals are toxic to human health and the environment and their presence in recycled products is therefore restricted by legal limit values.



Pigments are used for color



Plastics should be sorted by color during the recycling process. White and transparent plastics reach the highest market prices followed by single color fractions. Mixed color plastic fractions are generally less valuable.



Red, orange and yellow colored plastics may contain lead- or cadmium-based pigments. When the presence of these heavy metals is suspected, plastic parts should be removed from the recycling process.



Plastic identification & sorting

The first thing to do when targeting WEEE plastics for valorization is to separate the plastics from other materials. This can be done manually without difficulties. The result, however, is a fraction of mixed plastics parts, including many different plastic types of which some contain undesirable additives. In order to set up a successful business model, recycling companies need to know which plastic types are present in their WEEE input and how they can recognize and sort out the ones that they can sell.

First clues

The more information a recycling company has about its input material, the better it can design efficient sorting processes. The specific function a part had to fulfill, and the product type it was obtained from, can be used as a first source of information. Some plastics for instance are used for very specific purposes and can be identified because of this. A transparent plastic sheet obtained through the dismantling of a flat screen, for example, is almost certainly made from PMMA plastic. Other plastics are commonly used in some devices, but rarely in others, and some can be found in almost any device. Knowing where different plastics are frequently used allows to estimate how much of which type can potentially be collected from a specific input. Figure 2 shows the average plastic composition of different WEEE categories⁴. Although the input a recycling company receives is often variable, these figures can be used to make rough estimates on the plastic composition of received shipments, as well as educated guesses about specific plastic parts (e.g. a plastic housing from a CRT TV is probably made from HIPS or ABS plastic). It is important to recognize, however, that the charts represent average values and that the exact composition of a specific input can be somewhat different in reality.

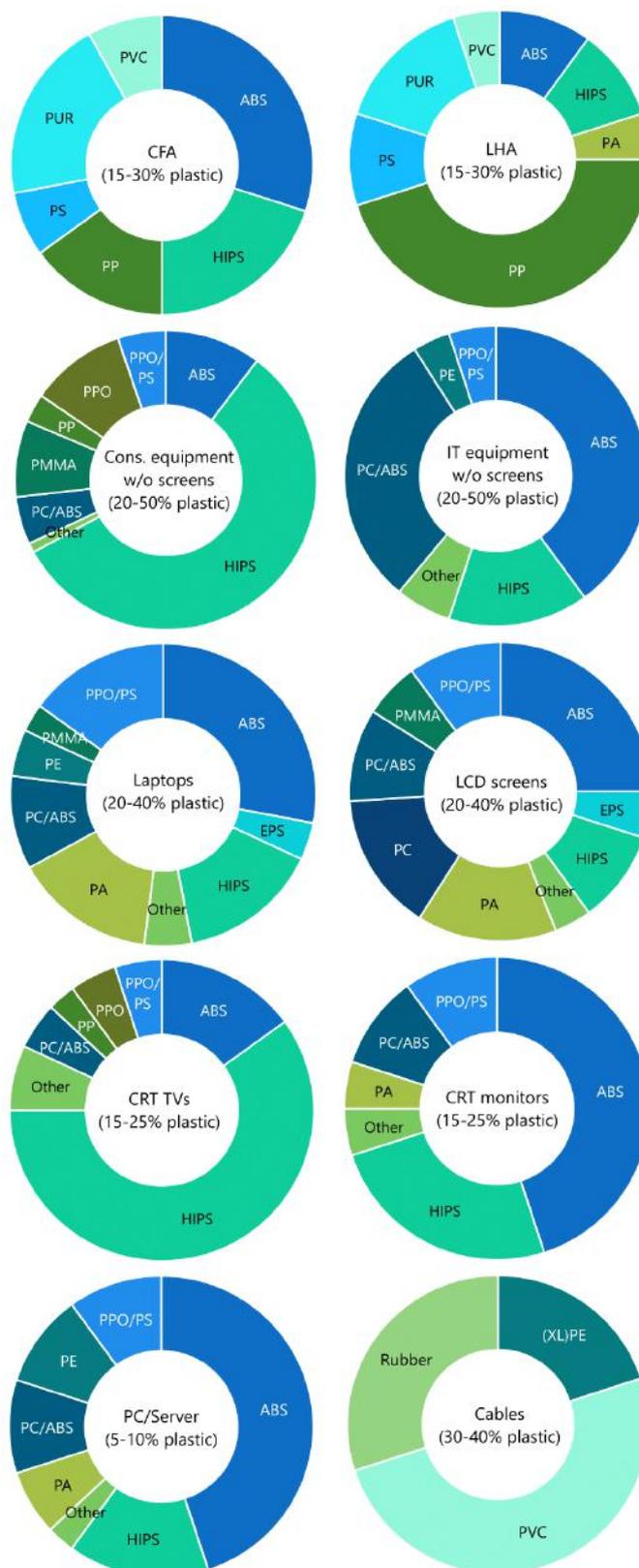


Figure 2: Average plastic composition of selected WEEE categories

⁴ Composition data based on literature (Wäger et al. 2010) and batch test analysis at Swiss WEEE recycling facilities



	ABS	HIPS	PP	PS	PE	ABS+PC	PVC
CRT screens	x	x				x	
Flat screens	x	x				x	
IT equipment	x	x				x	
Large Household Appliances (LHA)	x	x	x	x			
Cooling and Freezing Appliances (CFA)	x	x	x	x			
Small electronic devices	x	x	x				
Cables					x		x

Table 1: Hazardous additives in main plastic types obtained from various WEEE categories. Red: BFR concentration potentially above legal threshold values, blue: heavy-metal concentration potentially above legal thresholds values, black: concentrations of hazardous additives generally below legal threshold values.

The origin of a plastic part can further be used as an indicator for the potential presence of problematic additives. BFRs for instance are generally found above legal threshold values in ABS and HIPS plastics from IT equipment, screens and small electronic devices (see Table 1).

Simple methods for plastic identification

The figures and table above are useful to narrow down the list of plastic types a part might be made of and determine the potential presence of hazardous additives. However, in order to actually identify plastic types and sort plastic parts accordingly, additional methods are needed. One possibility is to use simple tests which can be performed manually and are therefore accessible to everyone.

ISO tag

According to the ISO 11469 standard, plastic parts weighing more than 100 grams should be marked with a visual identifier. These markers are sometimes difficult to find and interpret, but they can provide useful information. A complete identifier consists of 4 terms indicating the plastic type, filler materials, plasticizers and flame retardants. Figure 3 shows the correct order of a complete identifier and how it should be interpreted.

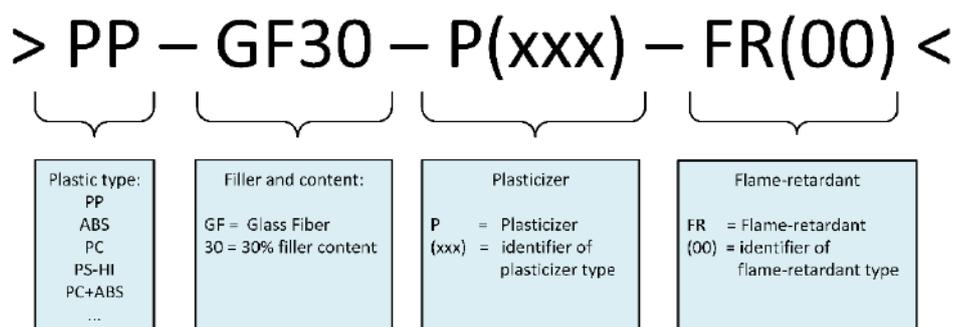


Figure 3: ISO tag interpretation

- The letters GF on an ISO tag refer to the presence of glass fiber as a filler material. This can be problematic in the recycling process. (See section 1 about additives)
- Flame-retardant identifiers 14, 15 and 18-21 may indicate hazardous BFRs. Plastic parts with these markings have to be removed and appropriately managed.
- **WEEE plastics are often unmarked, mismarked or only show incomplete tags. The information obtained from an ISO tag should therefore be used with caution.**



Sink/float test

The density of a plastic depends on its type and the presence of certain additives. It is possible to use these characteristics to separate lighter from heavier plastics. In fresh water for instance (density = 1.0 kg/l), only very light plastics float, while medium weight and heavy plastics sink. Adding salt to the water will increase the density of the solution and cause slightly heavier plastics to float as well. The density ranges in Figure 4 can be used to determine which plastics will float in a specific solution and design sink/float tests to separate plastic types of different densities. Sink/float tests require only a bucket, water and some salt. The tricky part is to produce a solution with the right density. One way to do this is to add a predefined amount of salt to the water. A solution with density 1.1kg/l for instance can be obtained by adding any of the following commercially available salts per liter of water:

- 150 grams of table salt (NaCl) or
- 180 grams of potash (KCl) or
- 110 grams of magnesium fertilizer (MgSO₄)

Alternatively, a hydrometer (see Figure 5) can be used to prepare saltwater solutions. Hydrometers float at specific levels depending on the solution density. They can be used to prepare solutions of any density based on any of the above-mentioned salts. Additionally, hydrometers can be used to monitor the solution during its use in sink/float tests. This is particularly useful because the solution density can change with temperature and due to the introduction of dirt and other foreign material. Continuously monitoring and adjusting the density (by adding more salt or water) leads to better results in plastic separation. Inexpensive hydrometers can be found on online marketplaces.

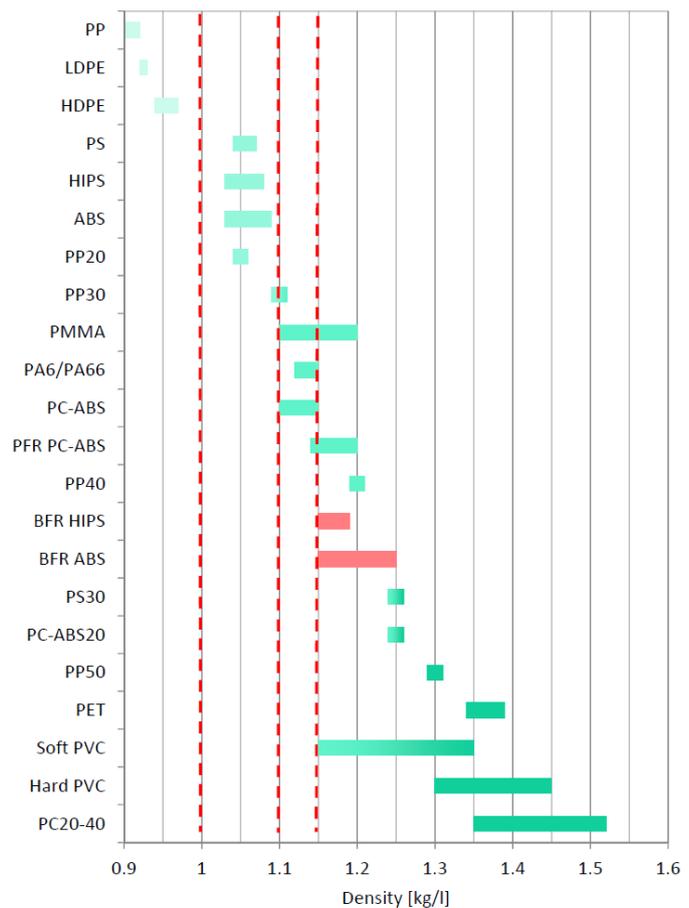


Figure 4: Density ranges of WEEE plastics



Figure 5: Hydrometer



Figure 6 shows two practical applications for sink/float tests that are particularly useful in the case of WEEE plastics. They can be used to target the main WEEE plastics and to separate BFR-containing from BFR-free fractions. Based on the plastic density ranges in Figure 4, these processes can also be adapted and further developed in order to target other plastic types.

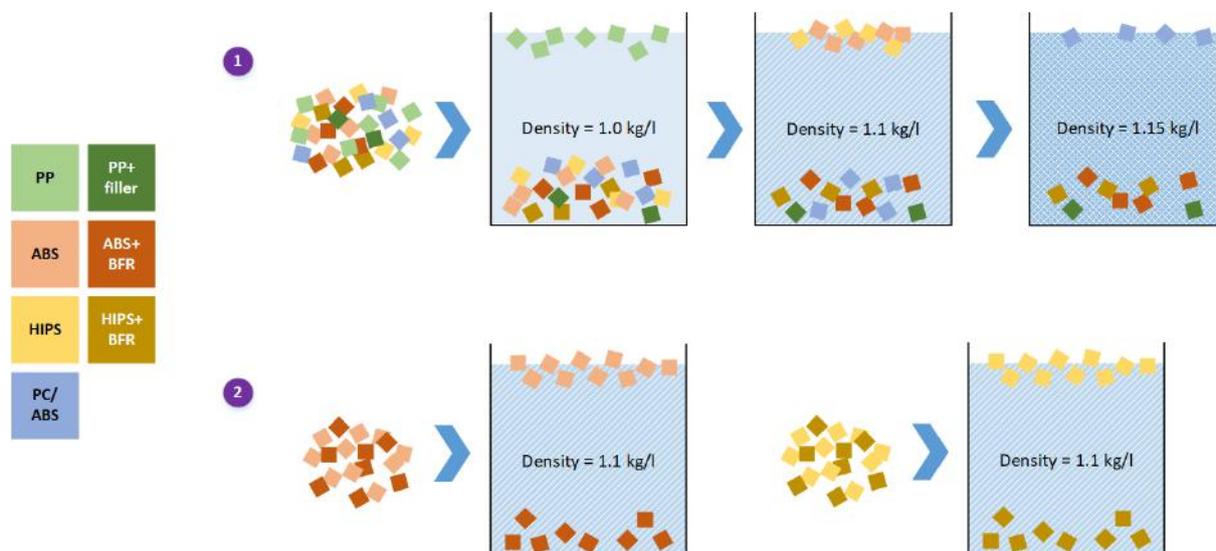


Figure 6: Practical applications of sink/float tests for sorting of WEEE plastics

Application 1: Density cuts for WEEE plastic sorting

Three density cuts can be used to identify and separate the main WEEE plastics:

- **fresh water (density = 1 kg/l):**
If the plastic floats in fresh water, it is either PP or PE. Because PE is rarely present in WEEE, it can be assumed that floating plastics are mainly PP.
- **salt water solution 1 (density = 1.1 kg/l):**
Plastics which sink in fresh water but float in the first salt water solution are likely ABS or HIPS, since these are the main WEEE plastics with densities between 1.0 kg/l and 1.1 kg/l.
- **salt water solution 2 (density = 1.15 kg/l):**
WEEE plastic parts that sink in the first salt water solution but float in the second one are generally ABS/PC, as this is the main WEEE plastic in this density range.

Application 2: Identification and removal of BFR-plastics

A solution with density 1.1 kg/l can be used to separate BFR-containing ABS or HIPS from BFR-free ABS or HIPS. The presence of BFRs increases the density of these plastics as can be seen in Figure 4. BFR-containing ABS and HIPS therefore sink in this solution while BFR-free plastics float.

When sink/float methods are used to test specific plastic parts, a piece of the part in question can be cut off and tested in a small bucket. This kind of testing requires only little amounts of salt and water. However, efficient and systematic sorting of plastic fractions based on sink/float processes is only possible with input material that has been shredded or otherwise reduced in size. In addition, much larger containers and higher amounts of salt and water are required to implement such applications.



Testing physical properties

Another way to obtain information and potentially identify plastic types is the testing of physical properties like hardness, breaking behavior or the reaction to specific solvents. Experienced dismantling and sorting workers can make educated guesses based on the origin of a plastic part and then verify their guess using such simple tests. With proper training and practice, good separation rates can be achieved with this methodology.

Reaction to solvents

Not all plastics react in the same way to solvents. The following tests are based on commercially available and non-hazardous solvents and can be used to identify certain plastic types.

- Limonene is a naturally occurring solvent found mainly in the skin of certain plants and fruits including lemons and oranges. Only PS and HIPS react with limonene. When a few drops of limonene are applied to these plastics, they dissolve slowly and become sticky after 2-3 seconds.
- Acetone is another commercially available solvent. It is less selective than limonene and reacts with PS, HIPS, ABS, ABS+PC and PC. When acetone is applied to PS, HIPS or ABS, the plastics dissolve and become sticky after 2-3 seconds. ABS/PC also becomes sticky, but a white deposit additionally forms due to the presence of PC. In the case of pure PC, only the white deposit forms but the plastic does not become sticky.

- Acetone can usually be bought at drug- or hardware stores.
- If pure acetone cannot be found, nail polish remover can serve as a substitute since acetone is its main ingredient.
- Limonene is less widely available. It is, however, often sold in 3D-printing shops and can also be found on online marketplaces.

Flexibility/breakability

A simple break-test helps to distinguish certain plastics. PS, for instance, is rigid and breaks easily. HIPS bends and will show white marks at the rupture, but it is difficult to actually break apart.

Hardness

Some plastics are harder than others. PE is quite soft and shows marks when scratched with a fingernail. PP is harder and therefore more difficult to scratch.

Sound when hit

Plastics sound distinctive when hit. Since sounds are difficult to describe, it is best to try this out by oneself with plastics of known type. This kind of testing works best with larger pieces (e.g. entire casings).



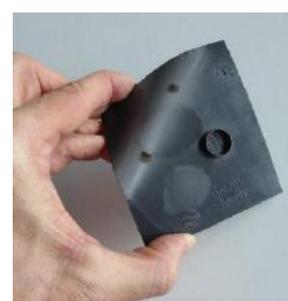
Sticky reaction to solvents



White deposit due to the reaction of acetone with PC



Broken PS



Bent HIPS



Scratched PE



Systematic plastic identification

Through studying the informal plastic recycling sector in India, the Swiss Federal Laboratories for Materials Science and Technology (Empa) developed a methodology to systematically identify the main WEEE plastic types and detect the presence of BFRs⁵. This methodology, shown in Figure 7, is based on the previously described testing of physical properties and sink/float methods. While it would be inefficient to apply full testing on every piece of plastic in an industrial process, the methodology can be used to identify specific plastic parts and thus gain information about the input material. In addition, it can serve as a useful tool to train dismantling and sorting workers on how to recognize the main WEEE plastic types. With experience, these simple tests only have to be performed from time to time while most plastic parts can be sorted efficiently and with good separation results without extensive testing.

1. Limonene test

The limonene test can be used first to recognize PS and HIPS plastics.

2. Break test

A break test allows to further distinguish between PS and HIPS. PS breaks easily while HIPS bends and white marks appear at the rupture.

3. Acetone test

Plastics that did not react with limonene are tested with acetone. ABS, ABS/PC and PC can be distinguished based on their reaction to acetone as indicated in Figure 7.

4. Sink/float test in fresh water (1.0 kg/l)

A sink/float test in fresh water is applied on the remaining plastics. The floating fraction consists of light plastics (PP and PE). Plastics that did not react to any of the solvents and sink in fresh water are none of the main WEEE plastics and are not identified with this method.

5. Scratch test

PE and PP plastics float in fresh water. In general, floating pieces are made of PP, as PE is not often present in EEE. To make sure, a scratch test can be used. PE is softer and can easily be scratched with a fingernail. PP is harder and it is more difficult to leave scratch marks on PP.

6. Sink/float test in salty water (1.1 kg/l)

Some of the ABS and HIPS plastics, previously identified using solvents, contain hazardous BFRs and have to be removed. This can be achieved using a sink/float test in salty water. When BFRs are present, the plastic is heavier and sinks in salty water with a density of 1.1 kg/l. BFR-free ABS or HIPS on the other hand will float in this solution.

⁵A. Haarman & M. Gasser, Managing hazardous WEEE plastic additives in the Indian informal sector, 2016

Web link: <https://www.dora.lib4ri.ch/empa/islandora/object/empa:18490>

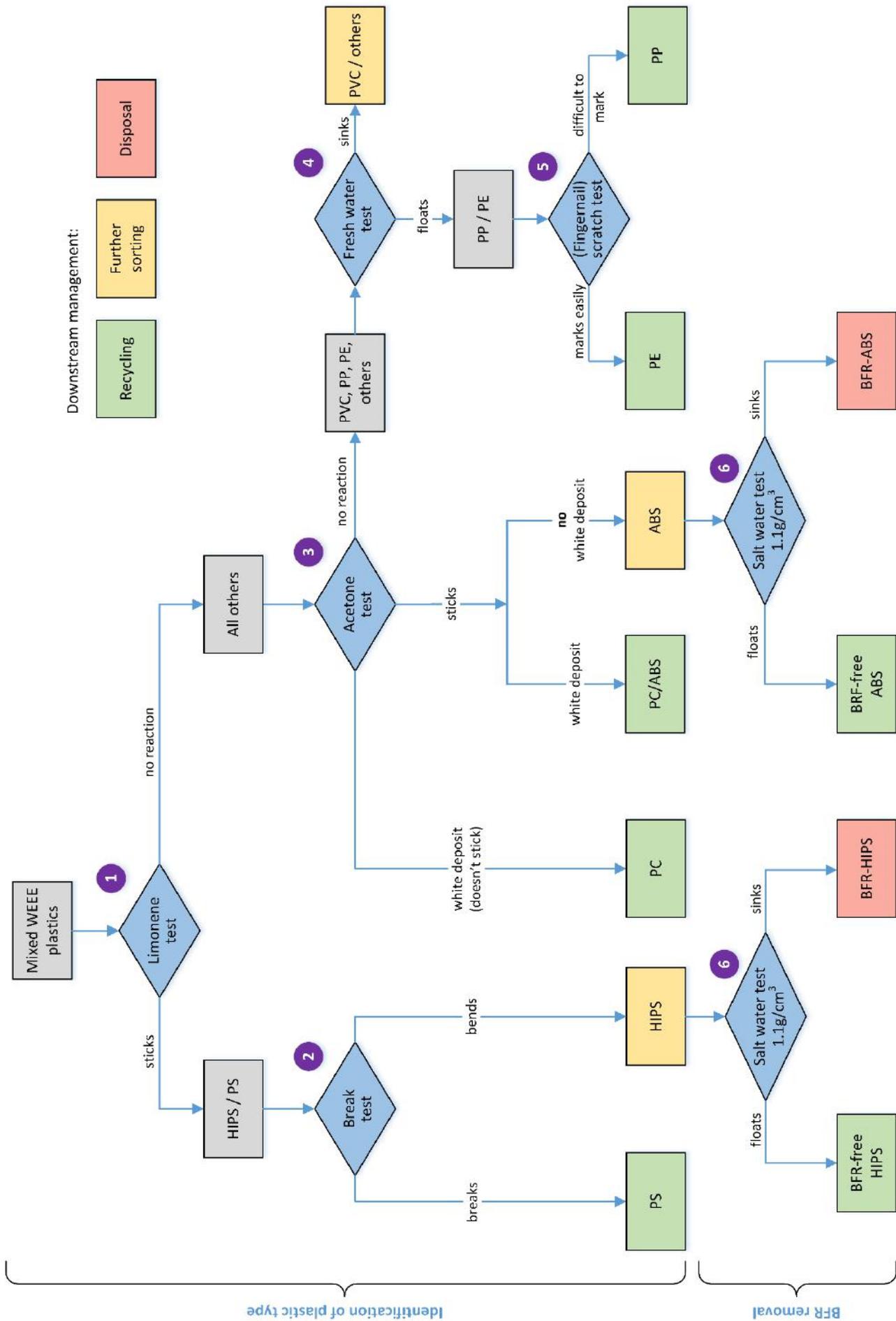


Figure 7: Systematic identification of WEEE plastics (Source: Empa 2016)





Advanced identification & sorting technologies

When throughputs are low or inconsistent, purely manual sorting based on the previously introduced methods is often the best choice. However, if a company processes large amounts of input material on a regular basis and has access to the required financing, the use of advanced identification and sorting technologies can become economically interesting. This is especially the case in settings where labor costs are high, since the use of such technologies results in a less labor intensive sorting process.

Handheld devices for identification

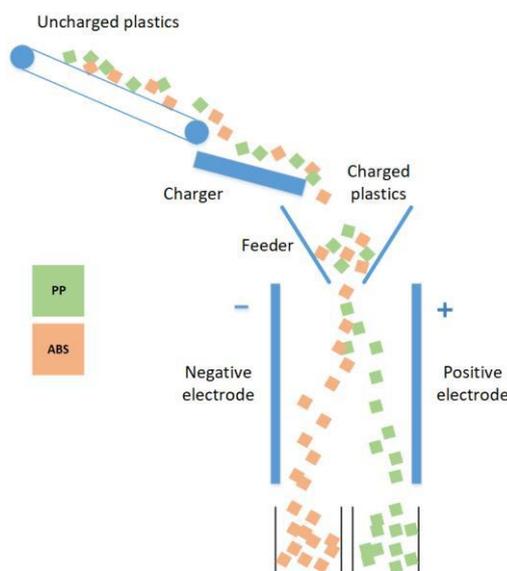
There are various handheld devices available which can identify the plastic type and/or the presence of hazardous additives. Different technologies exist with sensors based on laser beams (LIBS), x-ray (XRF) and near-infrared waves (NIR). These devices are costly, can break easily and require training to be used, but they are efficient and precise and can identify many different plastics and additives.



Handheld plastic identification device

Semi-automated identification and sorting

Plastics react differently to electrostatic charging. Electrostatic separators use this to sort plastics automatically. These separators can often process more than 1000 kg of plastics per hour. They require, however, a pre-sorted input (i.e. best results are achieved with only two plastic types as input) which is homogeneously sized (i.e. plastics have to be shredded in advance). Electrostatic separators require a certain amount of operating space and incur continuous operation costs due to power consumption. Investing in such a device only makes sense if constant and high throughputs have to be processed. This technology is also sensitive to moisture and certain salts. When combining sink/float methods with electrostatic separation, table salt (NaCl) and potash (KCl) should not be used and only well dried material should be fed into the machine.



Electrostatic plastic separation

Fully automated identification & sorting

Fully automated processing lines combine various technologies (e.g. optical sensors, XRT technology etc.) which allows automatic sorting of plastics by type, color and additive content. Such an installation is highly efficient but also very expensive and should only be considered in situations where the cost for manual sorting is very high and financial means are sufficient to cover the large investment.



Fully automatic plastic sorting line



Potential customers & markets

After determining which plastics can be obtained from a certain input and how these plastics can be recognized and sorted, recycling companies need to identify markets for their outputs. A range of potential customers exists, from small local plastic processors to large international manufacturing firms. Not every industry is interested in the same plastics, and not every customer prefers the same level of pre-processing. Some will be happy to take mixed plastic fractions directly, others will ask for complete housings of specific plastic types, and still others will want pure and shredded fractions, or even extruded plastic pellets. Before deciding which processes to implement, recycling companies should investigate which products they can sell best and define their business model accordingly.

Sector specific use of plastics

Due to the differences in their physical properties (strength, flexibility, hardness etc.), the demand for specific plastics depends on the industry sector. A good place to start is therefore to contact producer associations of industries where the plastic a recycling company intends to sell is commonly used. The administrators of such organizations can often provide information about which of their members might be interested in buying specific plastic fractions. Evidently, one industry that can potentially process any WEEE plastic type is the EEE-industry which should therefore be contacted first.



The EEE industry can process all types of recycled WEEE plastics

Other industries that might buy WEEE plastics are shown in Figure 8 together with the plastic types each sector might be interested in. Plastics from WEEE should not be sold to industries making toys or products that come into contact with food and water. Although some of the plastics containing hazardous additives can be separated, 100% removal of these substances is practically impossible. When recycled WEEE plastics end up in toys or products such as food packaging or jerry cans used to carry drinking water, users are exposed to remaining contaminations which poses a health risk.



Figure 8: Plastic types used in different industry sectors



Pre-processing requirements

The amount of pre-processing that should optimally be applied depends on customer preferences. While every additional step adds value to the final product, investments into pre-processing only make sense as long as there is market demand for the obtained product. Before investing into a technology, recycling companies should therefore collect information about customer requirements and the prices that can be obtained for different products.

Entire casings

- **Mixed:** Plastic recycling companies might be interested in buying dismantled WEEE plastics as a whole and then sort and process the material themselves.
- **Hand-sorted:** SMEs that produce plastic parts can often pre-process plastics themselves because they have to deal with scrap that accumulates during the manufacturing process in any case (faulty products, leftovers from the manufacturing process etc.). These manufacturers might not want to pay higher prices for processed plastic flakes and will rather buy entire casings of specific plastic types.

Plastic flakes

- **Mixed & dirty:** Plastic recycling companies which have the equipment to sort mixed plastic flakes might buy such a fraction.
- **Sorted & dirty:** SMEs that produce plastic parts with low quality requirements (fence posts, chairs etc.) will sometimes use sorted but unwashed plastic flakes directly in their manufacturing process. Other potential buyers of sorted plastic flakes might be plastic recycling companies specialized in refining plastic flakes to extruded and compounded secondary plastic pellets.
- **Sorted & clean:** Manufacturers who produce higher quality products, but can deal with plastic flakes instead of extruded pellets, will want to buy pure and clean flakes.

Extruded plastic pellets

International brand plastic manufacturers require, in general, extruded and compounded secondary plastic pellets of high quality. When plastic pellets are sold, a feedback-loop should be kept with the buyer to continuously improve the compounding formula and quality of the supplied product.

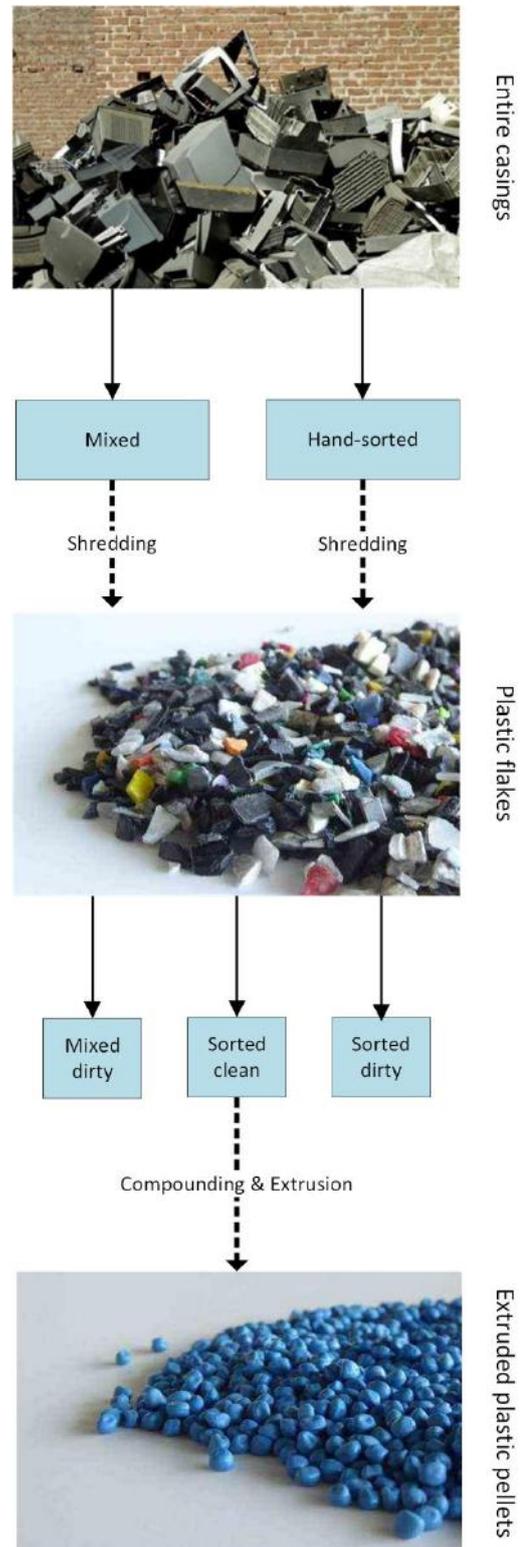


Figure 9: WEEE plastic pre-processing



Laws & regulations

In some countries there are many small and big plastic manufacturers processing almost any kind of plastic. In others, the markets for recycled plastics are very narrow and recycling companies might consider exporting some of their products. In both cases, there are laws and regulations which have to be considered. These laws and regulations determine limit values for hazardous substances in plastics (BFRs and heavy metals) and regulate their export and trade. It is in every company's best interest to make sure that their products are legally compliant, because this will allow them to reach better markets on the national and international level. Using simple methods such as the ones described earlier (manual pre-sorting and sink/float separation), the levels of hazardous substances can, in general, be reduced below the currently defined legal limit values with reasonable effort.

National laws & regulations

National laws and regulations on hazardous additives in recycled plastics may vary between countries. Information on such regulations and the currently applying legal limit values can be obtained from the national ministries of environment or industry.

International standards and treaties

Various international standards define limit values for hazardous substances in plastic products and regulate exports and trade of hazardous plastic fractions.

Limit values: EU-regulation: Restriction of Hazardous Substances Directive (RoHS)⁶

- 1000 ppm (0.1%) limit value for various BFRs (PBBs & PBDEs)
- 1000 ppm (0.1%) limit value for various heavy metals (Pb, Hg, Cr)
- 100 ppm (0.01%) limit value for cadmium (Cd)

European WEEE treatment standard series EN/TS 50625⁷

- 2000 ppm (0.2%) limit value for total bromine

Trade: The transboundary movement of hazardous wastes (including WEEE plastics) is regulated by the Basel Convention.⁸

- After January 1st 2021, exports of mixed plastic fractions (with the exception of PE, PP, PET mixtures) require the Prior Informed Consent (PIC) procedure⁹. This procedure states that before an export shipment containing hazardous substances can leave the country of origin, permission has to be granted by the country of destination.
- PIC procedures complicate exports and often make them impossible. These complications can be avoided by only exporting pure plastic fractions with hazardous additive contents below international standard levels.
- In the case of PVC, even pure fractions will be subject to the PIC procedure. This is due to the fact that PVCs are halogenated plastics, often contain heavy metals as heat stabilizers or in the form of pigments, and are therefore considered as hazardous.

⁶ More information available on the website: https://ec.europa.eu/environment/waste/rohs_eee/legis_en.htm

⁷ The European WEEE treatment standard is developed by the European Committee for Electrotechnical Standardization CENELEC. More information available on the website: <https://www.cenelec.eu/>

⁸ More information available on the website: <http://www.basel.int/>

⁹ More information available on the website: <http://www.pic.int/Procedures/PICProcedure/tabid/1364>



Process design

After determining their target products based on input and market analysis, recycling companies need to design processes to efficiently sort out and process their target plastics according to market requirements. Various factors, such as the availability of input material, the company's financial means, local labor costs, etc., will determine which processes can be implemented cost-efficiently. The optimal process design is the one which leads to the required product quality (purity, removal of undesirable additives) and state (housings, granulates, pellets) at the lowest cost.

Manual pre-sorting

Dismantling- and sorting staff can identify and sort many plastic parts based on experience and occasional testing. A well-trained team of sorting workers will reach high separation rates with purely manual pre-sorting, which might already suffice for certain customers. Even if density separation or advanced sorting technologies are used later on, manual pre-sorting can improve the achieved separation efficiency significantly. Furthermore, sorting plastics by color can be done most efficiently before any size reduction is applied and will result in higher market prices for the obtained single color fractions. At this stage, it can also be considered to use handheld identification devices to improve the detection potential for problematic additives and simplify the identification of plastic types. However, it should be kept in mind that such devices are costly and require regular maintenance.

Baling

When complete housings are to be sold or transported to other facilities, recycling companies might consider buying a hydraulic press to bale such fractions for easy transport. The significant reduction of volume will reduce both transportation cost and the required storage space.



Baling machine

Size-reduction

Unless the intended final output consists of complete housings, size-reduction is required for further processing of WEEE plastics. Applications such as sink/float separation as well as advanced sorting technologies require inputs of similar and relatively small size. In addition, reducing bulky plastic housings to smaller sized pieces also leads to a reduction in volume and therefore savings in storage space and transportation cost. This size reduction can easily be accomplished using a plastic shredder which will produce uniformly sized flakes of 3 to 8 mm depending on the model. Plastic shredders of varying sizes and throughputs are available on online marketplaces.



Plastic shredder

- Size reduction is often a necessary requirement for further processing steps and reduces transportation cost and the required storage space.
- Plastic shredders are useful to process large volumes as even small shredders generally have throughput capacities of 100-200 kg / hour. Such high throughputs are in general not required for small recycling companies. It might therefore be interesting to share one shredder between several companies in order to reduce individual investment, maintenance and operation costs.
- Depending on labor cost, a viable alternative to shredding may be to cut plastics into smaller pieces by hand (e.g. using machetes, hatches or shears).



Sink/float separation

The sink/float separation methods introduced in the section on plastic identification can be developed into full scale sorting of shredded plastic flakes. If ABS and HIPS plastics were pre-sorted beforehand, sink/float separation can be used to efficiently remove BFR-containing plastics from these fractions. Another possible application is to separate mixed, shredded plastics into different density cuts to be further processed with advanced sorting technologies (e.g. electrostatic separation). The following density cuts could be used for such an application:



Sink/float process with plastic flakes

- density < 1kg/l: PE and PP
- 1kg/l < density < 1.1kg/l: Mainly BFR-free ABS and HIPS with some PS and medium filled PP
- 1.1kg/l < density < 1.15kg/l: Mainly PC/ABS with some heavily filled PP
- 1.15 < density: BFR-containing HIPS and ABS, PVC, other heavy plastics

Washing

WEEE plastics often contain foreign material such as dirt or glue residues from stickers. In general, product quality will improve if these impurities are removed in a washing step. A basic solution (e.g. based on caustic soda) should be used and waste water disposed of through an industrial sewage system. Simple techniques such as a settling tank can be used to re-use the water as much as possible and keep operating costs low.

Automated sorting based on advanced technologies

Semi-automated or fully automated sorting technologies are often used in industrialized countries where labor costs are too high to justify manual sorting processes. If high throughputs, stable markets and the financial means to invest in such equipment are available, the use of technology-based sorting processes might be considered.

Compounding and Extrusion

If a market for high quality secondary plastic pellets exists, recycling companies might consider implementing this final processing step to further increase the value of their products. Pure and clean plastic flakes are mixed with new additives based on customer requirements (compounding) and fed into an extruder where the plastic is heated and pressed into homogeneous and uniformly sized pellets.



Plastic extruder in a recycling facility

Laws and regulations

Plastic recycling is an industrial activity and as such is subject to local laws and regulations. The processes a company implements will determine which laws and regulations apply to its business. If only manual activities such as dismantling and manual sorting are performed, the legal requirements for a company might be different than when equipment such as shredders or electrostatic separators are used. A company should always investigate which laws and regulations apply to their planned activities and act respectively (e.g. obtain the required licenses for their business).



Managing non-target plastics

Once the target plastics have been sorted out, processed and sold, the non-target plastics and hazardous fractions are left. Recycling companies need to find environmentally sound solution for these left-over materials and make sure that worst practices such as uncontrolled dumping and open burning of plastics are avoided.

Viable solutions for non-hazardous plastics

There are various possibilities to further valorize, if possible, or dispose of non-hazardous plastic fractions for which no specific market can be identified. As a general rule material valorization should be prioritized, followed by thermal valorization and controlled landfilling.

Recycling

Not every recycling company focuses on the same plastic types and it is possible that some of the non-target plastics of one company could be further processed by another. Although good prices might be difficult to achieve since some of the marketable plastics have already been removed, further recycling is always the best solution for non-hazardous plastics.



Recycling



Downcycling

Downcycling

Although the recycling of mixed plastic fractions results in low material quality, some manufacturers might be interested in buying mixed plastics at low prices to be used in the manufacturing of products with low quality requirements such as wood-plastic composites, plastic chairs, fence posts or others.

Filler material in infrastructure

Waste plastics can potentially be used as fillers in construction materials such as concrete or asphalt. Although this application results in a loss of the plastic for further recovery and recycling, it does provide environmental benefits through the substitution of raw materials necessary for the production of these construction materials.



Filler material in infrastructure

Controlled incineration

Plastics have a high calorific value and important amounts of heat are released when plastics are burnt. This heat energy can be recovered either for the purpose of energy-generation in waste incineration plants, or by using plastic as alternative fuels in energy-intensive industries such as metal smelting and brick- or cement manufacturing. The burning of plastics leads to the release of toxic fumes containing dioxins and furans, which are hazardous to human health and the environment. Plastic incineration can therefore only be considered as a good practice if adequate emission control and air treatment measures are in place. As a result, the environmental viability of plastic incineration is variable and has to be assessed for each individual solution.



Controlled incineration

Controlled landfilling

If no other viable solution is found, landfilling can be considered. Because the presence of plastics increases the risk of fires in landfills and dumpsites, only controlled landfills (e.g. hazardous waste- or sanitary landfills) with proper management should be considered where care is taken to prevent fires.



Controlled landfilling



Viable solutions for hazardous plastics

Best available techniques (BATs) regarding the management and disposal of hazardous fractions are often defined on an international or country level¹⁰. However, in many regions of the world these BATs are not accessible because the required infrastructure, e.g. hazardous waste incinerators or hazardous waste landfills, simply does not exist. Identifying the best alternative solutions is often challenging as long term impacts of such suboptimal solutions are difficult to evaluate and compare.

Hazardous waste incineration

Incineration at very high temperature (around 1100°C) destroys hazardous organic substances including BFRs. Hazardous waste incinerators operate at these temperatures and apply state of the art emissions control in order to remove toxic fumes and heavy metals. At present, the incineration of plastics containing substances such as BFRs and heavy metals in hazardous waste incinerators is considered BAT.



BAT incineration

Hazardous waste landfill

Hazardous waste landfills are equipped with specific control mechanisms to keep hazardous substances from dispersing into the environment. Such landfills often have separate compartments, are equipped with impermeable liners and a leachate collection systems and should be properly managed. Hazardous waste landfills provide a viable disposal solution for BFR and heavy metal containing plastics.



Hazardous waste landfill

Filler material in infrastructure

The use of plastics containing hazardous substances as fillers in construction materials can be a viable alternative to BAT incineration or landfilling. The requirement is that hazardous substances are stabilized (i.e. do not leach out over time) within the infrastructure (e.g. road paving).



Filler material in infrastructure

Recycling and downcycling

Recycling BFR-containing plastics into products which require flame retardancy, or downcycling hazardous plastic fractions into products in which the toxic substances are stabilized, can be the most viable solution in regions where BAT incineration or landfilling is not accessible. If hazardous plastics are recycled or downcycled due to lack of access to better solutions, it has to be made sure that these plastics are only used in products with long-term use and minimal human exposure (e.g. plastic beams used in construction).



Recycling & Downcycling

Non BAT incineration

Incinerating BFR-containing plastic fractions or PVC in non-BAT incinerators or as alternative fuels can lead to various issues. Due to the flame retardant effect of halogens, incomplete combustion is often a problem when temperatures are not sufficiently high, and complete destruction of the organic pollutants is not achieved. Additionally, acid gases (HCl and HBr) are formed which are corrosive and can damage the infrastructure where the plastic is incinerated. These corrosive effects are especially problematic when halogen



Non BAT incineration

¹⁰ BAT guidance for plastics containing PBDEs (a group of restricted BFRs) can be found here: <http://chm.pops.int/Implementation/NIPs/Guidance/GuidanceonBATBEPfortherecyclingofPBDEs/tabid/3172/>



levels are above 1%, which is often the case for brominated plastics and PVC. If such a solution is nevertheless chosen to dispose of hazardous plastic fractions, only small amounts should be incinerated at a time to keep concentrations of acid gases low. Additionally, flue gas treatment (dry or semi-dry scrubbing with basic absorbents) should be in place to remove acid gases. The amount of POPs that are released to the environment when non-BAT incineration is applied can be highly variable and depends on the combustion temperature and emissions controls (e.g. dioxin abatement measures) in place. Using hazardous plastics as alternative fuel in a modern cement kiln operating at high temperatures might be close to BAT in terms of impacts. Incineration of the same fraction in an old metal smelter without emissions control on the other hand would be little better than open burning.

Sanitary landfill

A standard sanitary landfill is equipped with an impermeable liner and a leachate control system and landfilling in such an installation can be considered a viable solution for hazardous plastic fractions. However, when these controls are missing or substandard, hazardous substances can disperse into the environment. Although better than uncontrolled dumping and open burning, the disposal of hazardous plastic fractions in substandard sanitary landfills should be avoided.



Sanitary landfill

Finding the best available solution

In many regions of the world there are few or no established solutions for waste plastics and fractions that cannot be sold often end up being dumped or openly burnt. Plastic recycling companies therefore need to be pro-active in identifying the most viable solution in their local context. A good first step is to verify which of the before mentioned infrastructures (landfills, incinerators) and industries (plastic recyclers, plastic manufacturers, metal- brick- and cement-industry) exist on a regional or national level. Once potentially available solutions have been identified, they need to be evaluated regarding environmental, legal and financial viability.

Environmental viability

Figure 10 indicates where different solutions are situated in relation to their environmental viability. A distinction has to be made between solutions for hazardous and non-hazardous plastic fractions. The figure can be used to compare different solutions. However, it should be kept in mind that the actual environmental and human health impacts depend on many factors and can be highly variable.

Legal viability

Before a specific solution is implemented, the local environmental authority should be consulted in order to verify existing laws and regulations regarding the chosen solution.

- Recycling companies should always try to identify and implement the best, economically feasible solution for non-target plastic fractions to protect the society and the environment.
- The implemented solutions should respect local laws and regulations.
- Plastics shall not be dumped in the environment. They will not degrade for hundreds of years.
- Open burning of plastics releases toxic fumes and harms both people and the environment. This worst practice has to be avoided at all cost.

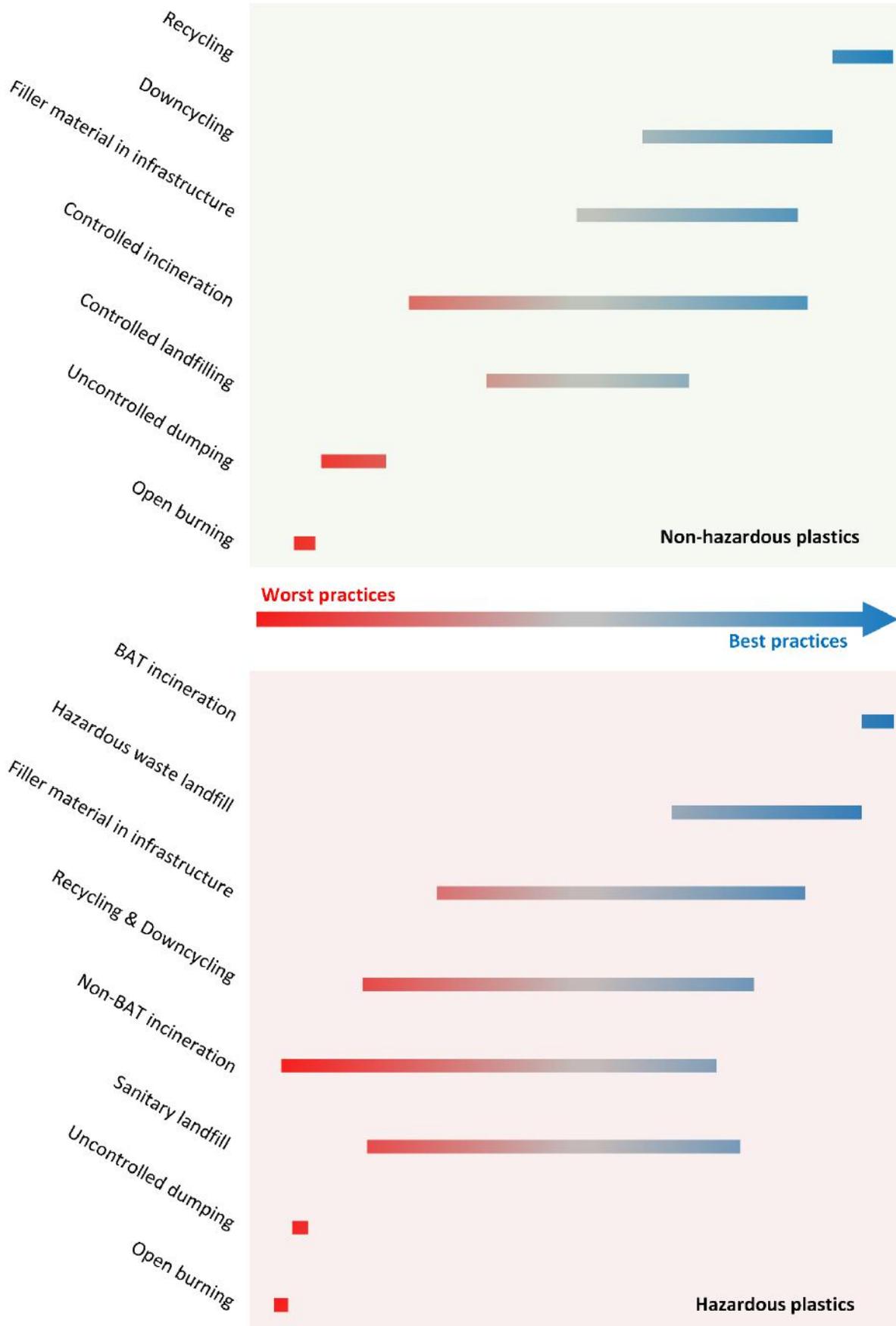


Figure 10: Environmental viability of management solutions for non-target plastic fractions