Downstream Technology Option for E-waste Recycling

GIZ E-Waste Programme Ghana
LOT 2: Recycling chains, business models, and capacity development

November 2019

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Accra, November 2019

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Acknowledgments:

This document is mainly based on the VDI guidelines on recycling of electrical and electronical equipment (parts 3, 4 & 5), the Dismantling guide for IT equipment by Schluep et al. (2015) and the UNEP report "Recycling - From E-Waste To Resources, Sustainable Innovation and Technology Transfer Industrial Sector Studies" written by Schluep et al. (2009).

In its structure this document tries to follow the structure outlined by the VDI guidelines.

1 Introduction

In support of the stakeholder process lead by the Ministry of Environment of Ghana (MESTI), this report presents an overview of downstream technology options for Ghana. The report aims to provide support to the implementation of the Ghanaian Hazardous and Electronic Waste Control and Management Act (Act 917). It should serve as a reference book, providing technology background information covering all parts of the e-waste value chain from collection to transport, manual and mechanical processing as well as refining and disposal.

Technological details are given for the categories "Screens & Monitors", "Lamps", "Large equipment" and "Small equipment and small IT and telecommunication equipment". An overview of further (mechanical) processing and refining technologies of output material is given for cables, printed wiring boards lamps and other relevant fractions.

It also should be noted that this report Should be seen as a supporting document for two additional reports, which were handed out to the Ministry of Environment, Science, Technology and Innovation (MESTI) by the GOZ e-waste programme for Ghana:

(i) The report "Operationalization model for an optimal recycling system in Ghana", which present a consolidate analysis of discussions and decisions related to the operationalization of Act 917.

(ii) The report "Business cases for selected recycling technologies in support of an optimal recycling chain in Ghana", which provides a financial assessment of different e-waste categories with data specific to Ghana, and as a basis for the financial viability of e-waste recycling technology options for Ghana.

2 The recycling chain

The recycling chain for WEEE consists of three main subsequent steps: i) collection, ii) pre-processing and iii) end-processing (incl. refining and disposal). For each of these steps specialized operators and facilities exist. The material recovery efficiency of the entire recycling chain depends on the efficiency of each step and on how well the interfaces between these interdependent steps are managed. If for example, for a certain material the efficiency of collection is 50%, the combined pre-processing efficiency is 70% and the refining (materials recovery) efficiency is 95%, the resulting net material yield along the chain would be only 33%.

The pre-processing step involves receiving whole appliances from collection and transport activities and may include manual and mechanical processing. At the manual processing step (manual dismantling) appliances are broken down into fractions and further into materials through mechanical processes and refining (see *Figure 1*). Manual processing is crucial for the purpose of depollution of appliances and fractions, separating hazardous from valuable materials respectively.

In this report steps following manual dismantling are considered downstream options. This includes mechanical processing, that can serve as a pre-processing or end-processing step, as well as refining, which is always an end-processing step. Refining usually entails technologies with high investment requirements, such as for large integrated smelters and is subject to an international market.

Depending on various factors, such as the size and economic development status of the country, volumes of e-waste, access to technologies and investments, etc. downstream options can be found on local, regional or international level. Typically, and also in the African context, downstream infrastructure can be found on local or regional level for some plastics and base metals, such as iron, steel and aluminium. Infrastructure for the further treatment of hazardous fractions is often missing locally and solutions need to be found either in neighboring countries or at the international level.

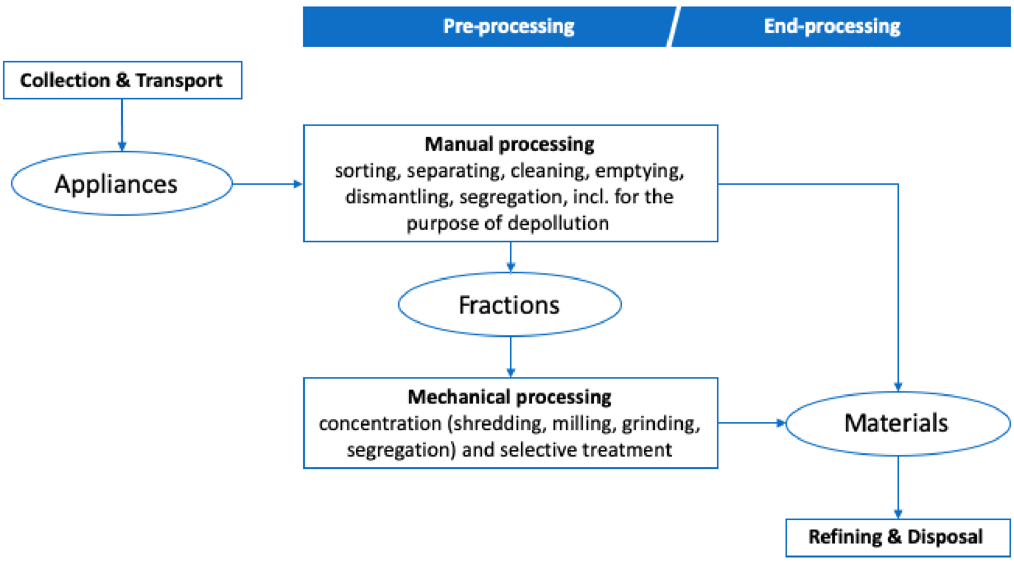


Figure 1: Schematic overview of the key processes in the recycling chain.

2.1 Collection & Transport

The first step in the recycling chain for WEEE is the collection and subsequent transport of waste material.

Collection is of fundamental importance for all WEEE collection groups as it determines the amount of WEEE that enters the recycling chain. When discussing collection systems and recycling technologies, it is crucial to include social and societal factors, as they are key to a high collection rate. Other factors influencing the collection rate are legal conditions, such as extended producer responsibility, if well implemented contributes to a higher collection rates. Generally, investment and technology requirements are low on this level of the recycling chain. Typical means for collection includes specific collection points, designated companies specialized in collection and informals engaged in waste picking.

The type of transport depends on the collection group. For example, lamps, CRT screens and monitors or refrigerators must be transported with more care than small, telecommunication and IT equipment due to the risk of leakage of hazardous substances.

Generally, WEEE should be safely separated from other waste and sorted in collection groups. Separated components should be transported in a manner that avoids release of hazardous substances. Therefore, special measure, such as the use of containers, that protect both human health and the environment and meet the requirements of down-stream processors should be used. Transport solutions should be designed to protect WEEE from breakage and to keep WEEE secure and protected from the elements. Shipments must be labelled with the correct contents' description and UN code, designed correctly and be fit for purpose. If breakage of fractions needs to be avoided (such as for lighting equipment), container with strong impact resistant material such as thick-walled corrugated cardboard should be used. Such containers should feature support structures and with feet to keep it off the ground so as not to absorb any water or moisture from the floor. It can also be placed on a pallet for extra protection. The container must be sized according to the volume being collected and the area application, such as office blocks or heavy industrial areas.

Correct handling of containers includes:

1) Usage of forklifts for loading and offloading trucks and for heavy or large containers
2) Usage of pallet jacks for moving smaller containers with heavy screen waste in the storage and treatment facility
3) Usage of drum trolleys for moving smaller containers with lamp waste in the storage and treatment facility
4) Do not exceed the weight rating of each item of carrying equipment and ensure staff do not lift heavy items

In the following sections of the report, an overview of collection and transportation procedures is given for different collection groups and fractions.

Cooling equipment

Temperature exchange equipment contains cooling and freezing appliances and must hence be treated with caution during transport. This is to prevent ozone depleting substances such as Chlorofluorocarbons and Hydrochlorofluorocarbons from escaping into the atmosphere. Special attention must be paid to the refrigeration circuit and the foam and Polyurethane, as they contain 25% and 75% of the ozone depleting substances, respectively[1].

Monitors

For screens and monitors it should be noted that transportation is large cost driver in the recycling industry. Suitable containers, packaging and stacking need to be factored into the collection and transport system to prevent unwanted breakage or contamination while the waste is in transit.

Once separated, the monitor stands should be removed, as this allows for denser packaging in containers made from cardboard, plastic or metal. Cathode ray tube (CRT) monitors can then be packaged by interlocking the monitors by stacking one row face down and the next face up. Computer monitors are typically packed into low stacks on wooden pallets for recycling and then shrink-wrapped.

Flat panel displays (FPD) can be placed screen down on a simple wooden pallet, at this point it would be ideal to separate out any plasma screens, these are easily identifiable as they are more than double the weight of any other FPDs of similar size. Also separating cold cathode fluorescent lamps (CCFL) containing screens from LED Screens is advisable where possible. The removed stands can be stored in a separate container as they are non-hazardous. Once arrived at the facility the screens should immediately be separated between CRT monitors and FPDs.

Even though there is a clear environmental benefit in maximizing the number of screens and monitors collected, it is crucial to avoid damaging the cathode ray tube during transport and handling. This is to avoid losses of the hazardous coatings on the front panel of the monitors[2].

Flat screen monitors contain crystal liquid glass and cold cathode fluorescent lamps. A critical step is to not break the backlight lamps during the transport, since they contain mercury. Mercury is highly toxic to humans, fauna and flora and can accumulate in organisms. As the backlight lamps are rather fragile, wearing an appropriate mask for offloading and unpacking of the screens is crucial, as mercury vaporizes at room temperature[3].

Lighting equipment

Lamps should not be stored more than 90 days. Lamps that need to be stored until enough volume for transportation is obtained should be stored in safe containers that are correctly labelled and preferably lockable[4]. In addition to mercury (see previous section), lamps often contain other hazardous metalloids, such as arsenic. Thus, collection and transport without breaking of the lamps is crucial to avoid having hazardous outputs.

More information on collection and transport of lamps, e.g. examples of different designs of lamp containers can be found in Annex 2.

Cables

As cables are not an own collection group but nevertheless an important part of WEEE, an additional chapter on the transport and storage of cables can be found in Annex 2.

General Best/Worst Practices for Transport

[1] Ibid., p.22.

[2] Schluep et al. (2009): Recycling - From E-Waste To Resources. Sustainable Innovation and Technology Transfer Industrial Sector Studies, p.25.

[3] Lenz et al. (2019): E-Waste Training Manual, p. 66.

[4] Ibid., p.93.

A worst practice that should be avoided while collecting and transporting WEEE is the non-compliant trading and transportation of WEEE.

Examples of non-compliant trading and transportation are[5]:

- Selling WEEE to non-compliant downstream vendors
- Violation of guidelines and legislations such as the Basel Convention or the locally applicable WEEE directive
- Failure to provide accurate shipping records and forgery of import/export permits
- False labelling of cargo and the transport of such goods

To avoid such worst practices, the following key points should be respected when trading and transporting WEEE:

- Identify non-compliance and act upon it
- A chain-of-custody scheme or certification system should be implemented
- Documentation and maintenance of (shipping) records is crucial
- Before transportation, the WEEE should be packed in an environmentally sound way that also protects human health
- WEEE should be properly labelled, using standardized classification systems, i.e. from the Basel Convention, the OECD and the European Waste Catalogue
- Only authorized transporters should be contracted. This ensures financial security in case of unforeseen events such as accidents.

2.2 Manual processing

Before fractions can be refined or disposed during the end processing steps in the recycling chain, they have to be pre-processed. Pre-processing requires less capital and technology investments compared to end-processing, as it mostly relies on manual labour or requires simpler technologies at lower costs. As a side-effect, this part of the value chain has a higher job creation potential. It is crucial that workers involved in the manual pre-processing steps wear adequate personal protective equipment (PPE). PPE includes a dust mask or a half-face Cartridge Respirators with activated carbon cartridges and suitable eye protection (safety glasses). This minimizes exposure to inorganic mercury vapours that can for example occur in LCD FPD process lines or when recycling fluorescent lamps. Furthermore, a proper half-face mask with exchangeable filters is more versatile than a normal dust mask, as it can be used in all areas, and due to its higher comfort helps to ensure workers wearing it consistently. In addition to a mask, employees should wear cut proof gloves or pick skin gloves suitable for protection against cuts and for easy tool usage. Gloves should not inhibit the dexterity required to complete the work. Steel capped safety boots should be worn to protect the feet from heavy containers that may shift and land on the workers feet. Full body overalls protect the worker from scratches and dirt that can result from handling recycling waste.

For the special case of CRT glass recycling, a cut proof apron should be worn to prevent any injury to staff. CRT Glass is extremely thick and can break in sharp corners, with the high lead content being an additional risk when handling broken CRT Glass. It should be ensured that spill clean-up procedures are adhered to and appropriate equipment is available for breakages or spills that may occur during storage, treatment or transportation of e-waste.

[5] The following paragraph is based on Lenz et al. (2019): E-Waste Training Manual, p. 18.

The goal of the manual processing step in the recycling chain is to seperate materials from WEEE and to prepare them for adequate treatment in the final steps of the recycling chain. This includes that hazardous substances must be removed and either treated or stored safely. This step is done in order to avoid the dilution of and/or contamination with toxic substances during the downstream processes. Critical components include, e.g., lead glass from CRT screens, light bulbs and batteries.

At the same time, valuable components can either be reused directly or directed to efficient recovery processes or adequate subsequent final treatment processes.[6]

At the end of the equipment's lifetime, disassembly can take place for the following reasons:

- *Separation of harmful substances or of components that contain them*:

  The statutory minimum requirements for pollutant elimination should be complied with in order to prevent the emission of harmful substances into the environment and the contamination of the unpolluted materials that are fed into the subsequent recovery stages.
- *Recovery of functional modules and components*:

  Functional components that may be used e.g. as spare parts, are recovered through non-destructive disassembly.
- *Enrichment of recyclable materials*:

  The purity of recyclable materials is increased where disassembly is used as the preliminary step for subsequent processes because materials are concentrated into groups of waste with high material contents.
- *Recovery of materials that cannot be separated through process engineering*:
  If certain materials cannot be recovered in a pure state through mechanical and/or process engineering methods, or material fractions cannot be removed using metallurgical methods, this can normally be achieved by disassembly[7].

The different steps in manual processing are explained in more detail in the subsequent chapters.

2.2.1 Sorting

During collection, WEEE is sorted for a first time according to different collection groups.
This report gives a special focus to the four collection groups:

- Screens and monitors
- Lamps
- Large equipment
- Small equipment, including telecommunication and IT appliances

The differentiation of collection groups facilitates both transport and manual processing, as e.g. in the four cases above, different ways of transportation and processing are require.

2.2.2 Separating

There are a variety of different separation techniques. A distinction can be made according to the rate of destruction. Separation techniques are either non-destructive, semi-destructive or destructive. Figure 2 gives an overview of the techniques.

[6] Schluep et al. (2009): Recycling - From E-Waste To Resources. Sustainable Innovation and Technology Transfer Industrial Sector Studies, p.13

[7] VDI 2343, part 3, p.3

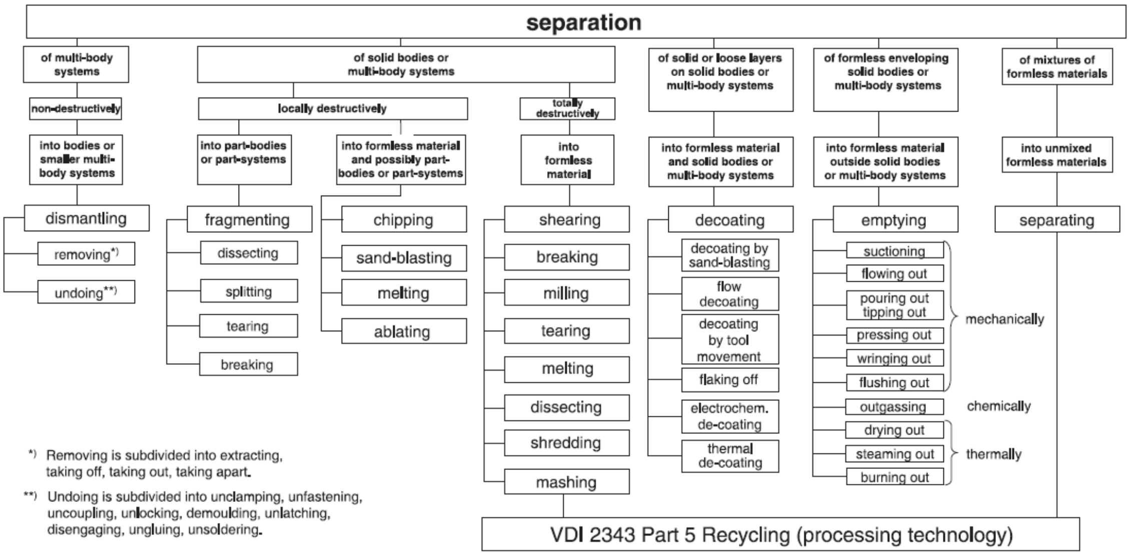


Figure 2: Classification of separation modes, as defined by VDI 2343, part 3, p. 5.

2.2.3 Cleaning

To avoid pollution in the separated material fractions or materials , WEEE must be cleaned before the appliances can be processed. Secondly, potential damage from dust or dirt towards the mechanical processing machines is avoided. More information on the (mechanical) removal of dust can be found in chapter 1.3.1.

2.2.4 De-gassing/Emptying

Some WEEE, as for example CRT and lamps, contain toxic gases. De-gassing is therefore crucial for such appliances before further manual or mechanical processing takes place.

2.2.5 Dismantling[8]

Dismantling of e-waste usually comprises the following steps:

1) The appliance needs to be opened, and the case is separated from the rest of the appliance.
2) Hazardous fractions are identified, localized and removed
3) The remaining components are dismantled, separated and sorted.

For illustration purposes, the dismantling of one appliance per collection group will be explained in detail.

Temperature exchange equipment

A modification of the general procedure is made for temperature exchange equipment, since it often contains hazardous components such as refrigerants and foam blowing agents. Therefore, there are only two steps that should be done during manual dismantling.

1) Cutting the power cable
2) Removal of all loose interior parts such as glass, plastic and steel.

Screens and monitors

[8] Lenz et al. (2019): E-Waste Training Manual, p. 46-84.

As there is a considerable difference in the dismantling of CRT monitors and flat screen monitors, dismantling steps for both appliances will briefly be explained[9]:

In a typical CRT monitor, one will find a cathode ray tube, a magnetic deflector, an electron gun, printed wiring boards, cables and of course the plastic case usually made of acrylonitrile butadiene styrene (ABS) or polycarbonate (PC). The CRT glass contains a large amount of lead, which is why breakage of the glass should be avoided and dismantling should take place in adequate facilities.

The dismantling steps are as follows:

1) Remove the plastic case and clean the plastic
2) To avoid implosion of the CRT body, the pressure in the CRT body needs to be equalized. To do so, place the monitor side with the flap away from your face before you remove the flap. After having it removed, carefully punch a hole in the CRT glass where the flap was fixed, using a screwdriver.
3) Cut and remove the cables. After that, Printed Wiring Boards (PWBs) and the magnetic deflector can be removed. While doing so, make sure that the electron gun at the top of the deflector does not get destroyed.
4) Break off the electron gun from the tube. Make sure to wear protective equipment and to only break the glass below the electron gun, not the complete funnel glass.
5) Remove all remaining screws.

When dismantling a flat screen monitor, it is especially important to carefully remove the crystal liquid containing the glass and the CCFLs. Protective gear must be worn as these lamps often contain mercury and as there is a high chance that they already broke during transport.

The dismantling steps are:

1) Place the monitor with the glass side down. This is to avoid breaking the glass. After that, remove the monitor stand. Monitor stands usually contain plastics and steal.
2) Remove and clean the casing.
3) Remove the front frame, cut off all cables and unscrew the fixing screws. This will allow you to access the PWBs.
4) Remove the steel cover protecting the layers and check if the LCD is illuminated by LEDs or by CCFLs
5) If it is illuminated by LEDs, remove the dark liquid crystal layer. Also remove all other layers until you get access to the backlights.
6) If it is illuminated by CCFLs, remove the steel cover at the back connection at the bottom left and right. This is where the backlight lamps are attached. Following this, remove the backlights. As they contain mercury, be careful while doing so and place the lamps in a container after removing them for the screen.
7) Separate the remaining materials according to their type. Make sure to have them unmixed.

Lamps

Lamps also follow a modified procedure. Lamps are an integral part of many other electronic and electrical devices and can be found in various other electrical and electronic equipment, such as in screens, e.g. from IT and telecommunication appliances. Other examples include ovens and fridges. Lamps must be sent to a certified lamp treatment facility. Dismantling of lighting lamps of various types before treatment is not encouraged. This promotes cherry picking where the value is stripped from the lamp and the hazardous portions are left. This sometimes also results in the non-value hazardous components being dumped illegally or ending in the general waste stream.

[9] For further information, consult Annex 1.

The treatment plant needs to recover some value to offset the treatment cost or it becomes too expensive for the client that pays for the waste to be treated. These facilities will therefore only accept whole lamps that have not been stripped of value.

If there is an EPR (Expended Producer Responsibility) scheme or similar funding the treatment facility, then this cost can be covered. Pre-dismantling can then be done in supported EPR centres. At adequate treatment facilities, differentiation between luminaires and LED lamps is before dismantling made.

Luminaires

Disassembly and dismantling of luminaires can be done manually by hand with basic tools. Luminaire is the correct term used for a light fixture (US English), light fitting (UK English), or an electrical device that contains an electric lamp that provides illumination. All light fixtures have a fixture body and one or more lamps.

The disassembly and dismantling would be achieved by:

1) Dissembling the luminaire from any other objects or components
2) Removing of the lamps from the luminaires
3) The lamps (light source) are stored in suitable containers and must go to specialized treatment
4) Separating various fractions that the luminaire may be comprised of such as wires, plastic, metal, glass etc.

Figure 3: Manual dismantling of luminaires (Reclite SA (Pty) Ltd 2019)

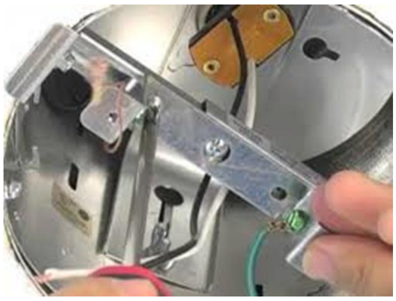


Figure 4: Manual dismantling of luminaires (Reclite SA (Pty) Ltd 2019)

LED lamps

Even though the advanced treatment equipment can separate fractions from LED lamps of various types, the option of very low-tech manual dismantling can be utilised in certain cases. This would not be applicable for fluorescent lamps, HID's, sodium vapour lamps etc, as this would be very dangerous with high health, safety and environmental risk factors.

Disassembly and dismantling of LED fixtures can be done by hand with basic tools, however it is relatively labour and time intensive:

1) Carefully dismantle the lamp by hand using the appropriate tools
2) Remove the printed circuit board which also holds the capacitor. This must go for specialised treatment.
3) Separate the different fractions such as plastic, glass, wires, metals etc.
4) Removal of diodes holders/strips from the luminaires – diodes/light source must go to specialised treatment

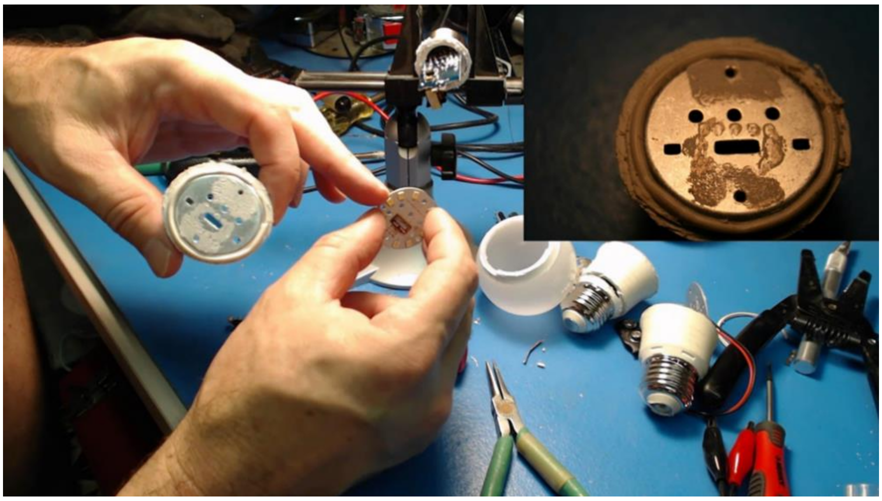


Figure 5: Labour and time intensive manual dismantling of an LED lamp (Reclite SA (Pty) Ltd 2019)

Specialised treatment or processing of lighting waste

All lighting waste can be recycled. The light sources (lamps) must NOT be manually dismantled prior to the treatment process as it is dangerous, this must be done in specialised automated treatment equipment.

Lighting waste must only be processed in specialised lamp treatment facilities. These facilities are technically competent and legally compliant. The treatment equipment has strict technical operating standards and removes all the hazardous components through crushing and separation such as the mercury, which is removed and separated safely, with no exposure to operators or the environment. For further information, consult chapter 3.2.

Large equipment

As an example for the dismantling of large equipment, the manual dismantling steps for a washing machine will be presented.

1) The main cable, connecting hoses, door, top and rear wall, plastic modules and capacitor need to be removed.
2) Removal of the control unit.
3) Removal of the coil in the water pump. It is made of copper and is therefore highly valuable.
4) Disassemble the housing; unhook the shock absorbers and unscrew the concrete weight.
5) Open the detergent container, remove the stainless-steel drum and separate it.

Small equipment, including telecommunication and IT appliances

As an example for the dismantling of small equipment, including telecommunication and IT appliances, the manual dismantling steps for a personal computer will be presented.

1) The Central Unit (CU) casing must be removed.
2) The screws holding the internal components must be removed, and then the connecting cables need to be unplugged and separated.
3) Drives, such as for floppy disks, CDs and hard disks should be removed
4) The main adapter should be removed for re-use.
5) The motherboard and all other PWBs can be removed. Batteries need adequate treatment and disposal. RAM, the network interface unit and the central processing unit can be removed, too.

2.2.6 Segregation

After manual dismantling, the appliances are segregated into different fractions. These fractions are shown for the four collection groups under study in the report as well as for temperature exchange equipment:

Table 1: Appliances and their respective fractions (Own elaboration based on VDI 2343, part 3 and Lenz et al. (2019)).

	Batteries	HDD and CDD	LCD backlight display	PWB	Cables	Plastic	Screws	Capacitors	Coils	Motors	Magnetic deflector	CRT Glass	Electron gun / getter platelet	Ferrous metals	Glass	Capacitor	Led diode	Lamp tube
Small equipment, IT and T	x	x	x	X	x	x	x							x	x			
Large equipment					x	x	x	x	x	x						x		
Screens and Monitors			x	x	x	x	x				x	x	x	x	x			
Lamps				x	x										x	x	x	x
Temperature exchange equipment*	* Temperature exchange equipment Even though temperature exchange equipment typically contains a large amount of plastics and ferrous metals, only loose interior parts should be taken out during manual dismantling. This includes glass, plastics and steel.																	

2.3 Mechanical processing

Mechanical processing, the next step in e-waste treatment, is normally an industrial and rather large-scale operation to obtain concentrates of recyclable materials in a dedicated fraction and also to further separate hazardous materials. Typical components of a mechanical processing plant are crushing units, shredders, magnetic-, eddy-current- and air-separators. The gas emissions are filtered, and effluents are treated to minimize environmental impact.

Mechanical processing can either serve as pre-processing or end-processing step. This subchapter includes a summarized description of the following mechanical processing types:

- Concentration processes
  - Crushing (shredding, milling)
  - Sizing (sieving and screening, separation based on particle dimension)
  - Sorting (magnetic, electric field, sensor based, by density, by force separator or other physical characteristics)
  - Recovery from dust

- Selective Treatment

The goal of the chapter is to give an overview of the different mechanical processing techniques and to serve as reference base for chapter 2 on downstream technology options.

2.3.1 Concentration processes

The first step of mechanical processing is the concentration of unmixed fractions, which is done through crushing, sizing and sorting. However, the concentration of unmixed fractions usually leads to the generation of dust of various degrees of fineness. Failure to take appropriate dust-removal measures can have several consequences such as poor working conditions or higher wear and tear of the machinery in use. Therefore, dust must be removed from the premises[10].

Crushing

Crushing can be done through, amongst other techniques, shredding and milling.

Through the crushing of electrical/electronic devices, or their fractions, their valuable materials are exposed. The exposure of the materials is fundamental for the subsequent separation of the materials into valuable end products[11].

A distinction can be made between coarse, medium and fine crushing, depending on the targeted crushing outcome. Another way to achieve the desired outcome is additional refrigerating or heating treatment, which can largely affect the behaviour under crushing[12].

An overview of crushing machines and their respective forms of stress application is given in table 2.

Table 2: Crushing types and appropriate forms of stress applications (VDI 2343, part 4, p.10)

Type of crushing	Appropriate form of stress application	Crushing machines (examples)
Production of pieces/particles of defined dimensions	shear stress impact stress fall-impact stress	guillotine shears alligator shears rotary shears rotary cutters cutting mills[a)]
	collision-impact stress (for chips, in combination with bending and torsion)	impact mills[b)] (of the most various constructions)
Separation crushing: • for smaller fractions from electronic/electrical devices	shear stress collision-impact stress together with compression-and-shear stress	cutting mills[a)] hammer mills[b)] (of the most various constructions, e.g. shredders, cross flow cutting units)
• for fibre composites, laminated materials	collision-impact stress together with compression-and-shear stress	impact mills[b)] (of the most various constructions) shredders, cross flow cutting units

a) Smallest permissible particle dimensions are limited.
b) cryotechnological pre-treatment where necessary

Most commonly used crushing machines for electronic and electrical equipment are fast-running hammermill crushers or shredders. Hammermill crushers or shredders can be used both for separation crushing and for the achievement of certain specific piece-size distributions. Crossflow cutting units and rotary shears are used for the mechanical processing of refrigerators.

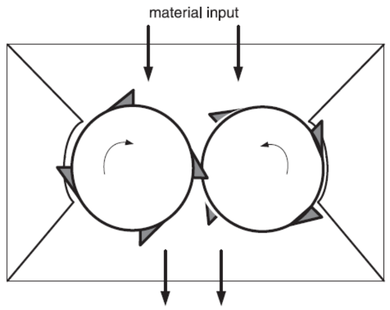
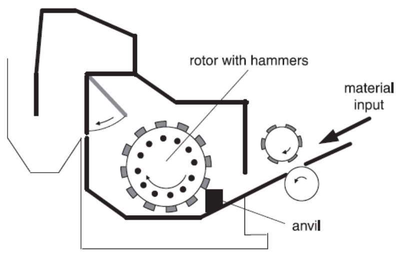
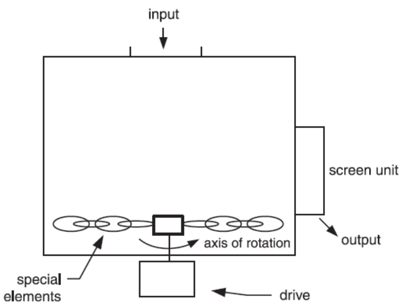
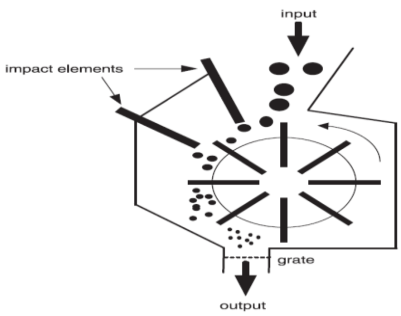
[10] VDI 2343, part 4, p. 30.

[11] VDI 2343, part 4, p.8.

[12] Ibid.

Cables and plastics are mostly processed with cutting mills. A schematic overview of the construction of these machines, including possible ways of application is provided below.

Table 3: Schematic overview of crushing machines and their application (VDI 2343, part 4, p. 13-17)

Schemata	Application
 ***Figure 6: Rotary shears (VDI 2343, part 4, p. 11)***	A rotary shear is used for pre-crushing, for example of cathode ray tubes or refrigerators
 ***Figure 7: Shredder (VDI 2343, part 4, p. 11)***	Shredders and impact mills are used for crushing and materials separation. Examples of appliances that are processed with these machines are large household devices, separated circuit boards, printers, vacuum cleaners or VDU glass.
 ***Figure 8: Cross flow cutter (VDI 2343, part 4, p. 11)***	A cross flow cutter is used for the crushing and separation of materials. It is mostly used on refrigerators, printers or vacuum cleaners.
 ***Figure 9: Impact mill (VDI 2343, part 4, p.12)***	An impact mill works similar to a shredder. Subsequently, it also aims at the crushing of materials and their separation. Appliances to be processed by such machines are, amongst others, refrigerators and vacuum cleaners.

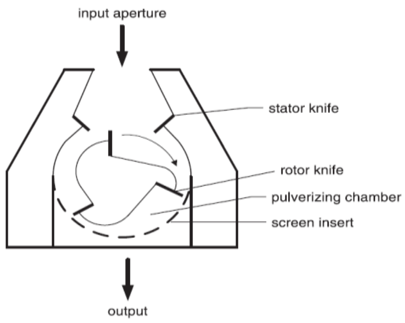


Figure 10: Cutting mill (VDI 2343, part 4, p. 12)

A cutting mill takes care of the follow-up crushing, e.g. of plastics or cables.

Sizing

After crushing, the materials need to undergo sizing procedures. The following table summarizes the different screening machineries and sizing procedures, their areas of application and their advantages as wells as disadvantages.

Table 4: Overview of screen machineries, their areas of application and advantages or disadvantages (VDI 2343, part 4, p.13-17)

Screen machinery	Description	Areas of application	Advantages/disadvantages
Stationary grates and screens	Stationary grates and screens work especially well for the separation of larger and coarser particles of bulk material. While the finer material falls through the robust profile bars, the coarse material slips along the inclined crates.	Coarse source material	Very robust and available at low cost. Has a high throughput rate, but the separation is not very precise
Mobile grates	The elements of the screen, respectively of the sieve tray are in motion relative to one another. This enables them to transport material.	Coarse source material	Machinery is limited when it comes to rod- or board shaped material
Rotating drum screens	The screen tray of a rotating drum screen is formed by the shell of a rotating drum. After the material is loaded into the drum, it constantly rolls around through the rotating movement. This leads the material to shift in axial direction. Finer parts will fall through the screen, and	Coarse to medium source material	The biggest advantage of rotating drum screens is their simple design. Furthermore, they do not vibrate during operation and have a minimal height difference. On the other hand, it is difficult to exchange the screen tray, there is danger of blockage and the machinery is very energy consuming.

	coarser parts reach the other end of the drum.		
Throw screens	There are two varieties of throw screens. The widely used throw screens with energized screen casing and II) Throw screens with energized screen tray Depending on the desired sizing process, either one can be applied.	While energized casings can only handle not hard-to-screen material, energized screen trays are also applicable for hard-to-screen material.	Both throw screens and flat screens rely on low investment costs only. Apart from the need for frequent cleaning, they have only little maintenance requirements, even though wear and tear is high.
Flat screens	The oscillating casing of the so-called tumbler screens or oscillating screens is mounted in an inclined position and moves in a circular motion of the screen level. This leads the material to slip back and forth on the screen for multiple times. The dry sizing of fine materials can be strengthened when using tray bushed or ball operated beating mechanisms.		

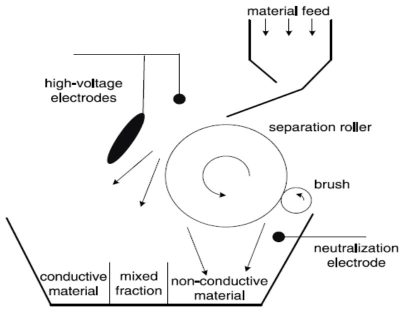
Sorting

After the sizing, the materials are sorted into fractions, i.e. divided into two or more products of different material composition. This is done by making use of the different physical or physical-chemical properties of the respective particles. As the sorting procedures rely on specific particle sizes, this step must be undertaken after the sizing.

In the following paragraphs, different sorting methods such as sorting by magnetic field, by electrical field, by density, sensor-supported methods and inertia-force methods will be described.

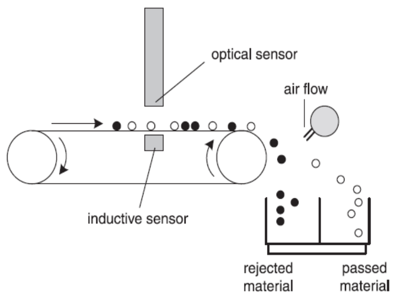
Technologies that rely on sorting in a magnetic field fall under the term of magnetic separation procedures. Magnetic separation can be further divided into over-belt magnetic separation, drum-design magnetic separation and eddy-current separation. In the case of eddy-current separation, further distinction into permanent-magnetic eddy-current separation and electromagnetic eddy-current separation can be made. Over-belt magnetic separators aim at the separation of iron and bulk material with iron content. Drum-design magnetic separators also aim at the separation, as well as at the retrieval, of iron and bulk material with iron content. They are mainly used in preparation processes and for higher volumes and mass flows.

Eddy-current separation is used to separate non-ferrous materials from the materials mix. Since there is acute danger of overheating if ferromagnetic particles get into the machinery, it is usual to set up eddy-current separation downstream of a magnetic separation. Separation is done according to the conductivity/density ration, which results in a high yield of magnesium and cooper. The most important component for permanent-magnetic eddy current separation is the revolving magnetic rotor of the separator. It creates a magnetic field, which leads to the repulsion of conductive materials. However, the magnetic field shows no effect on-conductive materials, which are hence thrown off. As mentioned before, separation is done according to ratio of conductivity and density. In addition to that, eddy-current separation depends also on size and form of particles that need to be separated. Electromagnetic eddy-current separation requires a large amount of electrical energy and hence leads to high separation costs. This is the reason why the separation method will not be further discussed here.



Another sorting option is the sorting in an electrical field. For this method, corona-induced roll separators are most commonly used. They separate electrical conductors and non-conductors. They furthermore distinguish between materials with different electrical load potential. They can retrieve metal particles in the range of 0 to 6 millimetres and work as described in the following figure.

Figure 11: Basic description of a corona-induced roll separator (VDI 2343, part 4, p.20)



Another category of sorting methods is the sensor-supported sorting. These methods use optical sensors to grade materials according to specific parameters such as colour, type of polymer material or conductivity. After previously chosen specific parameters are detected, the materials are sorted using a nozzle system. The basic design of such machinery is presented in figure 12.

Figure 12: Structure of an automatic sorter, consisting out of a conveyor belt, optical sensor and inductive sensor (VDI 2343, part 4, p.22)

An overview of sensor-supported sorting technologies is given in the table below.

Table 5: Sensor-supported sorting technologies and their area of application (VDI 2343, part 4, p.21-25)

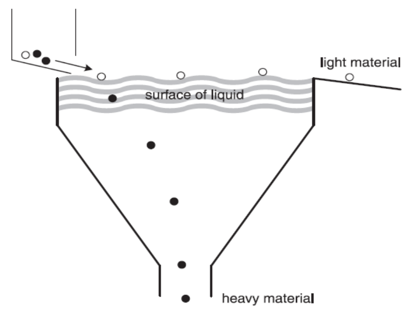
Technology	Procedure	Area of application
Near-infra-red spectroscopy	To sort the materials, they are irradiated with infra-red light. Sorting is done depending on the reflected proportions of beams belonging to certain wavelengths.	Used to sort plastic polymers, can differentiate between 15 different plastics.
Colour camera/CCD-camera	Colour cameras serve to identify articles according to their colour and shape. They are used for the generation of mono-fractions and for the separation and recovery of non-ferrous metals. This technology is mostly used in combination with an inductive sensor,	Used to sort metals and composites.

	in order to identify conductive/non-conductive materials.	
X-ray transmission technology	X-ray transmission technology is a relatively new approach. Density and thickness of the materials to sort are the factors the X-ray transmission technology relies on.	Used to separate VDU glass, aluminium, heavy metals and plastics according to their additives.
Electrical/inductive field	The materials to be sorted pass at least one row of small electromagnetic metal coils, which are installed directly under the conveyor belt. In an electrical/inductive field, non-conductors lead to no disturbance and pass through the machinery. The technology allows the identification of mixed substances containing small amounts of metals, for example circuit boards. As this technology offers a good option for the concentration and recovery of non-ferrous metals, it is often combined with an eddy-current separator.	Used to differentiate between conductors and non-conductors.

Methods that sort by density are yet another type of sorting option. They rely on a uniform particle size and an appropriate difference in the density of the sortable substances.

Sink-float methods are, amongst others, used for the preparation of non-ferrous fractions. Other forms of application are the separation of pure metals fractions and the separation of plastics. The liquid used as separating media can be either water, saline or dense media, whereby in practice the latter one is most commonly used.

The operating principle of such methods is presented in figure 13.



Sorting by jigging is another method of sorting by density. Hereby the sortable materials are loaded on a tray where a fluid is pumped in through the apertures and flows up and down periodically. This leads to the layering of the substances according to their densities.

Figure 13: Principle of operation for sink-float methods (VDI 2343, part 4, p. 25)

Separating tables function on similar basis as jigging does. However, this method can also consider the particle size and shape of the substances. In practice, the only table that is widely used is the vibrating table, whereby the wet-washing and the hydro-tables are the most important models. Separating tables are used for the preparation of cables and the separation of metals.

The last group of sorting methods is the inertia-force separators. As even dust contains very small metal fractions, cyclone air separators are used to regain extremely fine metals with a particle size of less than one millimetre. On the one hand this favours the recovery of valuable materials and on the other hand it relieves the dust separators after sorting machinery from a part of its load. Another option is the use of zig-zag classifiers, which separate recyclable substances from residue substances. By using air flows, they transport particles of less than 10 millimetres upwards in a standing sorting tube, constructed in a zig-zag form. The lighter material will pass upwards while the coarser or heavier material will fall downwards. This method is mainly used for light shredder fractions.

Removal of dust[13]

Dust can either be removed at its source by suction or can be separated from the air.

To remove dust by suction there are two methods available. The dust can either be suctioned off at the source and treated in a central separator or treated decentral at the source. While the first option is more cost intensive, the second one is mainly suitable for facilities with only a small number of dust sources. For large facilities with numerous sources of dust generation, a central separator is recommended. Regardless of the chosen option, it must be assured that dust is captioned as exhaustively as possible right after its generation. To achieve maximum removal rates, suction hoods should be used.

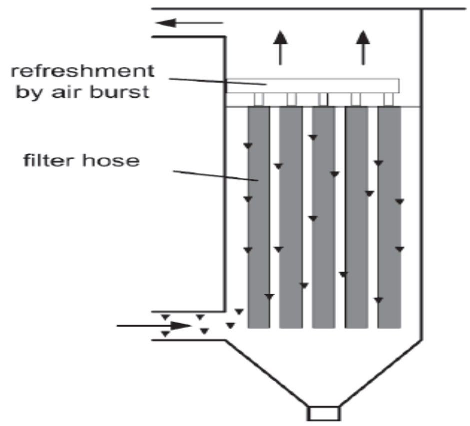


Figure 14: Hose filter system with air burst refreshment system (VDI 2343, part 4, p. 33)

To separate dust from the air, pouch, hose or cartridge filters are most commonly used. Hereby, the dust-air mix flows from the outside, through the filters, to the inside of the machinery. Figure 14 gives an overview of the process.

For system maintenance, highly compressed air is blown through the filter from the inside. Afterwards, the dust can be collected using machinery such as rotary airlocks.

2.3.2 Selective treatment

For selective treatment of WEEE, the European Committee for Electrotechnical Standardization (CENELEC) offers a comprehensive overview. In their European standard on collection, logistics & treatment requirements for WEEE – Part 1: General treatment requirements, Annex F, it is stated that[14]:

"1. As a minimum the following substances, mixtures and components have to be removed from any separately collected WEEE:

- polychlorinated biphenyls (PCB) containing capacitors in accordance with Council Directive 96/59/EC of 16 September 1996 on the disposal of polychlorinated biphenyls and polychlorinated terphenyls (PCB/PCT) 1,
- mercury containing components, such as switches or backlighting lamps,
- batteries,
- printed circuit boards of mobile phones generally, and of other devices if the surface of the printed circuit board is greater than 10 square centimeters,
- toner cartridges, liquid and pasty, as well as colour toner,
- plastic containing brominated flame retardants,

[13] This paragraph is based on VDI 2343, part 4, p. 30-33.

[14] European Committee for Electrotechnical Standardization (2014): EN 50625-1, Collection, logistics & Treatment requirements for WEEE – Part 1: General treatment requirements, p. 34f.

- asbestos waste and components which contain asbestos,
- cathode ray tubes,
- chlorofluorocarbons (CFC), hydrochlorofluorocarbons (HCFC) or hydrofluorocarbons (HFC), hydrocarbons (HC),
- gas discharge lamps,
- liquid crystal displays (together with their casing where appropriate) of a surface greater than 100 square centimeters and all those back-lighted with gas discharge lamps,
- external electric cables,
- components containing refractory ceramic fibres as described in Commission Directive 97/69/EC of 5 December 1997 adapting to technical progress for the 23rd time Council Directive 67/548/EEC relating to the classification, packaging and labelling of dangerous substances 2,
- components containing radioactive substances with the exception of components that are below the exemption thresholds set in Article 3 of, and Annex I to, Council Directive 96/29/Euratom of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionising radiation 3,
- electrolyte capacitors containing substances of concern (height > 25 mm, diameter > 25 mm or proportionately similar volume)

These substances, mixtures and components shall be disposed of or recovered in compliance with Directive 2008/98/EC.

2. The following components of WEEE that is separately collected have to be treated as indicated:

- cathode ray tubes: the fluorescent coating has to be removed,
- equipment containing gases that are ozone-depleting or have a global warming potential (GWP) above 15, such as those contained in [] foams and refrigeration circuits: the gases must be properly extracted and properly treated. Ozone-depleting gases must be treated in accordance with Regulation (EC) No 1005/2009,
- gas discharge lamps: the mercury shall be removed.

3. Taking into account environmental considerations and the desirability of preparation for re-use and recycling, points 1 and 2 shall be applied in such a way that environmentally sound preparation for re-use and recycling of components or whole appliances is not hindered."

2.4 Refining & disposal[15]

The following section describes refining options for metals, synthetics and glass. It gives an overview of the objective of refining, the critical steps to consider and the risks related to the refining of e-waste.

Refining of resources in e-waste is possible and the technical solutions exist to get back raw metals with minimal environmental impact. Most of the fractions need to be refined or conditioned in order to be sold as secondary raw materials or to be disposed of in a final disposal site. During the refining process three flows of materials are paid special attention: Metals, synthetics and glass.

Recovery can be divided into two operational pathways.

[15] This subchapter is based on VDI 2343, part 5, p.3-5.

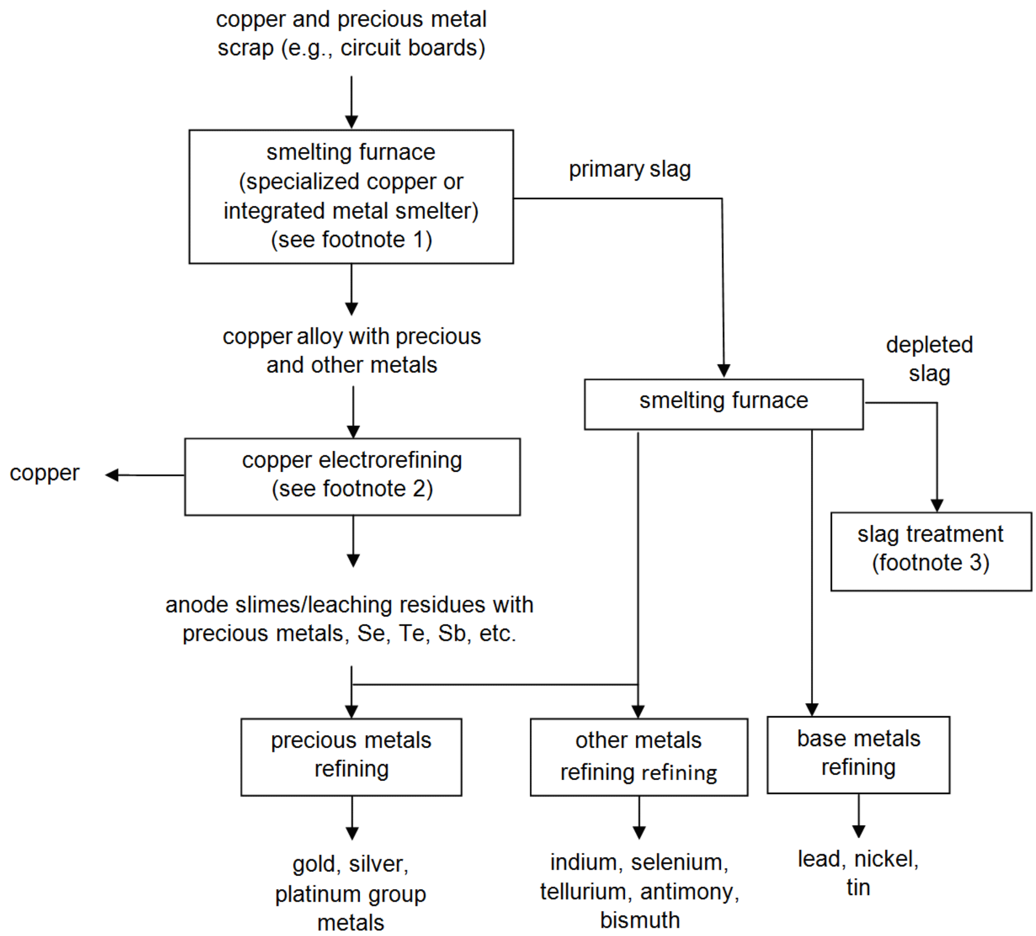
Material recovery

Material recovery is further divided into mechanical and chemical recovery. Material recovery is mostly used where the waste is clean and sorted in fractions. It aims at substituting primary materials and at the utilisation of the material properties of the waste for both the original and other purposes.

The unit operations or equipment's used for material recovery are often combined can be roughly divided into the following group of methods[16]:

- Pyrometallurgy, which uses high temperatures to chemically convert the feed materials. This procedure separates metals and impurities into different phases, this allows to recover valuable metals. In the smelter of furnace, combustion of fuel or electrical heating generate high temperatures. Technical appliances falling under this category are Examples submerged lance smelters, converters, rotary furnaces or electric arc furnaces. An exemplary process flow is shown in figure 15.

[16] Schluep et al. (2009): Recycling - From E-Waste To Resources. Sustainable Innovation and Technology Transfer Industrial Sector Studies, p.28f.



fn 1 – smelters differ in process flow and metals produced. For treatment of materials with plastic content, e.g., circuit boards, special emission pollution control treatment is required for all smelters.

fn 2 – either (1) copper anode directly electrorefined to cathode, and electrorefining residues (slimes) are further treated, or (2) copper alloy is leached, leachate is then electrorefined to cathodes, and leaching residues are further treated. Residues without value are disposed.

fn 3 – slag is stabilized and made suitable for construction products. Residues without value are disposed in controlled disposal operations.

Figure 15: Exemplary flow sheet of pyrometallurgical recovery of Copper and precious metals. (Partnership for Action on Computing Equipment (2011): Guideline on environmentally sound material recovery/recycling of end-of-life computing equipment, p. 39.)

- Hydrometallurgy based methods use strong acidic or caustic watery solutions in order to selectively dissolve and precipitate metals. Methods are for example leaching, cementation or solvent extraction.
- Electro-metallurgical methods form the last group. They use electrical current to recover metals. Example are electro-winning and electro-refining of copper or zinc.

Thermal recovery

Thermal recovery aims at the generation of thermal or electric energy. This is done through the use of high calorific value.

Before recovery, the quality of the fractions has to be assessed. Depending on the quality, a primary treatment process might be required first. To choose the appropriate recovery method, a systemic approach must be followed. This means that the whole process chain should be considered, not only separate processes. Points and issues to be taken into account are:

- Costs for logistics
- Costs for energy and the recovery rate
- Is the recovery product usable and marketable?
- How many emissions does the recovery process cause?
- Are there any problematic substances? If yes, they need to be destructed concentrated and destructed.

An overview of the recovery and disposal paths for WEEE is given in the following figure.

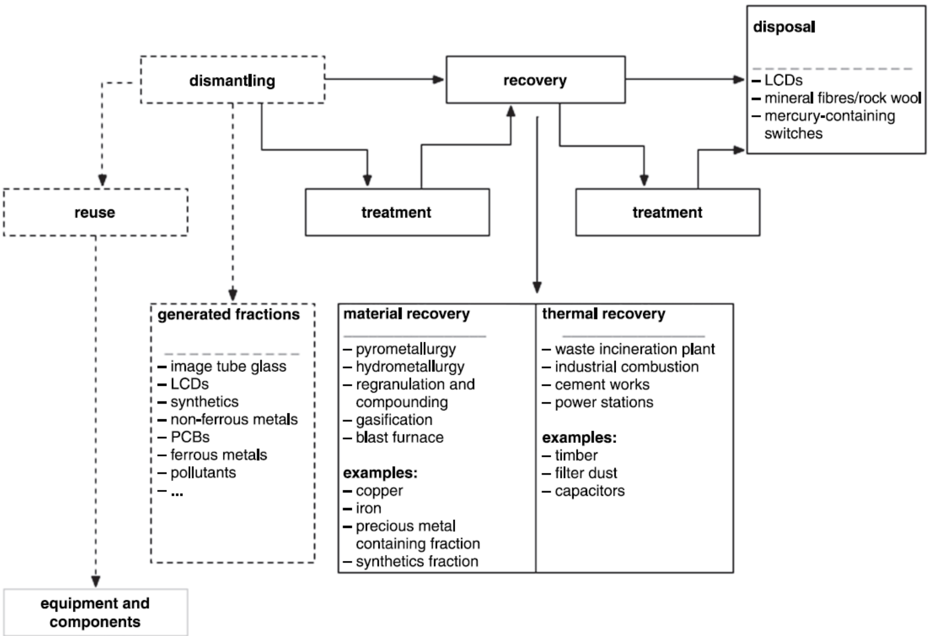


Figure 16: Recovery and disposal paths for WEEE (VDI 2343, part 5, p.5)

Secondary raw material can also be redeployed directly in new products. E.g. plastics can be implemented in a whole range of new products, such as roof tiles, fence poles, insulation material etc. Crucial before redeploying secondary raw material is to clarify the composition of hazardous substances and to know potential environmental impacts.

Disposal

Even though recovery of fractions from WEEE must be the ultimate goal, unfortunately, not all fractions of WEEE can be recovered. Non recoverable fractions, or hazardous waste fractions need to be disposed in hazardous waste treatment facilities. There are two options that are recommended (due to the lack of other options), namely landfills and incineration.

Landfilling

Landfilling is one of the most widely used methods of waste disposal. However, landfills do often not fulfill the highest standards and as a result are subject to possible leakages from waste into the subsurface [17]. The leachate often contains heavy metals and other toxic substances, which can contaminate ground and water resources. Even state-of-the-art landfills that are sealed to prevent toxic substances from entering the ground are not completely secure in the long-term. Older landfill sites and uncontrolled dumps pose a much greater danger of releasing hazardous emissions.

17 Renou et al. (2008): Landfill leachate treatment: Review and opportunity, p.1.

Mercury (e.g. to be found in mercury switches), Cadmium (batteries) and Lead (lead-acid batteries) are amongst the most toxic leachates. Mercury, for example, will leach when certain electronic devices such as circuit breakers are destroyed. Lead has been found to leach from broken lead-containing glass, such as the cone glass of CRTs. When polybrominated flame retarded (PBDE) plastics or plastics containing cadmium are landfilled, both PBDE and cadmium can leach into soil and groundwater. Similarly, landfilled condensers emit hazardous PCBs.

Besides leaching, vaporisation of hazardous substances is also of concern in landfills. For example, volatile compounds such as mercury or a frequent modification of it can release di-methylene mercury. Finally, landfills are also prone to uncontrolled fires that can release toxic fumes.

Significant environmental impacts from landfilling could be avoided by conditioning hazardous materials from e-waste separately and by landfilling only those fractions for which there are no further recycling possibilities and ensure that they are in state-of-the-art landfills that respect environmentally sound technical standards.

Incineration

Incineration is the process of destroying waste through burning at high temperatures. Because of the variety of substances found in e-waste, incineration is associated with a major risk of generating and dispersing contaminants and toxic substances. The gases released during the burning and the residue ash is often highly toxic. This is especially true for incineration or co-incineration of e-waste with neither prior treatment nor sophisticated off-gas treatment or flue gas purification. Studies of municipal solid waste incineration plants have shown that copper, which is present in printed wiring boards and cables, acts a catalyst for dioxin formation when flame-retardants are incinerated. These brominated flame retardants - when exposed to temperatures between 600 and 800° - can lead to the generation of extremely toxic polybrominated dioxins (PBDDs) and furans (PBDFs). Polyvinyl chloride (PVC), which can be found in e-waste in significant amounts, is highly corrosive when burnt and also induces the formation of dioxins. Incineration also leads to the loss valuable of trace elements which could have been recovered had they been sorted and processed separately.

A low input worst practice of WEEE disposal and secondary metals recovery is open burning. As open burning of WEEE has severe impacts for human health and the environment, the practice should be avoided. Since open fires burn at relatively low temperatures, they release many more pollutants than in a controlled incineration process at an MSWI-plant. Inhalation of open fire emissions can trigger asthma attacks, respiratory infections, and cause other problems such as coughing, wheezing, chest pain, and eye irritation. Chronic exposure to open fire emissions may lead to diseases such as emphysema and cancer. For example, burning PVC releases hydrogen chloride, which on inhalation mixes with water in the lungs to form hydrochloric acid. This can lead to corrosion of the lung tissues, and several respiratory complications. Often open fires burn with a lack of oxygen, forming carbon monoxide, which poisons the blood when inhaled. The residual particulate matter in the form of ash is prone to fly around in the vicinity and can also be dangerous when inhaled.

3 Downstream technology options

The aim of this chapter is to give an overview of downstream technology options for four different collection groups. The collection groups concerned are screens & monitors, lamps, large equipment and T, IT and small equipment.

3.1 Screens & monitors

Screen technology was first developed utilising CRT monitors and as technology advanced more compact and technologically advanced screens where developed, currently sold as flat panel display montitors (FPDs)

CRT Monitors and CRT-Television sets are no longer being manufactured and most are now at the end-of-life stage. Modern screen technology no longer requires the bulky construction of a leaded glass tube and electron gun. Instead other components such as CCFL's, (O)LEDs or other methods of producing visible light are being used in screens today.

Due to hazardous nature of the actual CRT Monitor, most recycling efforts only concentrate on the removal of the valuable electronic components. It is important when looking at the recycling of CRT screens to include the whole recycling process and to have an outlet for the leaded glass fraction.

Understanding how many different types of television and monitor screens are available for recycling and the different methods used for recovery of valuable material, allows organisations to maximise the recovery potential of key components and valuable materials.

Most LCD screens made before 2009 contain mercury, which makes these types of flat panels hazardous waste. Newer flat screens are mercury-free but may contain other hazardous materials, such as heavy metals and flame retardants.

All screen types use different phosphor powder compounds or coatings in some form or another either to generate light directly (OLED, Plasma) or indirectly (LCD, CRT).

Phosphorus powders contain a variety of elements ranging from Rare-Earth Elements to heavy metals, such as Cadmium, Gallium, Indium and Arsenic among others. Therefore, it is vital to separate and recycle these resources for their financial value and possible toxicity.

Further, more detailed information on CRT and FPD processing can be found in Annex 3.

3.1.1 CRT screens

CRT screens are no longer being produced. Hence investment into fully automated recycling plants is discouraged and will not be investigated in detail. Nevertheless an overview of the recycling steps for CRT screens is given below.

CRT screens require the use of a CRT separator. Typical separator technologies are diamond cutting disc and the hot wire technology. Both technologies achieve the same in that the front-and cone glasses of the cathode ray tube can be separated from each other. Front-and cone glass will be separated at the connecting line of both glasses. The funnel glass is the lead containing, funnel-shaped rear part of glass from the cathode ray tube.

In the hot wire technology, a wire made of nickel-chromium alloy will be placed at the connecting line around the screen. The different glasses will be separated by a heating up and through the consequently resulting tension of the glass connecting line.

The diamond cutting disc requires the diamond tipped blades to cut completely through the glass to separate the screen. This requires additional suction equipment and can lead to leaded glass dust particles being present. Therefore, the hot wire method is preferred as it minimises the formation of free dust particles and usually results in a cleaner separation of the two halves.

The fluorescent layer, which could be contaminant-laden, will be manually removed by the integrated vacuum cleaner, after opening the cathode ray tube. Subsequently the different types of glasses and the separated metal parts are transported to a further re-utilization.

An overview of the processes and techniques for CRT recycling is given in figure 17 below.

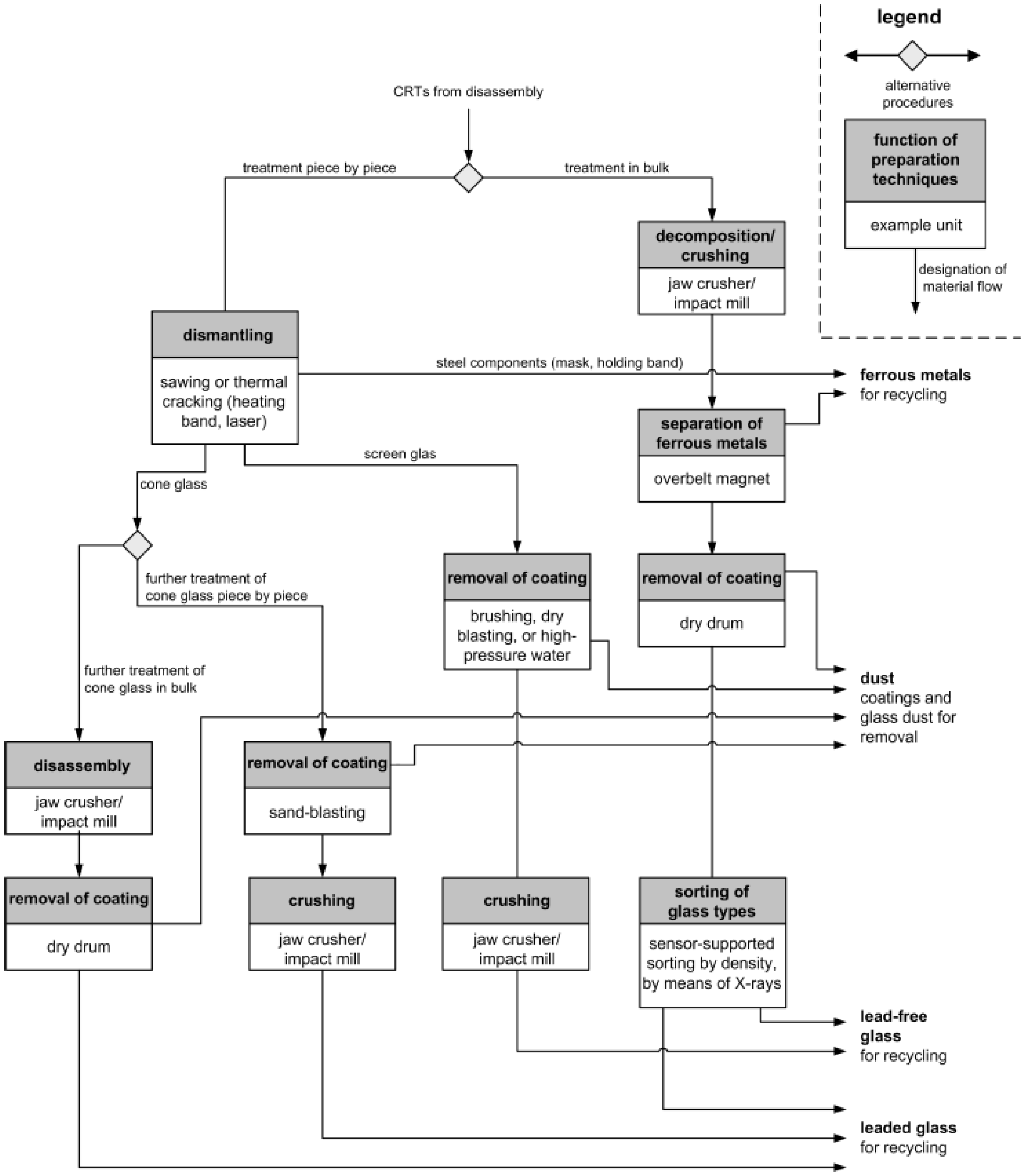


Figure 17: Options for CRT preparation techniques (VDI 2343, part 4, p. 54)

3.1.2 Flat panel displays

A more common use is the use of a semi-automatic recycling, whereby the removal of the casing or hazardous task are being done by machinery and the separation of the fractions is done by manual removal.

Flat panel processor

An example of such technology is flat panel processor (FPP), the flat panel processor is a versatile machine to disassemble a large range of LCD panels. The processor allows for secure extraction of the fluorescent lamps and separation into the different fractions. The processor can be fed manually or mechanically via conveyor belts. The FPP cutters automatically make two cuts at the perimeter of the panel, allowing for clean and safe separation. The processor can be fed with panels up to 1600mm x 1200mm and 60kg.

Flat panel processors require the FPD stands to be removed prior to feeding into the machine. For best handling this is advised to be done on receiving and sorting the panels. Several studies have been performed assessing if manual or automatic separation is the most efficient form of recycling for FPD's:

One of the first studies on LCD dismantling, compared the time taken to dismantle LCDs using different techniques: manually, by water-jet cutting, by laser cutting and by circular-saw cutting[18]. This study found that manual dismantling is the preferred choice as it involves the least cost per item and results in higher quantities and quality of the recovered materials. Kopacek (2008) also estimated that a dismantling time of the backlighting systems of less than 1.4 min would make manual dismantling preferable to other systems, even with high labour costs.

This would then be in direct comparison to the fully automated recycling option with less cleaner fractions.

Assuming an average content precious metals in PCBs, it has been calculated that the manual extraction of PCBs, compared to shredding-based treatment, would allow for the additional recycling of 46.2 g of copper, 0.44 g of silver, 0.15 g of gold and 0.03 g of palladium from a small (51-cm) display; and 80.7 g of copper, 0.77 g of silver, 0.25 g of gold and 0.05 g of palladium for a large (94-cm) display[19]. Based on the current market values of metals, estimations of the revenue to be gained from such recycling activities range between €3.5 and €4.3 (for a small display) and between €6.1 and €7.6 (for a large display).

Additionally, the LCD will be left intact and could if need be recovered in a cleaner separate step. The average content of indium in a display is assumed to be 234 mg/m2, which corresponds to 58.5 mg/kg of display[20]. Once displays are dismantled, thin-film-transistor (TFT) panels can be sent for selective processing; for example, the indium content could be separated by acid leaching or vaporisation, which has a recovery yield of about 85%[21]. Indium can be then purified by solvent extraction, electrowinning or smelting. Purification processes can recover almost 99% of indium[22]. Overall, it is estimated that about 80% of the indium contained in displays can potentially be recycled. The recyclable indium content of, for example, 51-cm or 94-cm displays, has an approximate economic value of €0.13 and €0.23, respectively.

Shredding process and separation process

There are different plants in operation that shred and separate FPD around the world.

The technology is based on a system that works under a negative pressure environment whereby the shredded fractions are fed into a density hydrostatic separator and then the fractions undergo various stages, including magnetic separation, eddy current separation and in some systems even density separation. However, losses occur as the PMMA plates are mixed with other plastics and contaminated as well as the LCD screens are being shredded and mixed with other glasses and or ceramics.

[18] Kopacek (2008): ReLCD: Recycling and re-use of LCD-panels.

[19] Ardente & Mathieux (2012): Application of the project's methods to three product groups.

[20] Kissling et al. (2012): Definition of generic re-use operating models for electrical and electronic equipment.

[21] Götze & Rotter (2012): Challenges for the recovery of critical metals from waste electronic equipment - A case study of indium in LCD panels.

[22] Ibid.

Some processes will use varying technological efforts to remove potential mercury contamination of the component parts within the process. These steps add additional cost to the overall process and are recovered from the recyclables or in the form of a gate fee for the waste received.

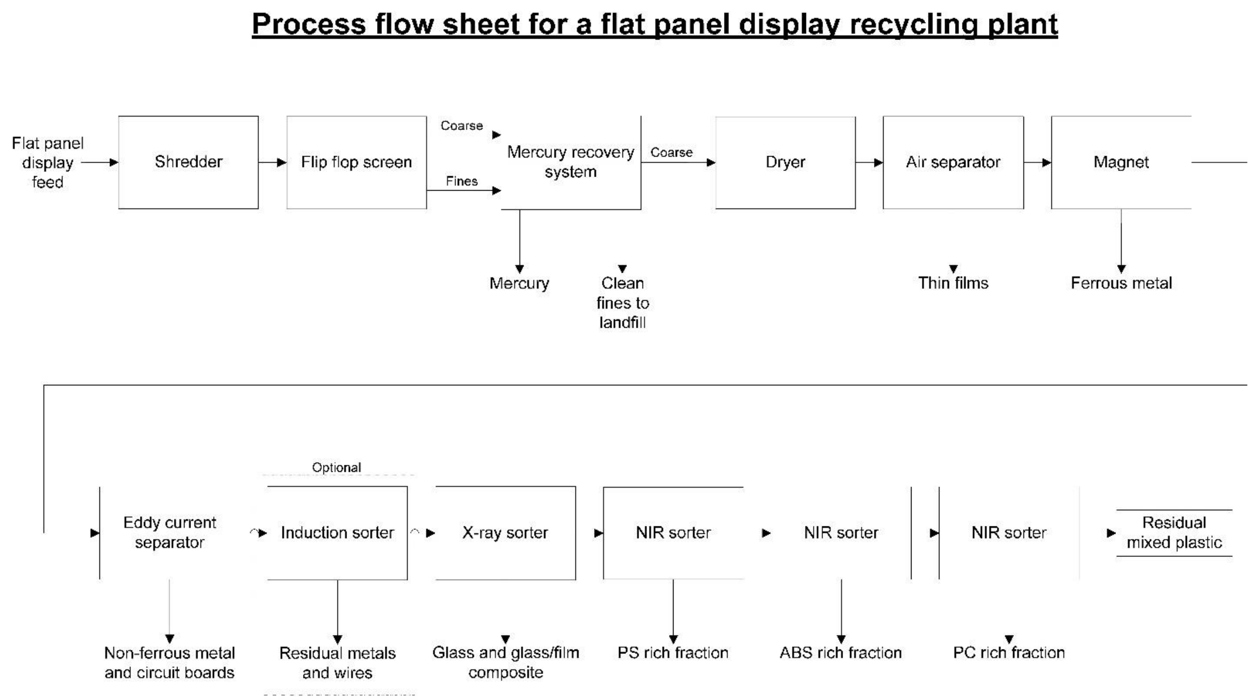


Figure 18: FPD recycling - detailed process flow (Cryan et al. 2010)

It emerges that the electronic display recycling sector is continuously developing, mainly due to the technological changes within this product group. Fluorescent lamps are being progressively replaced by alternative and energy-efficient ‘mercury-free’ systems (mainly light-emitting diodes—LEDs) in newer electronic display designs[23]. The absence of mercury, together with the lower costs and safety risks, will contribute to the future diffusion of shredding-based processing for displays, although this could lead to higher losses of resource and the downcycling of other recyclable materials.

CCFL’s, PWBs, TFT panels and PMMA boards are currently the key components that are extracted and sorted during the recycling of electronic displays, as they contain hazardous substances, scarce and precious metals, and valuable plastics. A design that facilitates the easy extraction of these components could help to divert them from other waste flows and ensure that they undergo optimised recovery treatment processes, which would improve the amount and quality of recycled materials[24].

Fully automated processes

There are systems currently being advertised that claim the fully automated (robotised) dismantling process of screens is already possible on a commercial level[25]. It is imperative to scrutinise these systems to ensure their fully functionality and effectiveness.

At the writing of this document no current studies have been available for fully automated systems.

[23] Buchert et al. (2012): Recycling Critical Raw Materials from Waste Electronic Equipment.

[24] Ardente, F. & Mathieux, F. (2014): Environmental assessment of the durability of energy-using products: Method and application.

[25] See for example https://www.fpdrecycling.com

3.2 Lamps

Many different types and shapes of lamps can be found for illumination in buildings as well as in other electrical and electronic equipment, such as information technology and telecommunication equipment. All these lamp types contain hazardous components or substances, which is illustrated in *Figure 19*.

Figure 19: Hazardous substances found in different types and shapes of lighting products (Reclite SA (Pty) Ltd 2019)

Most lamps contain heavy metals such as mercury and metalloids such as arsenic. Mercury, being the most hazardous one, is highly toxic to humans, fauna and flora, as it has the capability to accumulate in organisms (bioaccumulation). When the lamp breaks, the mercury is released as vapour or elemental form and be a threat to handler's or consumer's health or the surrounding environment. This is because Mercury is an odourless neurotoxin and can be inhaled without you being aware of it.

Metallic mercury (Hg) is an odourless and silver coloured fluid. It is the only metal which is liquid at room temperature. It is important to know and remember that mercury vaporises at room temperature. This also applies for mercury which is blended with fluorescent powder or amalgamated to glass and/or metals. Mercury is insoluble in water, but it easily forms amalgams with other metals and it cannot be "neutralized" to less toxic substances in the environment. Mercury can pollute both the air (in vapour form) and water if allowed to encounter surface or ground water.

Regular blood-tests of handlers should ensure that limit values of mercury (50nmol/l blood) are not exceeded. If these rules are followed the risk of negative health effect is minimal. In severe cases of contamination or exposure special caution must be taken and correct clean-up and health measures must be taken.

Handlers need to be monitored for mercury exposure and this is done as follows:

- Annual mercury blood monitoring of all handlers to check mercury concentration levels in the bloodstream. A baseline test must be done at the start of the handler's employment to establish mercury levels before working with the waste. Urine tests are also sufficient, but more frequently.
- Indoor air quality testing must be performed around the operating equipment on a biennial basis to ensure that the engineering controls are still effective.

It is important for the handler to be taught the following:

- PPE should always be fit for purpose. That means that it must protect the person against any potential harm that may arise from the activity or task for which it is being used.
- When dealing with waste lighting lamps, the main areas of potential exposure are through inhalation (Breathing), ingestion (Mouth) or injection (Cuts).
- Inhalation occurs when working without an appropriate breathing device, in an environment into which harmful vapours have or are being released.
- Ingestion occurs when solid particles enter the body through swallowing. Ingestion can also occur through contact with the skin or mucus membranes.
- Injection occurs when the skin is punctured through a cut or similar injury, and consequently, toxins enter the blood stream.
- In the case of breakage, do not clean up the spill with a vacuum cleaner or similar device, but follow the correct clean-up procedures.

Lamps that contain small printed circuit boards, capacitors etc., precaution must be taken so that separated components recovered after treatment are managed correctly.

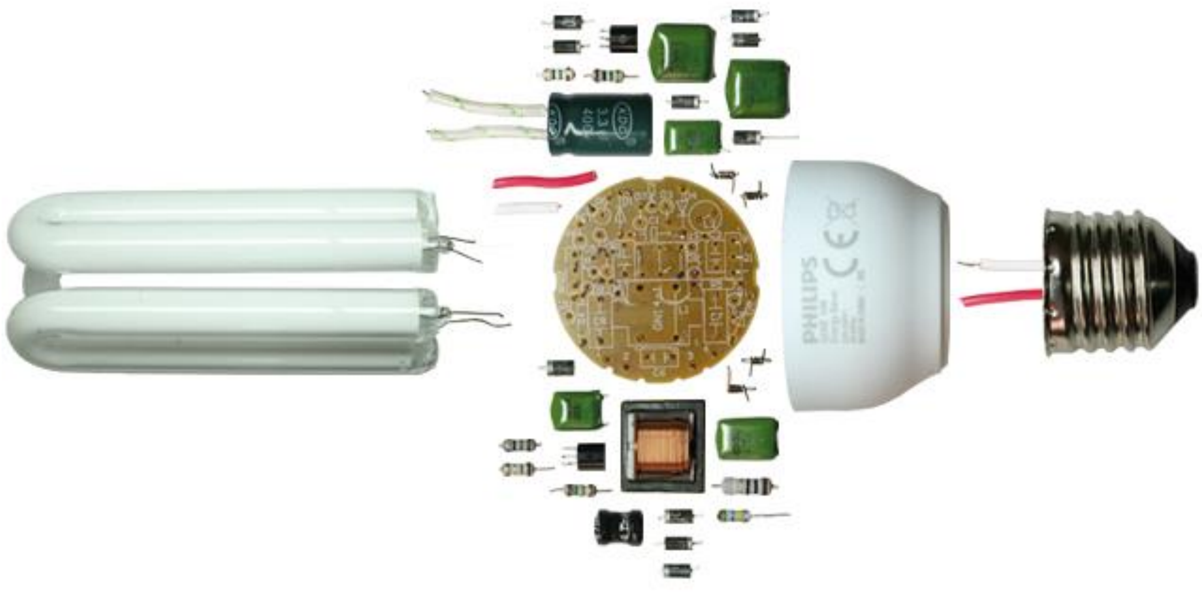


Figure 20: Components of a compact fluorescent lamp (Reclite SA (Pty) Ltd 2019)

Figure 20 shows the components of a common household compact fluorescent lamp. *Figure 21*illustrates the components of a standard LED household spot lamp. Note the small printed circuit board and the capacitor. These together with the LED diodes and lamp tube (CFL) contain heavy metals and hazardous substances and should be treated in a specialised lamp treatment facility.

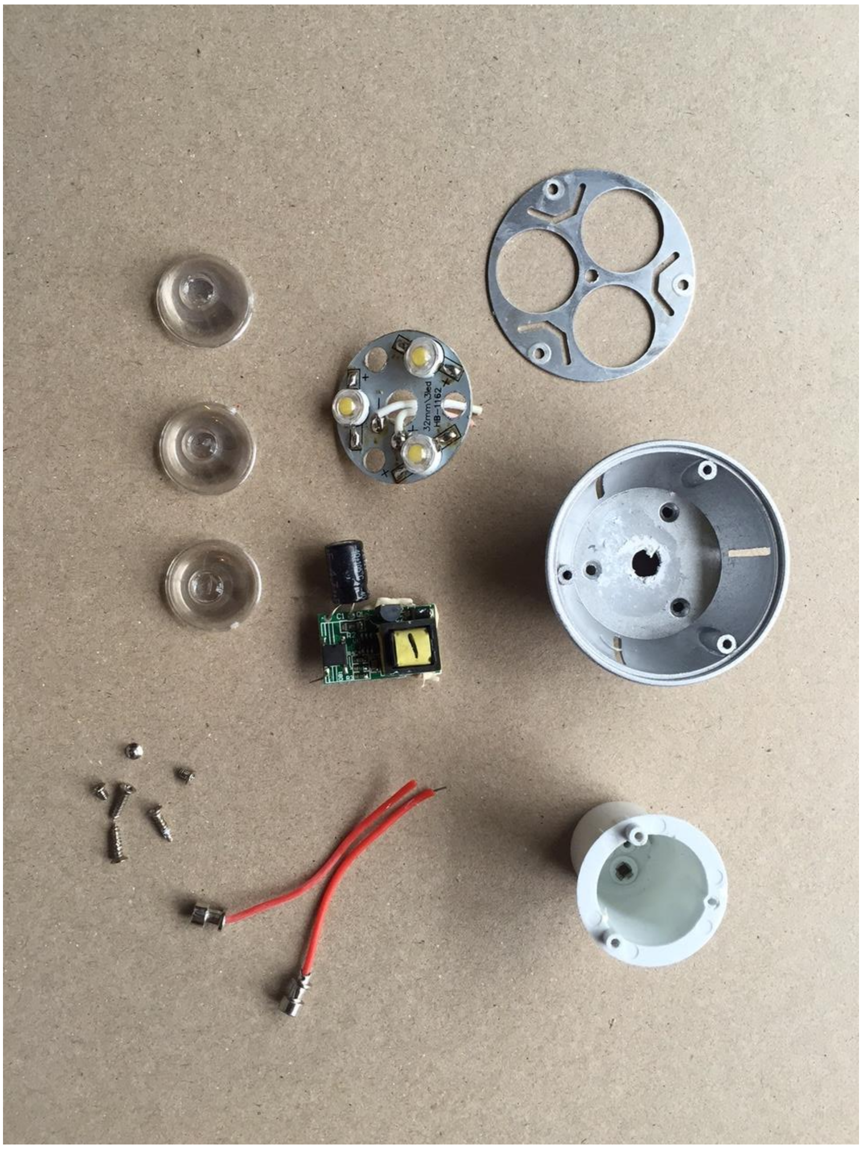


Figure 21: Components of an LED household spot lamp (Reclite SA (Pty) Ltd 2019)

Lamp localisation in other electrical and electronic equipment

Lamps can be found in various other electrical and electronic equipment, such as in screens of information technology and telecommunication appliances, and for illumination in ovens, fridges, among others. This equipment must be de-polluted during dismantling and the lamps must be sent to a certified and competent lamp treatment facility. Further information can be found in chapter 2.2.1 and 2.5.4.

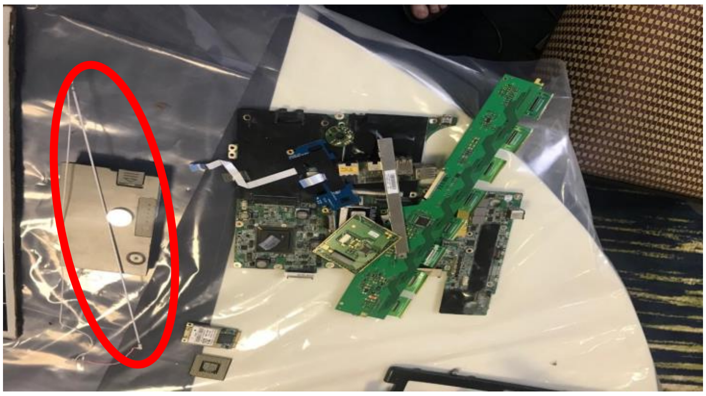


Figure 22: Fluorescent lamp found in laptop screens containing high concentrations of mercury (Reclite SA (Pty) Ltd 2019)

3.2.1 Treatment processes

As Reclite SA (Pty) Ltd. is one of the leading companies for lamp recycling in Africa, some of the information provided in this chapter is based on the example of Reclite SA (Pty) Ltd.

Overview

A general overview of the waste process flow from collection to final advanced treatment is illustrated in figure 23. The different steps of the lamp waste treatment processes are as follows:

- Pre- processing / dismantling
- Lamp crushing and fraction separation through lamp processor
- Final advanced treatment or beneficiation of fractions

Figure 23: Lighting waste process flow from collection to final advanced treatment (Reclite SA (Pty) Ltd 2019

Pre-processing

Mechanical drum top crushing

Although this method is being used less globally, this practice still occurs in some countries.

Drum top crushing using hepa-filters is a form of pre-treatment and needs to be strictly controlled and must strictly follow the manufacturers operational guidelines. Do not use manual drum top crushing mechanisms (hand turned) as these are unsafe and have a high health, environmental and safety risk.

The drums used need to be UN rated for mercury, and the drum weights when filled must not exceed 180 Kg's for safe handling and transportation. The drum must be labelled and sealed with a suitable clamp seal that does not easily open. Safe loading and unloading for transportation and storage guidelines must be adhered to.

The sealed and labelled drums containing the pre-crushed lamp waste is transported to the final processing plant for further crushing and separation.

It is important to note that only linear fluorescent tubes can be pre-crushed in this unit and under no circumstances must any other lamp type be crushed in this unit, especially HID (high intensity discharge lamps). This pre-crushed material musty be free on any other contaminants, water, and must not pre-treated with wet or dry chemicals such as sulphur. The drum must be sealed, labelled and prepared for transportation to the final treatment/recycling facility.

Figure 24: Drum top crusher with HEPA-filtration (Reclite SA (Pty) Ltd 2019)

Safety precautions during clean-up or in case of breakage

Do not use a vacuum cleaner for broken fluorescent lamp residues and follow proper clean up procedures.

Figure 25: Safety precautions during clean-up or in case of breakage of lamps (Reclite SA (Pty) Ltd 2019)

Use sticky tape, such as duct tape, to pick up any remaining small glass fragments and powder, thereafter, wipe the area clean with damp paper towels or disposable wet wipes.

Figure 26: Safety precautions during clean-up or in case of breakage of lamps (Reclite SA (Pty) Ltd 2019)

Figure 27: Safety precautions during clean-up or in case of breakage of lamps (Reclite SA (Pty) Ltd 2019)

Different technologies used for lamp treatment

There are different technologies for mechanical lamp treatment in the world. The two major types are dry processing (no water or chemicals added) and wet processing (water and chemicals added). The preferred technology is the dry process as this eliminates the need to manage additional chemicals and waste streams from the process.

The two major dry technologies are found in the EU. The preferred technology (based on the number of units operating worldwide exceeding that of the other technology) is from Sweden. A comparative survey was conducted on the two dry technologies involving various recyclers that produced feedback and the comparison is shown in table 6, where items that had a common thread in terms of feedback is presented.

The remainder of this document will focus on this technology only as an option for lamp treatment.

Table 6: Comparison of the two major dry technologies for lamp treatment (Reclite SA 2019)

Recycler Survey	Sweden	Other EU
Manufacturing comparison	Specialist manufacturer of a full range of machines for recycling of lamps and recovery of mercury.	A recycler who has built their own machine based on Swedish design and now sells this to others.
Manufacturing comparison	Has delivered more than 380 machines to Recyclers and lamp manufacturers world- wide during the 30 years they have been in operation. All machines are CE marked and follow the European machine directives for machine supply. Manufacturer has a great number of equipment that has been in operation for up to 20 years. Technology is WEEELABEX certified.	Has supplied lesser machines worldwide < 20. An Australian recycler had one of each and preferred Swedish machine, stopped using other machine.
Manufacturing comparison	Minimizes the use of high wear items such as conveyors wherever possible steel augers are used that are long lasting and relatively simple to replace in any country with an existing concrete industry.	High use of conventional conveyors; very little automation and interlocking of machine; highly dependent on highly skilled operator.
Manufacturing comparison	Has a wide range of size options, and offers other treatment options for by products from lamps such as full mercury recovery equipment.	Manufactures 2 different machines and crushers, mercury recovery equipment and no special HID processor.
Operational comments	Air filtration system is 3 stage system with use of cyclone self-cleaning and maintaining filter cartridges and double back up activated carbon filters with leak monitoring.	Simple high maintenance bag filters and large single stage activated carbon filter dome. High use of activated carbon without any redundancy or leak monitoring.
Operational comments	Supply their machines under warranty and guarantees regarding emissions and residues on glass. Many results were received from various recyclers from accredited laboratories showing air emissions results and fraction cleanliness.	Appears sturdy, but only crushes (reduces volume); mercury powder and other contaminated mercury fractions are sent to other facilities for mercury recovery and processing, or where not available to landfill. At the time of the survey no representative or accredited laboratory results could be made available for glass residues or emissions.
Operational comments	Machinery can be constructed on small space, the crush & separation plant fits into a 20-foot container which makes operation very easy in small spaces and ideal for smaller applications. Is very flexible on layout and size options.	Machinery is made in a specific layout; very little experience with modification due to low amount of plants being used worldwide.

Recycler Survey	Sweden	Other EU
Operational comments	Is the best available technology in the world to date, after lab analysis done on fractions from both technologies, Swedish machine produces cleaner fractions with no residues, making it more desirable for downstream vendors and treatment options. Produces a cleaner powder fraction.	Very dirty glass produced, still has plenty of residue such as powder and mercury contamination. End caps are not separated completely, still contain wires and glass (from linear tubes) and plastic ends with electronics (CFL's). Further high investment is needed to purchase machines that can further process these fractions to be cleaner.
Operational comments	Good value for investment	Not so good value for investment

In the following, the Swedish dry technology for lamp treatment will be described in more detail.

Swedish dry technology for lamp treatment

The machine capacity of the Swedish dry technology for lamp treatment ranges from 200 kg per hour (Model LP 200) to 1200 kg per hour (Model LP1200). The most common machines used worldwide are listed in table 7. Numbers are based on average weights.

Table 7: Most common machines of the Swedish dry technology used worldwide (Reclite SA (Pty) Ltd 2019)

Model No.	LP 400	LP 600	LP1200
Capacity in kg/hour	400	600	1 200
Linear Fluorescent tubes (1.2m - 4ft)	1 491	2 236	4 472
Drums of crushed CFL's per hour	5	8	15

A schematic of the technology can be seen in *Figure 28*.

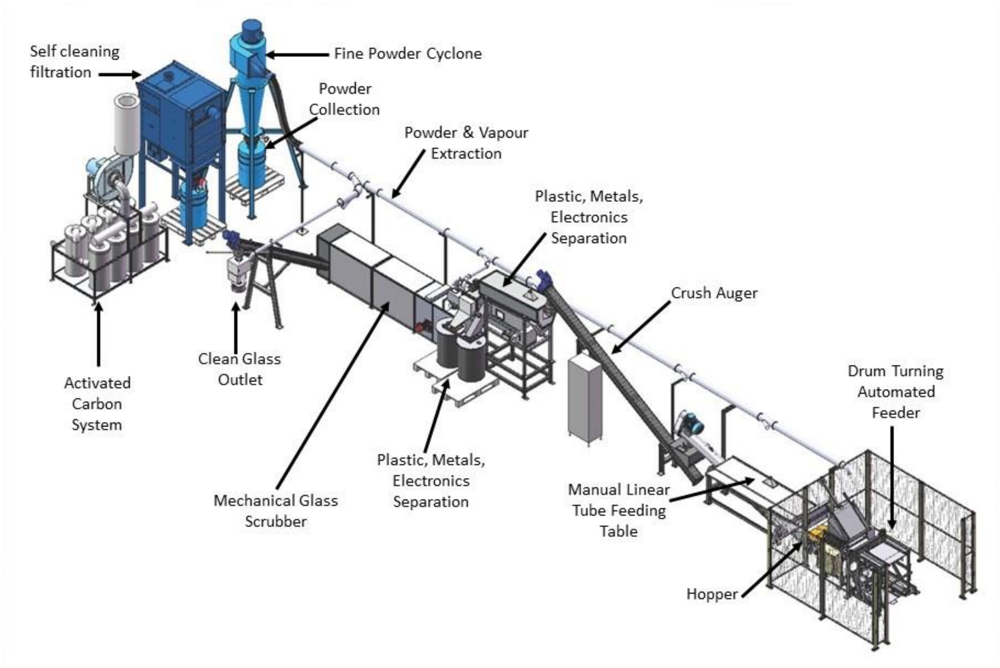


Figure 28: Schematic of the Swedish dry technology for lamp treatment (MRT system 2019)

Utilising drums for storage of whole CFL's is the most effective method and this what the drum turner should be used for. Although the machines do treat crushed material in drums proceed with caution as contamination is harder to detect.

The machine utilised by Reclite SA in South Africa is a LP 600 (see *Figure 29*). The machinery has been installed in a U-shape configuration for operations space efficiencies. It is important to note that the machine can run both drums and manually fed linear lamps at the same time.

Figure 29: Swedish dry technology machinery type LP600 at Reclite SA in South Africa (Reclite SA (Pty) Ltd 2019)

Operational features of the machinery as summarized in table 8.

Table 8: Operational features of the LP600 as installed at Reclite SA in South Africa.

Packaging removed from lamps	• All recyclable general waste such as paper, cardboard, plastic, tetra pack etc. will be separated from the non-recyclable waste and deposited into the various dedicated containers provided on site
Preparation and processing	• Waste is stored in the production que for processing • Waste is stored for no longer than 3 weeks before processing • Lamps are crushed and separated in the treatment machine into various fractions • Fractions are weighed and recorded in the inventory/mass balance system • This is processed according to health and safety procedures and machine operating parameters • All fractions go to authorised final advanced processing treatment and recyclers either internally or externally
Documents and certification	• A waste manifest must be handed to the generator upon collection/receipt of waste. • A weight slip is generated upon receipt of lighting waste. • A recycling/destruction certificate will be generated after processing. • Copies of documents and certificates must be kept safely for a minimum of 3 years.

3.2.2 Fractions separated and recovered in the lamp processing step

The fractions listed below are recovered from lamps. For illustration purposes, the fractions recovered from a fluorescent tube are presented in *Figure 30*.

If there are off-take partners or facilities available locally or regionally, fractions can be sent to these facilities, and if not, international off-take partners or further treatment options must be considered at possible further cost, as landfill should be the last option considered. Re-use or disposal options for the recovered fractions may include:

- Plastic - Non-BFR plastics can be pelletized to make new plastic products or send to further recycling, see chapter 2.5.6.
- BFR Plastic - send to landfill or for energy recovery.
- Electronics (ballasts, starters, circuit boards, wiring, LED diodes) - further recycling, see chapter 2.5.2 and 2.5.4.
- Ferrous metals - sent to smelters, into steel fabrication, see chapter 2.5.8.
- Non-Ferrous Metals - sent to smelters, see chapter 2.5.7.
- Glass - sent to further processing, can be used in industrial applications or other options such as road filler material or landfill.
- Leaded glass – sent to landfill, possibility of use in certain industrial sectors or smelters. Leaded glass can be used in a lead smelter to make industrial glasses, alternatively if enough feedstock is available a specialised glass smelter can be used to separate the lead from the glass liberating the lead in ingot form and the glass for further processing
- Phosphor powder and LED diodes- further processing to recover minerals or send landfill, see chapter 2.5.5.
- Mercury (captured in activated carbon from vapour form, pellet form) - further processing or high hazard landfill facility, see chapter 2.5.5.

It may be a requirement from the off-take facilities that an assay report is given that cleanliness and quality of the fractions are proven to be suitable for re-use in some instances.

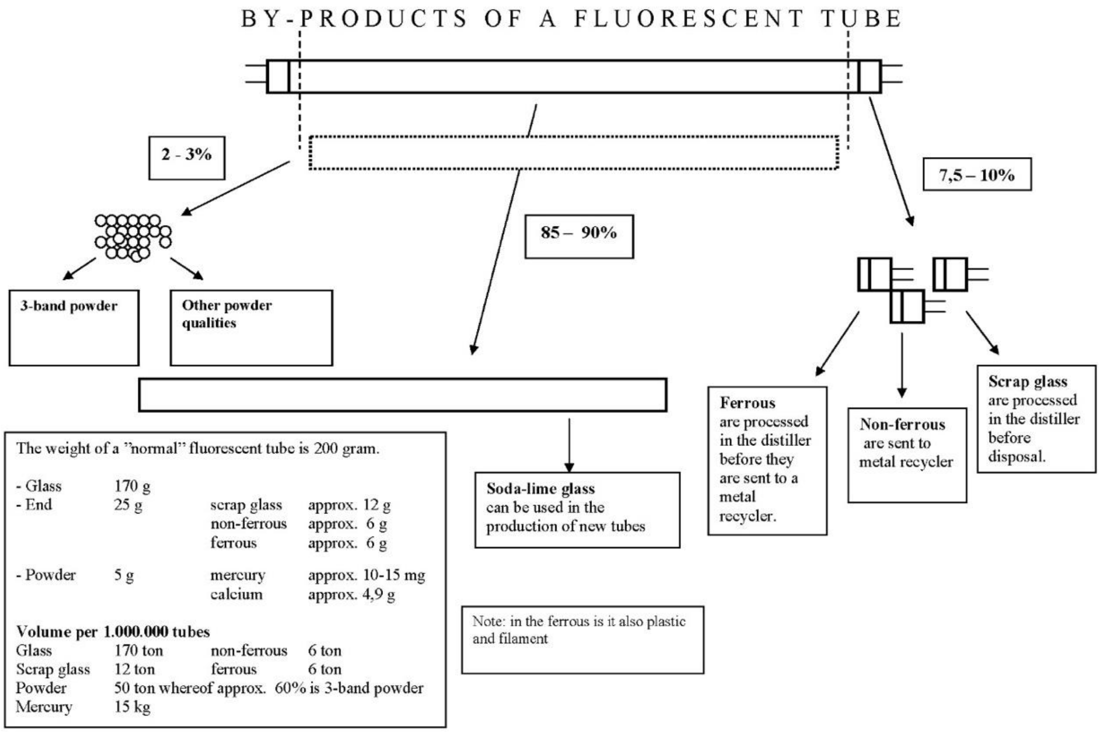


Figure 30: By-products from a linear fluorescent tube (Reclite SA (Pty) Ltd 2019)

3.3 Large equipment

Appliances falling under the collection group "large equipment" are normally mechanically processed in large-scale shredder units. After the crushing and decomposition of materials in the shredder, the fractions undergo sizing and sorting procedures.

The first step of mechanical processing for large WEEE is the reduction of volume. To do so, large WEEE undergoes a process of pre-compaction, provided that the harmful substances have already been extracted. This can for example be done by means of rollers. Hereby, the rotor revolution creates centrifugal forces, which in turn set the hammers in a rotary motion. After this pre-compacting, the material is pressed onto the striking side of the anvil, which is placed in front of the grate beneath the rotor. By the blows of the hammers, this leads to a further reduction of the materials in terms of size. Further information on the procedure can be found in chapter 1.3.1.

Afterwards, the material, which is now significantly reduced in size, passes through the grating. Hereby, the grating sizes the fractions. From there on, the fractions are carried into the wind classifier unit that will sort the fractions. To facilitate the transport, the two units should be connected via a conveyor belt. As dust and air from the shredder room contain micro particles of metals, they should be treated in an attached dust-removal system. An example of machinery to use here is the high-capacity cyclone, which divides light substances such as textiles or foams from heavier fractions. Further information on the technology can be found in chapter 1.3.1. Dust and other remnants can then either be reconditioned and recycled respectively or disposed.

The ferrous fractions from the shredder heavy fractions are extracted using a magnetic separator. Using an eddy-current separator, the remaining, non-ferrous fractions can be further reconditioned. Other options for further reconditioning are sensor supported picking procedures or manual sorting.

After sorting through the wind-classifier, the remaining non-metallic fractions are either prepared for disposal, to serve as substitute fuels or treated for further metal separation. To do so, screening machines such as screening drums, further crushing units, e.g. hammer mills and sorting technologies, e.g. magnetic and eddy-current separators are used. Further information about screening, crushing and sorting technologies can be found in chapter 1.3.1.

A last crucial step is the exhaust purification. During the whole shredding process, suction extraction should be carried out. To purify the exhaust air, inertia-force separators and wash-method dust removal are applied. The dust can afterwards be disposed.

Other output materials are shredded light material such as plastic-rich fractions and ferrous-meta-rich fractions, which can both be further recycled. On the other hand, there are also non-ferrous fractions produced. They contain primarily copper and aluminium and can, after further refurbishing, be recycled, too. Another output material is the shredder residue, which contains primarily mineral material but also rubber and plastics that can be recycled.

The mechanical processing of large electronic and electrical equipment is summarized in the figure below.

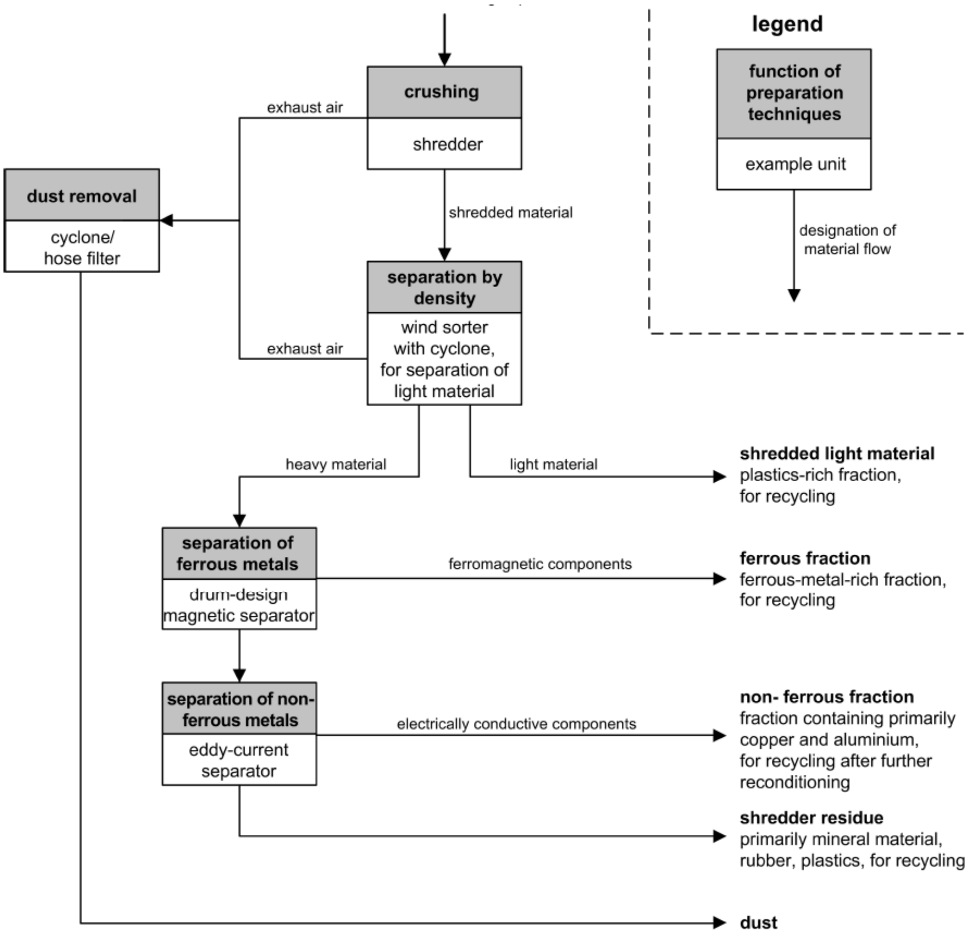


Figure 31: Schematic overview of the mechanical processing of large WEEE (VDI 2343, part 4, p. 36)

3.4 Small equipment, IT + T[26]

This sub-chapter gives an overview of mechanical processing procedures for small equipment, IT and T equipment. An exception is made for visual display units, which are, due to their special construction and composition as flat panel displays, explained in chapter 2.1.1.

Even though the devices belonging to this collection group fulfil a wide range of different functions and can heavily vary in terms of size and weight-units, these devices are processed using the same procedures.

They range from toasters, electric razors and mobile phones to even modern-day car-keys, and generally have a high proportion of plastics paired with a relatively high non-ferrous metal content.

Since the devices are very heterogenous in composition, the aim of preparation is to create fractions that are as homogeneous as possible and to thus facilitate the following recycling processes. Typical fractions that are created include fractions rich in specific types of plastics, aluminum, brass and copper and ferrous metals, always depending on the respective downstream processing procedures.

Normally plants with one to three stages are run, whereby each stage consists of a crushing process, followed by a sizing and a sorting process. Before separation can take place, the materials need to be crushed. Crushing is the necessary precondition for separation processes. This is because some sorting techniques only function at optimal levels only. Therefore, the creation of a certain, pre-defined particle size is crucial. Through crushing, there can furthermore be a homogeneous and pre-defined range of particle sizes achieved. For further information on crushing techniques, kindly consult chapter 1.3.1.

After crushing, the sizing process makes sure the required particle fractions for downstream processes are prepared. This is because sorting techniques depend on specific pre-conditions, such as particle size or specific distribution of particle sizes, e.g. when using an eddy-current separator or a pneumatic table respectively. More information on sizing techniques can be found in chapter 1.3.1.

After crushing and sizing, the last step is sorting. The sorting technique applied hereby depends on the material fractions that need to be sorted. Magnetic separation is applied to extract ferrous-metal fractions. The ferrous-metal fractions can still include plastics and non-ferrous metals adherent to the ferrous-metals fractions if decomposition has been insufficient. An example could be sleeves moulded into plastics casings.

Generally, plastic components are unproblematic for the metallurgical processes to follow. For the separation of individual plastic polymers, either sensor-supported sorting techniques or techniques that sort based on density, such as sink-float methods, are applied[27].

On the other hand, copper for example can have negative effects on the quality of the later refined material. Therefore, an additional treatment step for ferrous metals may be needed.

Aluminum pieces can, be separated by eddy current if the particle size is below one centimeter. However, the aluminum fractions can be polluted with copper content. This would make a further separation step necessary, e.g. through sink-float separation[28].

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[26] VDI 2343, part 4, p. 45-49.

[27] Schiemann, J (2007).: Handbuch Verwertung von Brennstoffzellen und deren Peripherie-Systemen. IUtA e.V. Kreislaufwirtschaft und Recycling, Duisburg.

[28] Windelen-Hoyer, U (1992).: Recycling von Kunststoff-Metall-Verbunden. Aus Schriftenreihe: Kunststoff + Recycling, München, Wien: Carl Hanser Verlag.

Generally, a high proportion of non-ferrous and precious metals can be found in the fractions resulting from the combined crushing and sizing processes. Currently neither eddy current separation nor sensor supported sorting techniques are suitable for small particle sizes of less than 2 mm. Such small particles can still be separated by applying techniques that separate by density: In a first step, plastic particles are filtered out, for example with a pneumatic table. In a second step, aluminium-rich and copper-rich fractions are separated by applying a sink-float procedure.

After mechanical processing of appliances falling under this collection group, typically output fractions are ferrous metals, non-ferrous metals, hard faced PCBs, plastic fractions such as ABS, PS, PE, PP and EBS, dust and undesirable substances that are manually extracted after a first decomposition step.

The mechanical processing of small electronic and electrical equipment as well as the process for IT and T equipment is summarized in the figure below.

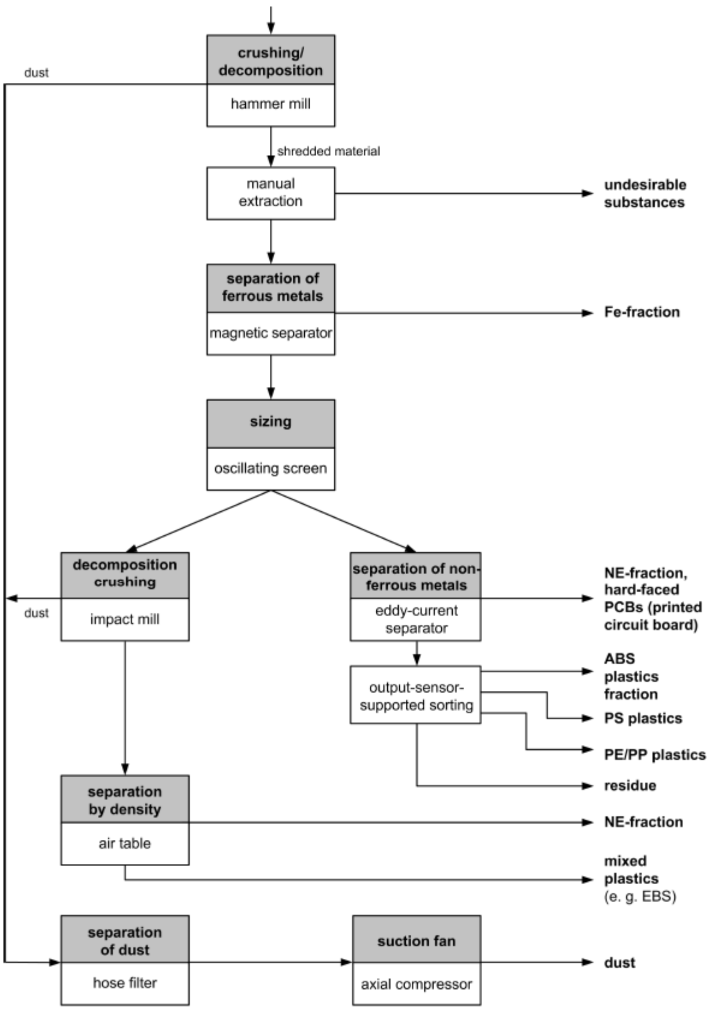

Figure 32: Schematic overview of the mechanical processing of small WEEE, IT and T equipment (VDI 2343, part 4, p. 47)

3.5 Further (mechanical) processing and refining of output materials

3.5.1 Cables

With the rapid development of the power industry and the constant update of electric and electronic products, the quantity of waste wires also increases. Because the copper contained in the waste cables is of high purity and its recycling energy consumption is low, waste cables have become an important source of raw materials for the reclaimed copper industry. Recycling of electrical cable waste requires a separation between the metal and the insulating material. Due to bad copper recover practices, best practice must encompass the harmless recycling and efficient utilisation of waste cables.

The recycling of these cables and wires mainly concentrates on the recovery of metals such as aluminium and copper, rather than other insulation.

Polymeric insulation materials from the waste data cables are often disposed into landfills or incinerated, since they have only lower value in the recycling chain. Based on the collection data of the South African recycler Reclite, it has been estimated that the major constituents are copper (~58%), polyvinyl chloride (~20%) and polyethylene (~16%). Similarly, polycarbonate (~3%), silicon rubber (~1%), steel (~1%) and other material (~1%) such as cotton cord were also present as minor components. Out of these, polyvinyl chloride is the dominant polymer present in data cables.

There are many different types and sizes of cables and wires, that can be found in households and different industries. The most common are found in day to day electronic and electrical products with the insulation materials being hazardous due to their inherent chemical properties if not treated utilising environmentally best practice and in a safe manner.

Wires can be divided into three major groups:

- **Bare copper wire**: Wire that is not insulated can be used in a variety of ways.
- **Enamelled copper wire**: This type of copper wire has a form of insulation made from enamel.
- **PVC wire**: PVC wire is the most common form of wire today.

In more detail, the most common cables and wires are listed as follows:

Table 9: Description for most common cable types

Type of cable	Description of the cable type
Coaxial cable	Coaxial cable, or coax is a type of electrical cable that has an inner conductor surrounded by a tubular insulating layer, surrounded by a tubular conducting shield. Many coaxial cables also have an insulating outer sheath or jacket and is used for radio frequency signals, for example in cable television distribution systems.
Fibre Optic cable	Fiber optic cable are long, thin strands of very pure glass about the diameter of a human hair. They are arranged in bundles called optical cables and used to transmit light signals over long distances. A fiber-optic cable, also known as an optical-fiber cable, is an assembly similar to an electrical cable, but containing one or more optical fibers that are used to carry light.
Direct-buried cable	Direct-buried cable (DBC) is a kind of communications or transmissions electrical cable which is especially designed to be buried under the ground without any kind of extra covering, sheathing, or piping to protect it.
Flexible cables	Flexible cables, or 'continuous-flex' cables, are electrical cables specially designed to cope with the tight bending radii and physical stress associated with moving applications.
Heliax cable	Heliax Cable is part of Coaxial Cable. This selection of Coaxial Cables is designed for signal transfers in am/fm radio, UHF/VHS TV, and other communication systems.
Non-metallic sheathed cable (or non-metallic building wire, NM, NM-B)	NM-B stands for Non-Metallic type B because it has a PVC (Poly Vinyl Chloride) jacket instead of a metal clad jacket, and Type B is for residential installations. It is a basic indoor electrical wire used to deliver power from an electrical box to lights,

	outlets and appliances. It cannot be used outdoors because the jacket is not prepared to handle the wear and tear.
Metallic sheathed cable (or armoured cable, MC)	MC stands for Metal Clad due to the interlocked armour surrounding the THHN wires (Thermoplastic high-heat resistant nylon-coated wire). The aluminium armour also acts as conduit when used for indoor applications. Many times, NMB electrical wire is required to be installed within conduit for indoor applications, but now MC cable can act as the electrical wire and conduit in one.
Multicore cable	A multicore cable is a type of electrical cable that combines multiple signals or power feeds into a single jacketed cable. The term is normally only used in relation to a cable that has more cores than commonly encountered and consists of more than one wire and is covered by cable jacket).
Paired cable	A type of cable that consists of two independently insulated wires twisted around one another. Composed of two individually insulated conductors that are usually used in DC or low-frequency AC applications.
Portable cord– Flexible cable for AC power in portable applications	A portable cord is a cable with multiple conductors used for temporary electrical power connections requiring flexibility. The cord can be employed in a range of applications, such as operating motors in small and large tools, equipment, power extensions, home appliances, and machinery.
Ribbon cable – Useful when many wires are required. This type of cable can easily flex, and It is designed to handle low-level voltages	A ribbon cable is a cable with many conducting wires running parallel to each other on the same flat plane. As a result the cable is wide and flat. Its name comes from its resemblance to a piece of ribbon.
Shielded cable – Used for sensitive electronic circuits or to provide protection in high-voltage applications.	A shielded cable or screened cable is an electrical cable of one or more insulated conductors enclosed by a common conductive layer. The shield may be composed of braided strands of copper (or other metal, such as aluminium), a non-braided spiral winding of copper tape, or a layer of conducting polymer.
Single cable (this name is also used for wire)	Single core cables are made up of a single conductor covered by a PVC insulation. They are mainly used in power and lighting circuits, both domestic and commercial applications. They are also used in the internal wiring of appliances suitable for installation in conduits and trunking.
Submersible cable	Submersible pump cable are designed for use in wet ground or under water, with types specialized for pump environmental conditions. A submersible pump cable is a specialized product to be used for a submersible pump in a deep well, or in similarly harsh conditions.
Twinax cable	Twinaxial cabling, or "Twinax", is a type of cable similar to coaxial cable, but with two inner conductors instead of one. Due to cost efficiency it is becoming common in modern very-short-range high-speed differential signaling applications.
Twin-lead	This type of cable is a flat two-wire line. It is commonly called a 300 Ω line because the line has an impedance of 300 Ω. It is often used as a transmission line between an antenna and a receiver (e.g., TV and radio). These cables are stranded to lower skin effects. Twin-lead cable is a two-conductor flat cable used as a balanced

	transmission line to carry radio frequency signals. It is constructed of two stranded copper or copper-clad steel wires, held a precise distance apart by a plastic ribbon.
Twisted pair	It resembles a paired cable, except that the paired wires are twisted. Twisted pair cabling is a type of wiring in which two conductors of a single circuit are twisted together for the purposes of improving electromagnetic compatibility.

For further information on different cable and wire sizes consult Annex 1.2.

Waste cable processing

Most cables received in recycling centres consist of a copper wire covered in PVC insulation. Recycling the copper makes sense, since it is a (naturally) non-renewable metal whose exploitation incurs serious environmental effects. Recycling of electrical cable waste requires a separation between the metal and the insulating material.

There are two approaches to cable processing: The low-tech option called wire stripping is used for low volumes. Hereby, the insulated copper wire scrap is stripped in order to divide it into insulation and clean copper wire scrap. The high-volume advanced tech option is called wire chopping. In this process, the insulated copper wire scrap is granulated and then separated in order to receive insulation scrap and clean copper wire scrap. Both processes are further outlined below.

In any case, a pre-processing step is necessary. Pre-processing is the step where the cables and wires are prepared before mechanical processing. Most copper cables and wire need some pre-processing to obtain the highest value. The insulation or other attached components brings its value down.

In this step all power plugs or connectors are removed manually from the cable by cutting them with the correct cable cutting tool. This is an important step as these items can cause damage to the mechanical processing equipment. It also important to remove any steel outer casings such as in the case of metallic sheathed or armoured cables.

The full process flow is outlined in figure 33.

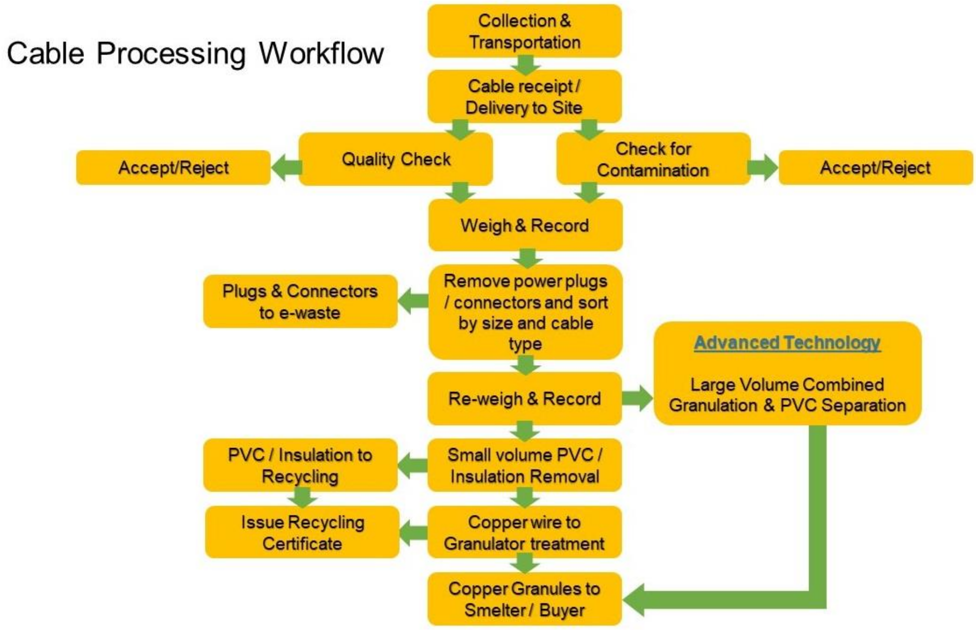

Figure 33: Cable processing workflow (Reclite SA (Pty) Ltd 2019)

Low volume low-tech processing

This involves the use of a combined manual and automated cable/wire stripping method, using machinery that is small and sufficient for the use in small ewaste facilities or pre-processing facilities. This method takes more time and labour, and therefore is only viable for small scale operators. There are many different types of machinery on the market and proper research should be conducted to find the option suitable for the purpose and operation. The following steps are followed for low tech processing.

Sorting

The cables are sorted by size as this is important for the low-tech machinery.

Insulation cutting and stripping

The cables are manually fed through the different sized cable points, or through a single size adjustable cable feeding point. The cable is pulled through and a sharp blade cuts the insulation along its length. Caution must be taken when using this machinery as there are pinch points and the risk of fingers or hands being possibly injured when feeding the cable through the machine. Always follow the manufacturers safety and usage instructions.

Copper wire manually removed from insulation

A worker then takes the cable or wire and manually strips or pulls the wire insulation casing off the copper conductor, exposing the copper core.

Fraction separation, storage and preparation for transport

The insulation or PVC is a re-usable resource, and the removed lengths of insulation are then placed separately in a container which can be sold to a plastics recycler for further processing, adding additional income for the small-scale collector or recycler. To achieve a higher income, the plastics should be cleaned from foreign material and then separated according to plastic type and content of BFRs. Separation can be done through sorting by density, e.g. sink-float process or separating tables. For further information on separating techniques, consult chapter 1.3.1. The plastics can then be recycled through mechanical, chemical or incineration processes. Further information can be retrieved from chapter 2.5.6.

Removing the insulation from the copper ensures that the small-scale collector or recycler or pre-processor can achieve a higher price by selling "cleaned" copper wire. The clean copper wire is placed in its own separate container and when sufficient volumes are reached is sent to a high-tech processing/granulation facility either in bulk bags or baled. Further recycling steps for copper are outlined in chapter 2.5.7.

A small machine for this scale of operation would cost in the region of $ 4000 to $6000.00.

High volume high-tech processing

This involves the use of a combined high-tech fully automated cable/wire PVC removal and granulation method, using machinery that is larger and sufficient for the use in large ewaste facilities or pre-processing facilities. This method is quicker, but more expensive in terms of capital layout, and therefore is only viable for large volumes of cables. There are many different types of machinery on the market and proper research should be conducted to find the option suitable for the purpose and operation. The basic functionality of the machine is as follows:

- The cables are fed with the insulation into the processing equipment into a hopper, with no prior size sorting required
- The cables and chopped into smaller pieces in the chopper

- The cables are then granulated further into smaller pieces which breaks up the various materials into fractions
- Any ferrous metal fractions are separated by magnetic separation and conveyed into a ferrous metal container
- The material is then granulated further, and all finer PVC dust is collection in a cyclone or chamber
- The copper granulates, plastic particles and non-ferrous metals such as aluminum is separated via electrostatic separation at the separation table and then conveyed into separate collection containers.
- Copper granulate, steel and aluminum fractions go to authorized final advanced smelting and the PVC granules and plastics go to authorized final treatment recyclers.
- The smelters then cast the copper into ingots, which is then traded on the metals exchange markets. These ingots will then be used to make new copper products.

Machine capacities range from small to medium cable recycling plants from 150 kg/h up to 1.700 kg/h and high capacity recycling ranging from 2.000 kg/h up to 10.000 kg/h (for all kind of cable).

All lines have a modular design for maximum flexibility and are tailored to suit specific requirements and facilities.

Further information on the economic values of cable recycling can be found in Annex 4.2.

3.5.2 Printed wiring boards and processors[29]

Printed wiring boards (PWB) often represent the most valuable fraction of WEEE. They contain several base, precious and special metals that can be recovered by specialized metal refineries. Amongst others, they contain iron, aluminum, copper, lithium, gold, palladium, silver and tin. With regard to their content of precious metals, different qualities of PWBs exist. A possible way to determine their grade (quality) is the gold content. Table 10 gives a potential classification of the board grades and corresponding PWB examples.

On the other hand, PWBs also contain several toxic substances like heavy metals or flame retardants. A major release of hazardous substances can be caused by an inappropriate treatment of the PWBs, e.g. uncontrolled wet chemical processes, incineration. Such processes present a high risk of losing value and usually imply harm to human health and the environment. In general, PWBs are preferably sold to refineries having high recovery rates and paying the best price for the material.

*Table 10: Possible classification of board grades according to the gold content. *prepared refers to the removal of heat sinks, Al frames, transformers, etc. (Schluep et al. 2015: Dismantling Guide for IT – Equipment, p. 89)*

Grade	Au content [ppm]	Occurrence (not exhaustive, not definitive)
Ultralow grade	up to 20 ppm	Unprepared boards from CRT monitors (TV & PC), HiFi, power supplies, small domestic appliances, etc.
Very low grade	up to 50 ppm	Prepared* boards from CRT monitors (TV & PC), HiFi, power supplies, small domestic appliances, etc.
Low grade	up to 100 ppm	Leached IT boards (very low to low grade)

[29] This subchapter is based on Schluep et al. (2015): Dismantling Guide for IT – Equipment, p. 89ff.

Medium grade	up to 200 ppm	IT boards (PC, server, printer), mixed connectors, LCD monitors, IT mother boards
High grade	up to 300 ppm	IT/telecom boards
Very high grade	above 300 ppm	Mobile phones, IT components (processors, etc.)

Due to the complex composition of PWBs, high recovery rates of the metals contained therein can only be met by an appropriate treatment in specialized plants. Different technologies like pyrometallurgy, hydrometallurgy, electrometallurgy or a combination of those are applied to recover the metals (for further information on these technologies, consult chapter 1.4). However, only integrated copper and precious metal smelter-refinery operations[30] – which combine different of the above-mentioned technologies – are able to cope with requirements such as environmentally sound treatment, high recovery rates, industrial scale of application, etc[31]. The main advantages of such combined plants are:

1. Recovery of multiple metals (in contrast to e.g. a treatment solely based on hydrometallurgical steps), allowing for a higher material revenue.
2. High efficiency (recovery rates) for the different metals, resulting in a higher material revenue.
3. Controlled processes that allow for a treatment under environmentally sound conditions (off-gas cleaning system, waste water treatment, etc.) and for safe conditions for workpeople.

PWBs or PWB containing fractions as well as small electronic devices such as mobile phones – once their battery has been removed – can be treated in integrated copper and precious metal smelter-refinery operations directly, meaning that no further size reduction is needed. They are then mixed with e.g. catalysts or other precious metal containing materials.

Such an integrated operation generally starts with a pyrometallurgy step. To separate the valuable metals, the PWBs and small devices are smelted together. This leads to a separation of the valuable materials. At the same time, organic compounds are converted to energy. Afterwards, different pyrometallurgy, hydrometallurgy and electrometallurgy unit operations can be used, depending of the aim of the refining process. An example of the different processing options is shown below[32].

[30] In short: Integrated metal smelter

[31] Schluep et al. (2009): Recycling - From E-Waste To Resources. Sustainable Innovation and Technology Transfer Industrial Sector Studies, p.29.

[32] Ibid, p.29ff.

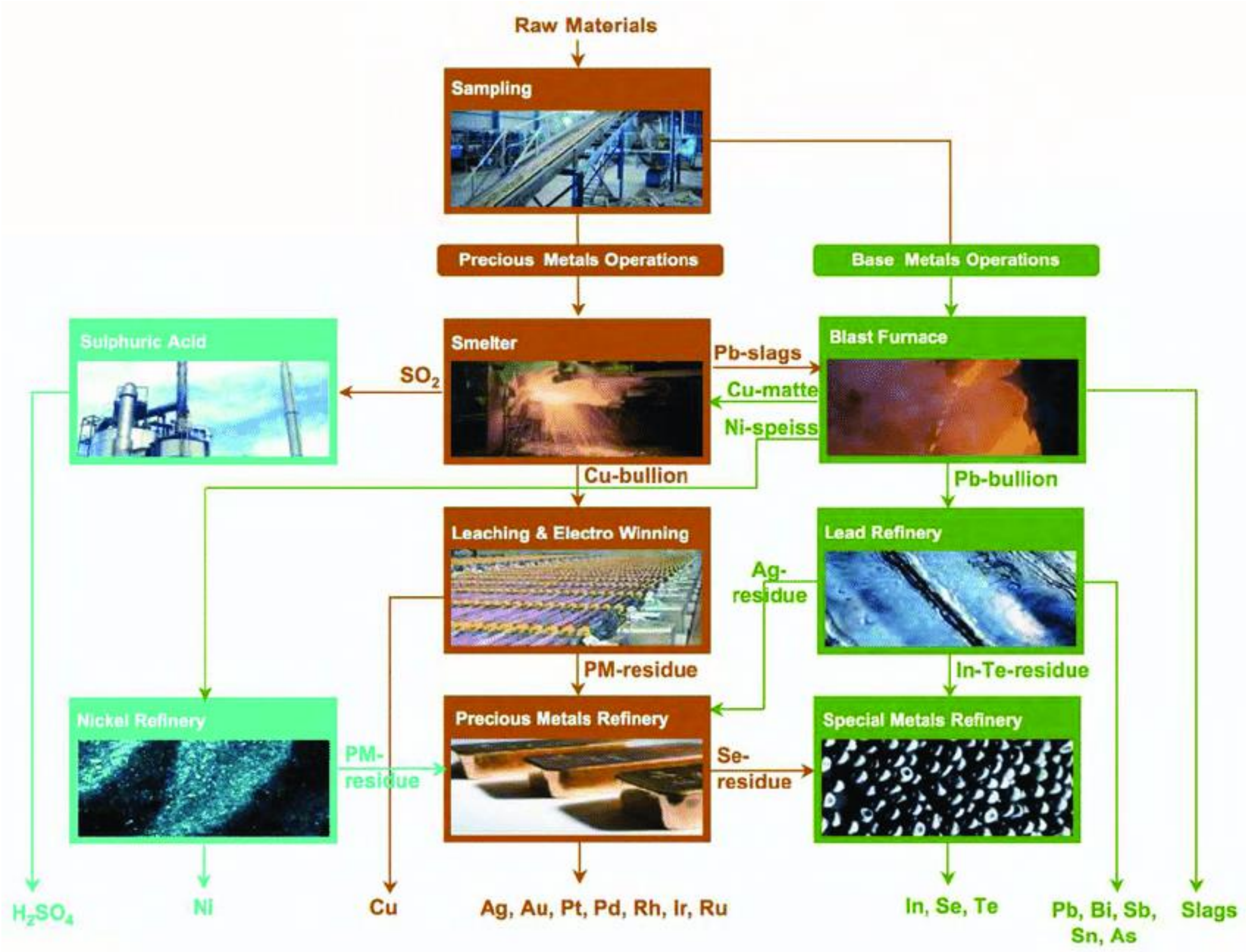

Figure 34: Example of how different pyrometallurgy, hydrometallurgy and electrometallurgy unit operations are used in the most appropriate/adequate combination to deliver an optimal recovery of materials according to Umicore Precious Metals Refining (Belgium). Smelter, blast furnace, lead refinery use pyrometallurgy unit operations; leaching, special metals and nickel refinery use hydrometallurgy unit operations and the precious metal refinery uses both hydro- and pyrometallurgy unit operations (Schluep et al. (2009): Recycling - From E-Waste To Resources. Sustainable Innovation and Technology Transfer Industrial Sector Studies, p.31)

High rates of recovered precious metal from complex e-waste materials are achieved through this integrated process. For example gold can be recovered at rates of over 95%[33]. It is therefore recommended to supply PWBs to integrated metal smelters on the global markets. Due to requisites like minimum lot shipment, it might be necessary to supply lower volumes of PWB to an intermediary. However, it should be ensured that PWBs are treated appropriately in any case.

3.5.3 Lead acid batteries

If incorrectly dealt with battery lead, plastic and acid, can negatively impact on the environment. Fortunately, these components are well suited to recycling. Lead-acid batteries top the list of the most highly recycled consumer product. Lead acid batteries are closed loop recycled, meaning each part the old batteries is recycled into a new battery. It is estimated that 98% of all lead acid batteries are recycled.

[33] Hagelüken, C. Recycling of electronic scrap at Umicore's integrated metals smelter and refinery. In: Erzmetall, 2006, 59, p. 152-161.

There are two steps to the treatment processing, a first processing step to separate the fractions and the lead smelting processing step.

Step 1 - lead acid batteries

In a first step the batteries are treated as follows:

The battery acid is drained from the batteries and sent to tanks for further treatment. This treatment can be done in two ways:

1. The acid is neutralized with an industrial compound similar to household baking soda. Neutralization turns the acid into water. The water is then treated, cleaned, tested in a wastewater treatment plant to be sure it meets clean water standards.
2. The acid is processed and converted to sodium sulphate, an odorless white powder that's used in laundry detergent, glass and textile manufacturing.

The battery is then broken apart in a hammer mill, a machine that hammers the battery into pieces. Further information on the procedure can be found in chapter 1.3.1. The broken battery pieces are then placed into a vat containing water, where the lead and heavy materials fall to the bottom and the plastic floats. At this point, the polypropylene pieces are scooped away, and the liquids are drawn off, leaving the lead and heavy metals. Each of the materials goes into a different recycling stream.
Afterwards, the polypropylene plastic pieces are washed, blown dry and sent to a plastic recycler where the pieces are melted together into an almost liquid state. The molten plastic is put through an extruder that produces small plastic pellets or granulate of a uniform size. The pellets are put back into manufacturing battery cases.

A summary of the activities in step one is outlined in Figure 35.

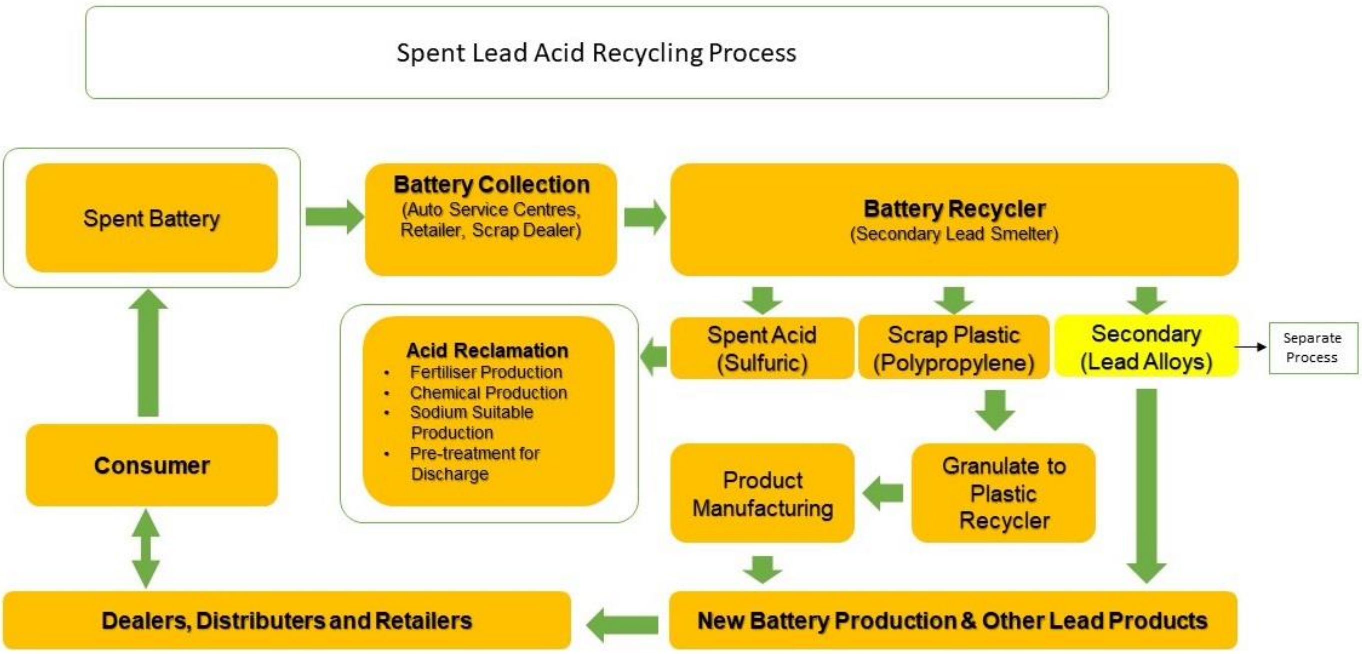

Figure 35: Overview lead acid battery recycling (Reclite SA (Pty) Ltd 2019)

Step 2 - Secondary Smelting

During the secondary smelting, differentiation is made between the following fractions.

Hard or Antimonial Lead

The component consists of furnaces which are used to melt the scrap lead under high heat to separate the metallic lead from a mixture of other substances. The mixture of scrap from this process consists of mainly: metallic lead, lead oxide (PbO), lead suplhate (PbSO4), and other substances/metals such as calcium (Ca), copper (Cu), antimony (Sb), arsenic (As), tin (Sn), and sometimes silver (Ag). The metallic lead produced from this process is also known as hard or antimonial lead produced and is packaged in a form of lead ingots, the furnaces are attached to a series of scrubbers which operate as part of a pollution abatement system to control air emissions.

Lead Refining

In this process, which may not be a part of the recycling facility, but in another refining facility, the antimonial lead is refined further in order to produce what is known as soft lead. The hard lead ingots are refined or "cleaned" by heated within smelting furnaces. It then passes through a blending kettle where additives are added which is used to produce special lead alloys. The molten lead is then poured into ingot moulds. After a few minutes, the impurities float to the top of the still molten lead in the ingot moulds. These impurities are scraped away and the ingots are left to cool. When the ingots are cool, they're removed from the moulds and sent to battery manufacturers, where they're re-melted and used in the production of new batteries.

Figure 36: Lead Ingots from the smelting process (Reclite SA (Pty) Ltd 2019)

Plastics recycling facility

The plastics facility reprocesses the shredded polypropylene plastic into palletised briquettes. The briquettes can be re-used in the making of new battery casings.

Acid Affluent Plant

The battery acid can be regenerated, but due to the low concentrations and contamination with lead sulphates, is limited to the battery industry, for use in other industries it would need to be cleaned and topped up with concentrated acid. There are technologies available which can provide the means to produce lead-free acid which can be processed further and converted into sodium sulphate (Na2SO4) and sold amongst others, to the laundry detergent, glass and textile manufacturing sectors.

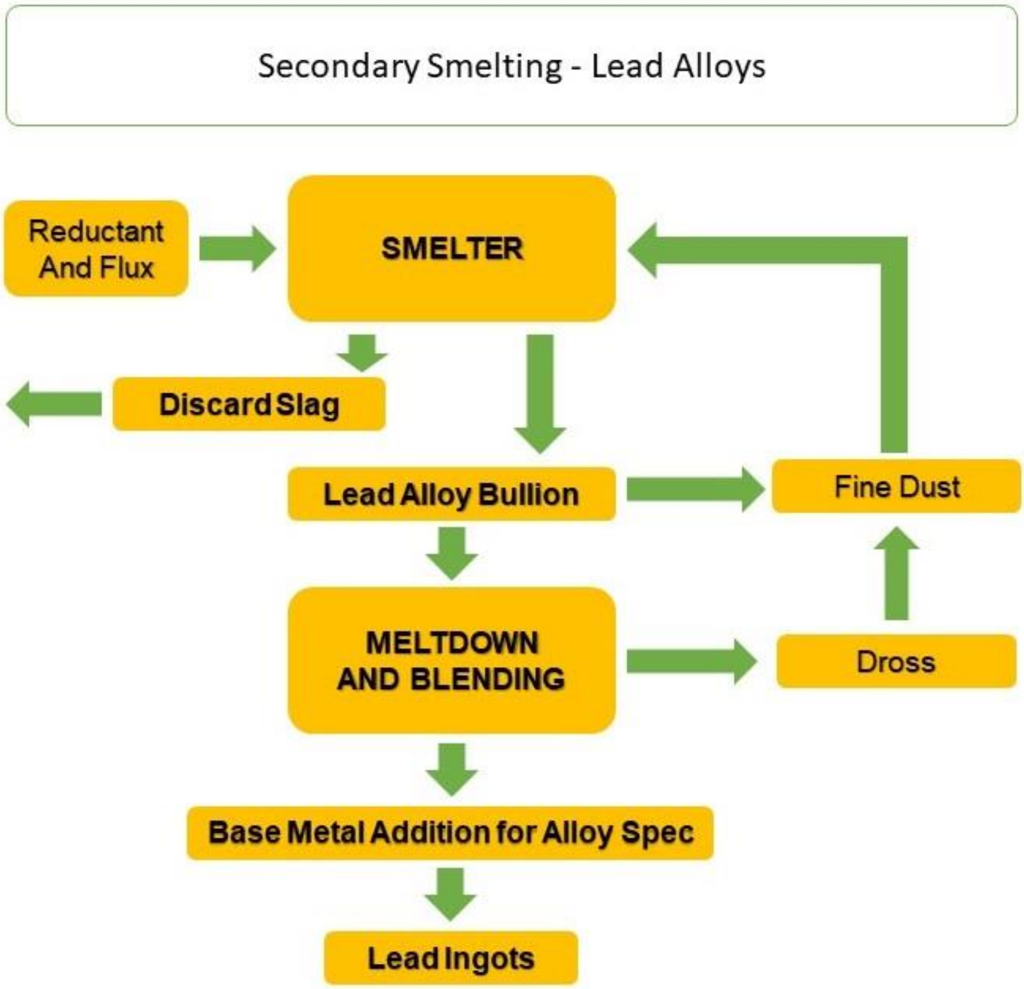

Figure 37: Overview of the second recycling step, including smelting for lead acid batteries. (Adaption by Reclite SA (Pty) Ltd., based on first national battery South Africa)

3.5.4 Lamps

This chapter summarizes some examples of advanced treatment processes for further beneficiation of some of the clean lamp fractions. The treatment processes are outlined following the example of Reclite SA (Pty) Ltd.

Glass cullet and non-BFR plastic

The crushed glass from the recycled lamps is processed further at Reclite SA (see *Figure 38*) to manufacture industrial products, such as paint additives. This beneficiation process requires an engineered glass and plastic processing machine to accomplish the required technical specification. The products are bagged and sold as commodities.

Figure 38: Reclite's glass and plastic processor (Reclite SA (Pty) Ltd 2019)

Mercury recovery as analytical grade

The mercury vapour or pellets that are captured from the lamp processor (ie. carbon pellets) can be recovered in an automated mercury recovery plant. The mercury is at 99% purity and can be sold as a commodity for use in other electronics etc. It is important to follow strict ethical value chain principles ensuring that the mercury is traded for safe and controlled use and does not end up in the wrong hands which can cause high health, safety or environmental risks.

Figure 39: Automated Continuous Mercury Recovery Plant (Sweden) (MRT system 2019)

Rare earth metals recovery

Reclite SA enriches its Phosphor powder to get higher yields from the processed phosphor powder and treated diodes from LED's, in it's developed process.

The enriched powder is treated in a rare earth recovery process to recover rare earth elements such as Europium and Yttrium among others.

Figure 40: Desirable REE oxide powders such as Europium and Yttrium (Reclite SA (Pty) Ltd.)

Figure 41: Example of a rare earth recovery plant (pilot) (Reclite SA (Pty) Ltd 2019)

LED diodes contain small amounts of rare earth elements. These diodes or light sources can be removed by hand (see *Figure 42*) for specialised treatment and recovery of rare earth material; however, it is labour and time intensive. Automated stripping systems are far more efficient, but the volume will need to be sufficient to justify the expenditure.

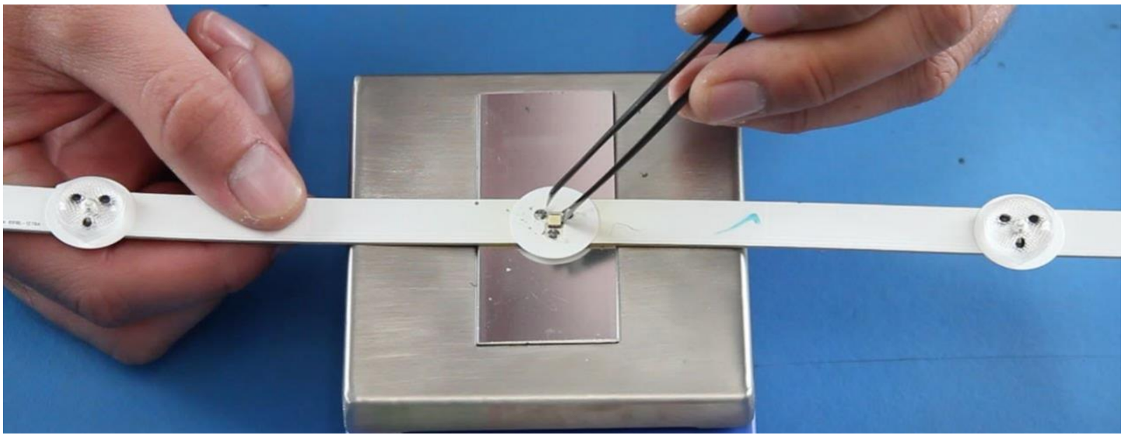

Figure 42: Manual removal of LED diodes (Reclite SA (Pty) Ltd 2019)

3.5.5 Other hazardous waste fractions from CRTs[34]

Cathode Ray Tubes (CRTs) are the main component in CRT monitors and CRT TV-sets. CRTs contain a large amount of hazardous substances such as lead, cadmium and barium oxide and therefore must be treated carefully in an adequate plant to avoid personal injury.

In CRTs lead is embedded in the glass matrix and does not cause direct danger. However, during grinding of the glass fractions, lead can be laid bare, eluted and transported by air. Lead and lead containing compounds are likely to be carcinogenic and uptake of lead can lead to acute and chronic poisoning[35]. In the environment lead accumulates in aquatic and biological chains. Lack of flue gas purification equipment can lead to higher lead emissions and environmental poisoning.

Cadmium containing compounds contained in the phosphor layer are classified as toxic and carcinogenic. They accumulate in kidneys and liver and can cause acute and chronic poisonings[36].

Using specially designed processes and machinery, the CRT glass body can be separated into panel glass, funnel glass, shadow mask and phosphor coatings. During this process all CRT coatings such as graphite and silicate conductive coating, iron oxide, aluminium oxide, and some other substances are removed. The exact composition of the coatings depends on who was the original CRT manufacturer.

One method to separate panel and funnel glass of CRTs is by hot wire cutting. Another option to separate the different glass fractions is to crush the CRT glass body as a whole. Separating the grinded glass splints can be done by the application of X-ray. X-ray detects lead containing glass splints and subtracts them from the pure glass fraction. Other toxic substances are washed out under controlled conditions.

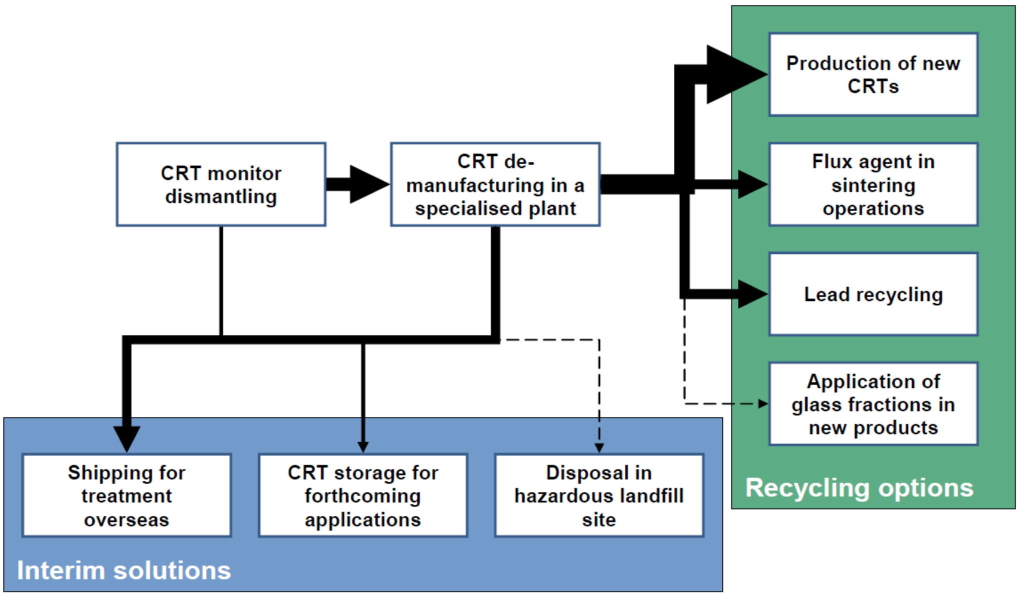

Figure 43: Recycling options and interim solutions for CRTs. Recycling paths to be preferred are highlighted with bold arrows. Dashed arrows indicate ultimate solutions, which should be avoided (Schluep et al. (2015): Dismantling Guide for IT – Equipment, p. 117.)

[34] This subchapter is based on Schluep et al. (2015): Dismantling Guide for IT – Equipment, p. 117ff.

[35] IARC (2006). Summaries & evaluations: Inorganic and organic lead compounds.

[36] WHO (2010): Preventing disease trough healthy environments. Exposure to Cadmium: A major public health concern.

The figure above shows recycling options and interim solutions for CRT glass treatment. They are further outlined in table 11. It is important to note that they heavily depend on locally available technology, hence not all recycling options are globally applicable.

Table 11: Treatment options for CRT glass (Schluep et al. 2015: Dismantling Guide for IT – Equipment, p. 117.)

Treatment	Description
CRT glass to CRT glass	The reproduction of CRT glass offers the highest environmental outcome and is currently the best way to recycle CRTs as primary raw material is substituted. In addition to removing lead from the municipal waste stream, CRT recycling avoids the environmental impacts associated with mining and processing raw lead from ore, by supplying lead in the form of CRT glass, for CRT glass manufacturing. It also provides significant savings in energy and saves resources such as water and other raw material inputs for the CRT manufacturer. The introduction of new technologies like HDTV and the preference of consumers for flat panel displays accelerate the rate of obsolescence and replacement of conventional CRT sets. As Liquid Cristal Displays (LCD) are replacing CRT monitors more and more, CRT recycling may be faced out in the long term. To cope with these changes, development of new applications for used CRT glass is required.
CRT glass to flux agent in sintering operations	If recycling to CRT glass is not viable, CRT panel glass can be applied as a slag former in sintering processes. Used in small amounts (up to 5% in weight), it can replace conventional flux agents improving the densification process and the mechanical properties[37].
Glass to lead recycling	CRT glass to lead recycling is a recycling process, where metallic lead (Pb) is recovered and separated from the CRT glass through a smelting process, where CRT glass acts as a fluxing agent in the smelting process. This process is a more automated process compared to —CRT glass to CRT glass recycling and might be more cost-effective. It also provides safer working conditions because workers are protected from lead dust because of the automated process and an emission control system. The CRT glass to lead recycling process has a high overall throughput. However, this process reduces the value of high-quality glass[38].

[37] Andreola et al. (2008): Recycling of CRT Panel Glass as Fluxing Agent in the Porcelain Stoneware Tile Production.

[38] Kang & Schoenung (2005): Electronic Waste Recycling: A Review of U.S. Infrastructure and Technology Options.

CRT glass to new products	To add heavy metals from CRTs to building materials or to give it to processes in the ceramic industry is critical because hazardous substances are diffusively distributed in the environment. This can lead to elution of these compounds by acid water. Nonetheless there are attempts to use CRT screen glass in the bricks and tiles production, as flux in brick and ceramic manufacture, in ceramic glaze, and in foam glass.

Phosphors are substances that exhibit luminescence and are often transition metal compounds or rare earth compounds of various types. They can contain both valuable and hazardous elements. The phosphor layer in a CRT monitor is very thin (few nanometres), thus only small amounts are used per monitor (ca. 5-7 g). It is a white powder that is coated on the inner surface of the panel glass.

The hazardous elements contained in phosphors powder are Yttrium, Cadmium, Barium and Lead. Hereby Yttrium makes up 17% of the phosphors powder in weight, Cadmium 0,8%, Barium 2.15% and Lead 7.53%.

There are two options for treatment:

- Storage: If possible, the elements contained in the phosphors should be recovered. Due to the lack of adequate technologies, this is not viable for many elements contained in phosphors at present. However, given the content of valuable elements and the rising prices for rare metals, it might be not only environmentally, but also economically advantageous to store the phosphors until appropriate technologies are available.
- Disposal in a HW landfill: It should be ensured that the phosphors are disposed in a safe landfill that prevents the release of the hazardous substances (e.g. leachate) into the environment.

Furthermore, each CRT contains an electron gun and at least one getter. The getter is a small, circular trough attached by a metallic stripe to the electron gun and filled with an earth metal, barium (Ba) being the most common. Barium is used to remove last traces of oxygen in the CRT. It is very reactive with air and water where it forms barium oxide. Barium is poisonous when dissolved in water. Therefore, the getter platelet should be separated from the electron gun and stored safely. This can be done by storing the getter platelet in drums protected against ingress, which will then be disposed as hazardous waste.

The electro gun consists of a high-alloyed nickel steel and can be commercialised as a recycling fraction.

3.5.6 Plastics[39]

Synthetics can be divided into four sub-categories, namely thermoplastics, thermoplastic elastomers, elastomers, thermosetting resins. Common synthetics can be classified within these four groups as described in *Figure 44*.

[39] This subchapter is based on VDI 234, part 5, p. 16-30.

Group	Abbreviation	Chemical name
Thermoplastics	ABS	acrylonitrile butadiene styrene copolymer
	ASA	acrylonitrile styrene acrylate copolymer
	HIPS	high-impact polystyrene
	PA	polyamide
	PBT	polybutylene terephthalate
	PCTFE	polychlorotrifluoroethylene
	PE	polyethylene
	PET	polyethylene terephthalate
	PMMA	polymethyl methacrylate
	POM	polyoxymethylene
	PP	polypropylene
	PS	polystyrene
	PTFE	polytetrafluorethylene
	PVC	polyvinyl chloride
	PVDF	polyvinylidene fluoride
	SAN	styrene-acrylonitrile copolymer
	SBR	styrene-butadiene rubber
TPE	TPE-E	thermoplastic copolyester
	TPE-S	styrene block copolymers
	TPE-U	urethane-based thermoplastic elastomers
Elastomers	ACM	acrylate rubber
	BR	butadiene rubber
	EVA	ethylene vinyl acetate
	SBR	styrene-butadiene rubber
Thermosetting resins	CF	cresol-formaldehyde resin
	MF	melamine-phenol-formaldehyde resin
	PF	phenol-formaldehyde resin
	PFA	perfluoroalkoxy alkane
	PUR	polyurethane
	RF	resorcinol-formaldehyde resin

Figure 44: Classification of common synthetics (VDI 2343, part 5, p. 17)

With regard to electrical and electronic equipment, thermoplastics such as ABS, HIPS, PS, PE, PP and PVC are most widely used. An overview of the variety of plastic found in WEE is given in the table below.

Table 12: Potential presence of hazardous additives by WEEE category and plastic type. Red indicates the potential presence of brominated flame retardants, orange stands for heavy metals (Bill et al. 2019, p. 7)

	ABS	HIPS	PP	PS	PE	ABS+PC	PVC
CRT screens	X	X				X	
Flat screens	X	X				X	
T, IT and small equipment	X	X				X	
Large equipment	X	X	X	X			
Cables					X		X

On average, the content of synthetics is about 20% by weight of electrical and electronic appliances. However, and as *Figure 45* shows, the content of synthetics can heavily vary depending on the appliance[40].

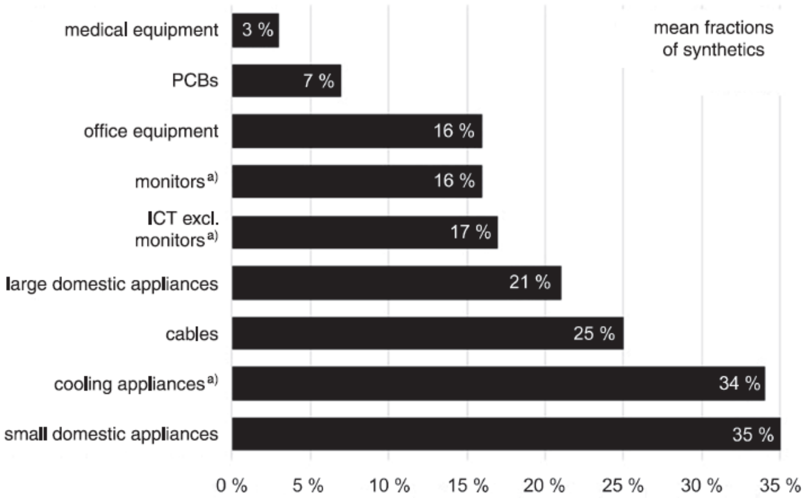

Figure 45: Percentage of synthetics in electrical and electronic equipment. (VDI 2343, part 5, p. 19 with data from VKE-03 and BDSV 2010 for datasets labelled with a))

All synthetics used in electrical and electronic equipment have in common that they need to insulate conducting parts, exhibit good workability and must resist breakage while still having a low weight. Next to their principal type, synthetics also differ in terms of added auxiliary materials and ingredients. To improve their quality, additional ingredients such as additives, filers or fibres can be added to synthetics. Fillers are used to reduce the number of synthetics used. They improve the workability and the materials properties. To improve the strength, rigidity or other properties of the material, fibres are added.

An example for additives is fire retardants. In electrical and electronic equipment, they are added in order to comply with international safety standards. Synthetics with added fire retardants are e.g. used for housings, cables and wires, PCBs or connecting elements. Since synthetics with additives have a higher density than synthetics without additives, they can be separated by means of density-based processes.

Another additive to synthetics can be heavy metals, which are, for example, used as stabilisers. In particular cadmium and lead are often used as thermo stabilisers in PVC. During recovery, special

[40] N.N. (2003): Kunststoffe in Elektro- und Elektronikgeräten.

attention should be paid to those heavy metals as in particular cadmium and lead should not be fed back into the life cycle of other products.

Third types of additives that require special attention are the propellants in polyurethane. These volatile substances are used in the production of polymer foams and should be handled separately in the course of WEEE recycling, due to their high negative environmental impact. This is as for example one kilogram of chlorofluorocarbon R11, which is used in cooling appliances, equals 4680 kg of CO_2.

There are three recovery types of synthetics from waste electrical and electronical equipment, i.e. mechanical recovery, chemical recovery and thermal recovery. An overview of the recovery paths for synthetics is given below in *Figure 46*. In addition, a short description on potential key steps and challenges to be aware of is given in the following.

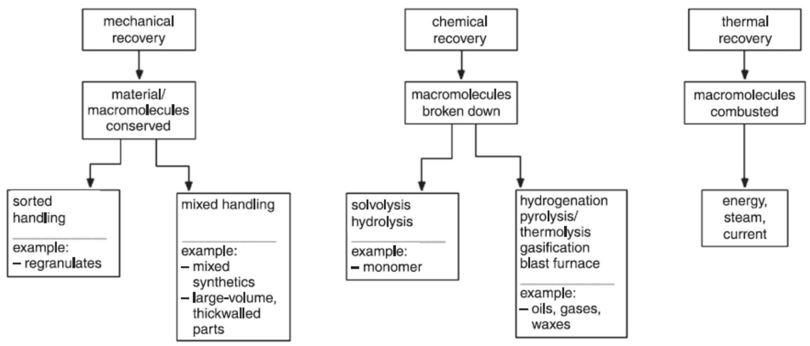

Figure 46: Recovery paths for synthetics. Source: VDI 2343 (2014): part 5, p.23.

For the mechanical recovery, it is crucial to separate the synthetics by sorted fractions. For the generation of these fractions, the following challenges must be considered. Firstly, WEEE can have a very complex construction and many small parts. Secondly, the separation of composite constructions is no easy task. Furthermore, it must be checked whether the synthetics contain any critical additives such as the heavy metals or flame retardants mentioned before.

To mechanically recover synthetics, the mill feed needs to be previously prepared through e.g. crushing, cutting, and if need be, washing and drying. If these steps are ensured, the mill feed can be converted into granulate form, through fusing and pelletising, the so-called extruding. Such granulate is used as new good in the processing of synthetics. However, it has to be noted that the materials quality decreases after each recovery round, which is the respective treatment step. Hence, it is often the case that the resulting granulate can only be used for the manufacturing of a product of lesser quality. To recover Polyurethane (PUR) foams from cooling appliances, the residual Chlorofluorocarbons (CFC) content must be low after a first treatment. Otherwise, the PUR foams should be sent to disposal facilities that can ensure the complete destruction of CFC content. Recovered PUR foams are most widely used to produce oil and chemical binders. If the synthetics contain added fire retardants, they should be disposed in an incineration plant.

For chemical recovery of synthetics, the following methods exist[41]:

- Hydrolysis requires perfect separation into fractions of the input material and a high cleanliness of these fractions. With this method, water or alcohols are used to decompose

[41] Novak, E. (2006): Verwertungsmöglichkeiten für ausgewählte Fraktionen aus der Demontage von Elektroaltgeräten – Kunststoffe.

polycondensates and polyadducts into their original monomers. A disadvantage of the method is the high costs it induces.

- Hydrogeneration requires temperatures of 400 to 500 °Celsius and a pressure of 150 to 250 bar to transform synthetic fractions into a mixture of liquid hydrocarbons.
- Gasification requires air and water vapor or pure oxygen to serve as gasification agent. The generated synthetic gas can be further processed into methanol or used as fuel gas.
- Pyrolysis largely destroys organic pollutants. In the process pyrolysis gas, and subsequently pyrolysis oils are generated while solid residues are left over.
- Indirect methods include amongst other the use of synthetics as agents, e.g. in the blast furnace process. However, this method is not suitable for the recovery of synthetics from WEEE, due to technical and economical limitations.

Another recovery option is thermal recovery. Due to their high calorific value, this method is principally attractive for the recovery of synthetics. There are several options for thermal recovery, such as waste-, mono-, and co-incineration plants. For more information, see chapter 1.4. The use of synthetics from WEEE in thermal recovery depends on their chemical, mechanical and calorific properties as well as the reaction properties of the fuel.

3.5.7 Non-ferrous metals[42]

The recovery of non-ferrous metals containing copper and precious metals is of high importance as they have a high economic value. Fractions containing non-ferrous metals are generated during dismantling or as a result of treatment. Examples for such fractions generated during manual dismantling are, amongst others, PWBs, transformers, copper cathodes or coils from the tubes display terminal. Cable granulate can serve as an example of a non-ferrous fraction generated during treatment.
Information and communication technology generally contains higher percentages of non-ferrous metal compared to consumer electronic equipment.

Copper rich fractions do not only contain copper and precious metals but also other important fractions such as iron, aluminum, tin, zinc or synthetics. For example, PWBs usually have a copper content of below 20%.

Despite the copper content of less than 20%, copper, and metal recovery in general, is highly economically attractive due to the other precious metals contained in the PWBs. Amongst said precious metals gold, silver and palladium can be recovered.

Even though metallurgical processes are costlier than mechanical processing, especially the treatment of less-thoroughly treated fractions in smelters makes sense. This is in order to avoid the loss of precious metals during laborious mechanical processing.

Depending on the desired outcome fractions and the technological limitations of the smelter, the copper-rich fractions have to undergo different processing steps. The different processing steps are presented in *Figure 47* and include smelting, converting, anode furnace and casting, refining electrolysis and noble metal recovery. The type and amount of associated metals in the feedstock and the smelting technique available determine whether the copper-rich fractions can be fed directly into process steps subsequent to smelting.

[42] This subchapter is based on VDI 2343, part 5, p. 11-13.

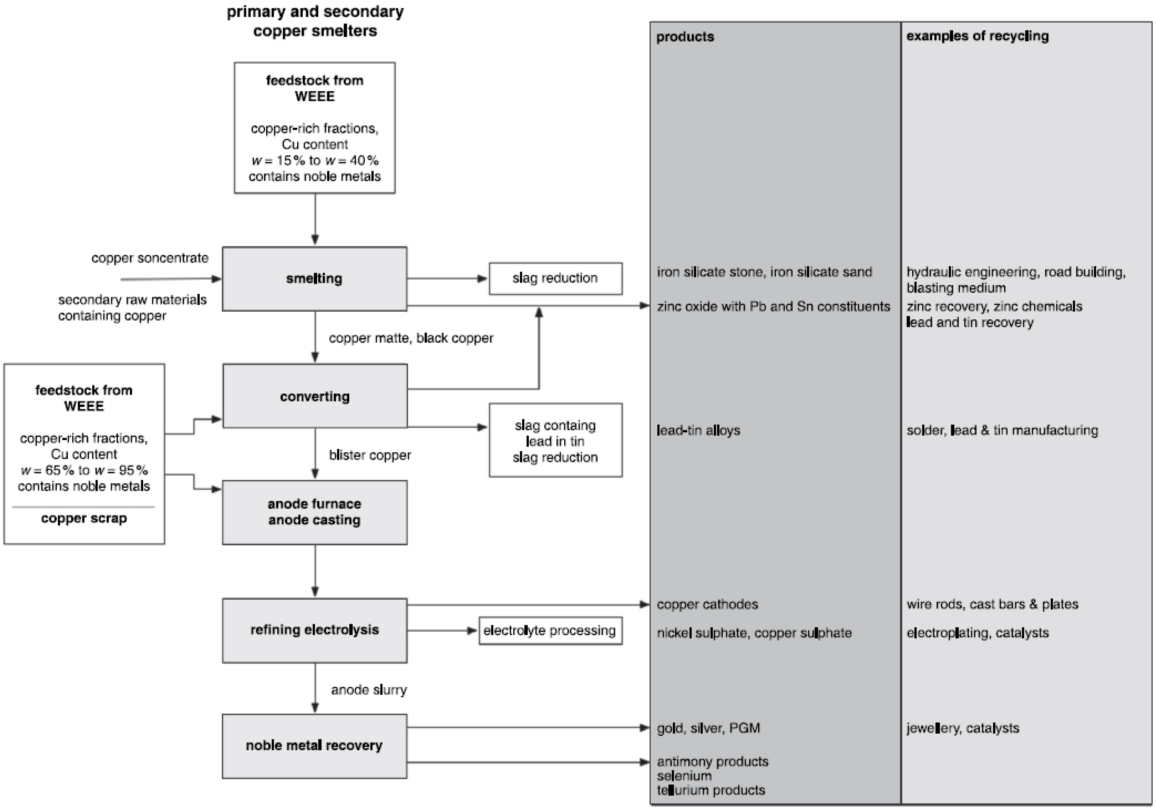

Figure 47: Recovery methods on non-ferrous and precious metals in primary and secondary smelters, presented in a schematic overview (VDI 2343, part 5, p.13)

3.5.8 Ferrous metals[43]

Ferrous metals are found in functional- (e.g. coils, transformers or motors) as well as non-functional electrical components (e.g. electrical housings or screws).

Fractions containing ferrous metals accrue during dismantling on the one hand and during treatment processes on the other hand.

The refining of ferrous scrap can generate revenues, e.g. in the production of steel. Minor impurities in the form of zinc, aluminum or synthetics, to name a few, can occur depending on the chosen treatment process. For the steel production, these impurities play a crucial role as for example copper impurities make steel brittle. In addition, copper is hard to remove from the steel using metallurgic processes. Hence, the tolerated concentration of these impurities depends on the desired type of steel, the type of recycling plant available and the whether the recycler is able to mix different kinds of feedstock in way that improves the quality of the steel.

There are two different procedures for the production of steel, mainly differentiated by the amount of ferrous-metals they require for steel production. While oxygen steel plants allow only around 5% ferrous fraction by mass to be used, electric arc furnaces use 98 % ferrous fractions.

[43] This subchapter is based on VDI 2343, part 5, p. 10.

Annex

Annex 1: General information on EEE and WEEE fractions

Annex 1.1: Detailed overview of component parts in CRT and FPD:

Liquid crystal/TFT display

They are made using a synthetic chemical with a high unit cost and high stability—is not very biodegradable. Liquid crystal's structure contains a large volume of benzene rings, fluorine, chlorine and bromine, which if buried, can leach into subterranean water systems and impact ecosystems. Liquid Crystal Displays contain other elements that are valuable in the market and depending on the market forces it might be financially value add to recycle the displays.

High recycling rates of indium can be achieved only when TFT panels are carefully extracted and before any mechanical treatment such as shredding[44]. Indium in electronic displays is generally also used together with other substances such as arsenic, phosphorous and tin. Indium arsenide (InAs) and indium phosphate (InP) semiconductors, and Indium tin oxide (ITO) are potentially hazardous and can cause lung disease and cancer[45]. Therefore, thin-film-transistor (TFT) panels must be manually separated from other waste flows to allow for indium recovery and to avoid the potential contamination of other recyclable fractions.

CCFL – Cold Cathode Flourescent light

This equipment must be de-polluted during dismantling and the lamps must be sent to a certified and competent lamp treatment facility due to their hazardous components.

The extraction of backlighting lamps is probably the most critical phase in display recycling. Each fluorescent lamp can contain up to 3.5 mg of mercury (EU, 2013), as confirmed by experimental analyses conducted by the European Electronics Recyclers Association (EERA) in European recycling facilities[46]. Lamps should be carefully extracted and safely stored for further recovery treatments. Lamps are also generally one of the most deeply embedded components in the electronic displays, so they can only be safely extracted at the end of the dismantling process. The extraction of backlighting lamps is a delicate process as there is a significant risk of accidentally breaking the lamps. Approximately 20–30% of the waste display boards in recycling plants already contained one or more broken backlights[47]. It is therefore recommended that displays be recycled in dedicated treatment facilities so as to avoid the possible release of mercury, which can cause health risks, pollute the environment and contaminate other recyclable materials.

CRT leaded glass

The CRT Monitor glass consists of two glass half's that are strongly joint together.

Separating the rear funnel section of the glass removes the leaded glass part from the thick front glass panel.

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[44] Lee et al. (2013): Recovery of indium from used LCD panel by a time efficient and environmentally sound method assisted HEBM; Li et al. (2009): Recovery of valuable materials from waste crystal display panel; Yang et al. (2013): Indium recovery from discarded LCD panel glass by solvent extraction.

[45] Lim & Schoenung (2010): Human health and ecological toxicity potentials due to heavy metal content in waste electronic devices with flat panel displays; Chou et al. (2009): Effect of operating parameters on indium (III) ion removal by iron electrocoagulation and evaluation of specific energy consumption.

[46] Krukenberg (2010): Challenges and conditions in the collection, transport and treatment chain of LCD displays.

[47] Ibid.

The CRT glass contains a large amount of lead which may be released when it breaks. Therefore, it is crucial to only conduct dismantling operations on monitors in adequate facilities. Further processing of CRT glass should only happen in industrial channels that have adequate facilities.

ABS, PC and other engineering plastics

All screens contain forms of engineering plastic with flame retardants (brominated flame retardants') used within the housing of the components. There usually is an internal metal carrier structure to hold heavier component parts.

The external (front and back) covers mainly constituted by acrylonitrile butadiene styrene (ABS) and polycarbonate–ABS blend (PC-ABS) with varying degrees BFR plastics.

PMMA

The LCD Display contains various sheets of plastic, with this is usually a layer of PMMA, this is highly valuable fully recyclable plastic and should be separated and stored for recycling. PMMA board is generally framed together with plastic optical components some PCBs and film connectors.

Cables

The different size internal and external data and power cables should be separated and the follow the further processing as per the best standards or a specialised cable recycler should be used.

PCB's

All screens use varying types of PWBs; CRT PCBs are very basic and low grade all the way to high end PWB's used in modern OLED smart Tv's with their own operating system; some of these will even contain a form of hard drive.

Ferrous and non-ferrous metals

All screens contain some form of ferrous and non-ferrous metals these should be separated between grades for further processing by metal recyclers. Depending on the area of where recycling takes place, fasteners/screws used within electronic components are usually worth more when being sold separately to traders instead of direct metal recycling.

When recycling CRT Screens and separating the rear funnel from the front panel, the internal mask and phosphorus powder are being liberated and can be separated for further recycling by secondary treatment sites.

When the containers are collected and transported to the long-term storage consolidation or treatment facility the storage practice described in Annex 2 must be adhered to.

Annex 1.2: Cable and wire sizes

The size of the cable or wire dictates how much current can safely pass through the wire. Electrical current is measured in ampacity, and each wire gauge has a maximum safe carrying capacity.

According to the IEC Standards (International Electrical Commission), the size is given as mm^2, it describes the total cross-sectional area of the copper conductor. Cable will be sized 1 mm^2, 2 mm^2, 4 mm^2 etc. and may be written as 1 mm, 2mm, 4mm. This is not the diameter of the cable.

The US System works on an American Wire Gauge (AWG) as illustrated below is a standardized wire gauge system for the diameters of round, solid, nonferrous, electrically conducting wire. The larger the

AWG number or wire gauge, the smaller the physical size of the wire. The smallest AWG size is 40 and the largest is 0000 (4/0)

Figure 48: IEC Standards (International Electrical Commission (Reclite SA (Pty) Ltd)

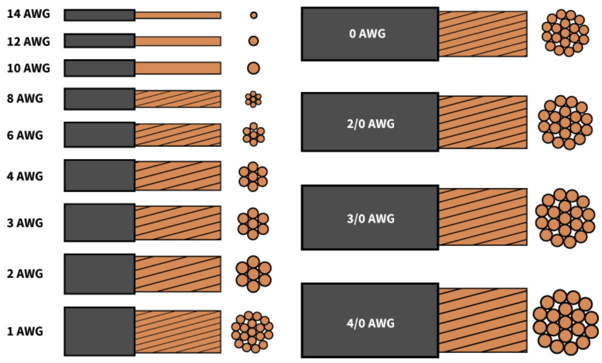

Figure 49:US System works on an American Wire Gauge (AWG) (Reclite SA (Pty) Ltd)

Cable number and size

Usually given as 19 x 0.41 or 19/0.41 which decoded means 19 strands of 0.41 mm diameter wire.

PP 1 SS 000 0.80-0.90 mm	PP 13 SS 6 1.90-2.00 mm	PP 25 SS 13 3.20-3.30 mm	SS 21 4.80-4.90 mm	SS 33 6.872-7.069 mm	SS 45 9.852-10.187 mm
PP 2 SS 00 0.90-1.00 mm	PP 14 SS 6 2.00-2.10 mm	PP 26 SS 13 3.30-3.40 mm	SS 22 4.90-5.10 mm	SS 34 7.069-7.272 mm	SS 46 10.187-10.540 mm
PP 3 SS 0 1.00-1.10 mm	PP 15 SS 7 2.10-2.20 mm	PP 27 SS 14 3.40-3.50 mm	SS 23 5.10-5.27 mm	SS 35 7.272-7.482 mm	SS 47 10.540-10.912 mm
PP 4 SS 1 1.10-1.20 mm	PP 16 SS 7 2.20-2.30 mm	PP 28 SS 14 3.50-3.60 mm	SS 24 5.27-5.44 mm	SS 36 7.482-7.700 mm	SS 48 10.912-11.304 mm
PP 5 SS 2 1.20-1.30 mm	PP 17 SS 8 2.30-2.40 mm	PP 29 SS 15 3.60-3.70 mm	SS 25 5.44-5.61 mm	SS 37 7.700-7.927 mm	SS 49 11.304-11.717 mm
PP 6 SS 2 1.30-1.35 mm	PP 18 SS 8 2.40-2.50 mm	PP 30 SS 15 3.70-3.80 mm	SS 26 5.61-5.78 mm	SS 38 7.927-8.164 mm	SS 50 11.717-11.97 mm
PP 7 SS 3 1.35-1.40 mm	PP 19 SS 9 2.50-2.60 mm	PP 31 SS 16 3.80-4.00 mm	SS 27 5.78-5.96 mm	SS 39 8.164-8.412 mm	SS 55 12.97-13.22 mm
PP 8 SS 3 1.40-1.50 mm	PP 20 SS 9 2.60-2.70 mm	PP 32 SS 17 4.00-4.10 mm	SS 28 5.96-6.14 mm	SS 40 8.412-8.672 mm	SS 60 14.22-14.47 mm
PP 9 SS 4 1.50-1.60 mm	PP 21 SS 10 2.70-2.80 mm	PP 33 SS 17 4.10-4.20 mm	SS 29 6.14-6.32 mm	SS 41 8.672-8.945 mm	SS 65 15.47-15.72 mm
PP 10 SS 4 1.60-1.70 mm	PP 22 SS 10 2.80-2.90 mm	SS 18 4.20-4.40 mm	SS 30 6.32-6.50 mm	SS 42 8.945-9.232 mm	SS 70 16.72-16.97 mm
PP 11 SS 5 1.70-1.80 mm	PP 23 SS 11 2.90-3.00 mm	SS 19 4.40-4.60 mm	SS 31 6.50-6.68 mm	SS 43 9.232-9.534 mm	SS 75 17.97-18.22 mm
PP 12 SS 5 1.80-1.90 mm	PP 24 SS 12 3.00-3.20 mm	SS 20 4.60-4.80 mm	SS 32 6.68-6.872	SS 44 9.534-9.852 mm	

Figure 50: Overview of cable numbers and sizes (Reclite SA (Pty) Ltd 2019)

There are electronic wire sizing gauges also available as shown in *Figure 51* below:

Figure 51: Electronic wire sizing gauge (Reclite SA (Pty) Ltd 2019)

Overall diameter

Figure 52 shows the overall diameter of the cable including insulation.

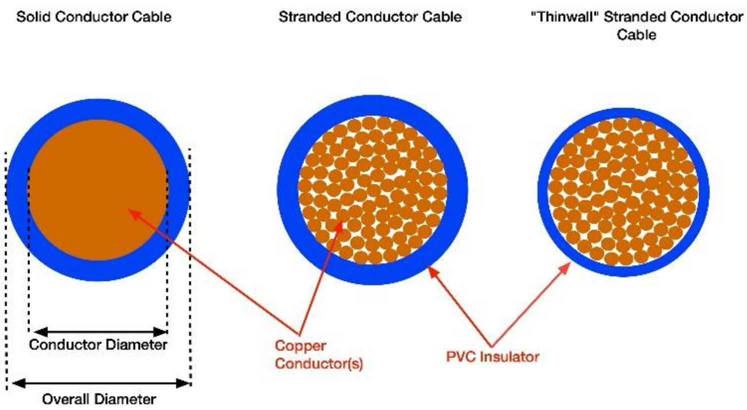

Figure 52: Cable diameter, copper conductors and PVC insulator (Reclite SA (Pty) Ltd 2019)

Annex 2: Storage and transportation requirements

Annex 2.1: Key storage requirements

All WEEE must be stored in containers. When the containers are collected and transported to the long-term storage consolidation or treatment facility the following storage practice must be adhered to:

1) The storage facility must be large enough to fit the volume, with adequate space for walkways and waste moving trolleys and equipment.
2) It must be dry and protected from the elements with power floated impermeable concrete floors.
3) It must be lockable with access control.
4) It must have appropriate HSE controls, such as fire extinguishers and emergency procedures.
5) The cage or box stack height must not exceed 3 containers.
6) The weighing equipment must be available for waste entering or leaving the storage facility, including separated packaging and fractions.
7) Mass balance and records must be kept for all waste brought in and taken out.
8) All containers must be labelled with information such as content type and weight.

Further storage requirements for CRT and FDP

1) Screens must be stored on an impermeable surface with sealed drainage. They must also be

stored under weatherproof covering or in enclosed weatherproof containers to prevent mercury contaminated rainwater being generated and to facilitate refurbishment/re-use activities.

2) Screens must be carefully stored and handled to prevent breakage of the fragile internal mercury backlights. Dropping, crushing or compacting screens is not acceptable. To prevent breakage, screens should be stored in containers e.g. cages or high impact wooden or carboard boxes and packed to minimise movement during handling and transport. Where pallets are used, screens should be stacked to prevent toppling or crushing of the display units. Where stacking containers on top of each other precautions must be taken to prevent damage to the displays in containers underneath.
3) Damaged or dropped screens are more likely to contain broken backlights and should be prioritised for processing. This may not be readily apparent by visual inspection alone, as internal backlights may have been broken by a shock pulse from dropping or shunting of a container. Shaking a screen may give a crude indication if any internal lamps are broken. A portable mercury monitor can also be used to measure mercury levels around containers in reception areas.

To help distinguish between screens containing mercury backlights and those backlit with light emitting diodes (LEDs) which don't contain mercury, monitors may have a sticker on the back of the unit indicating their type. Where there is uncertainty it should be assumed that the display contains mercury backlights as this is the most common type of FPD.

Any screen items containing lithium batteries (e.g. rechargeable lithium ion batteries in laptops) present a potential fire/explosion risk (e.g. if they short-circuit or are exposed to water) and should be stored appropriately to prevent damage (as detailed above).

Further information on containment and short-term storage of lamps

Examples of different designs of lamp containers are presented in figure 53-56.

Figure 53: Comparison in design of Small volume containers in a warehouse for spent lamp collection (left correct / right incorrect). The badly designed container on the right collapses and is prone to moisture absorption from the floor as it is not off the ground (Reclite SA (Pty) Ltd 2019)

Figure 54: Examples of container designs for different volume and storage requirements (Reclite SA (Pty) Ltd 2019)

Figure 55: Lockable powder coated steel container (Reclite SA (Pty) Ltd 2019)

Figure 56: Lockable moulded plastic containers (Reclite SA (Pty) Ltd 2019)

Containers should be manufactured from recyclable materials so that they can be recycled at the end of their useful life. Materials that are recyclable include cardboard, steel, aluminium and recyclable PET. Materials that are non-recyclable and should be avoided are fibreglass and BFR plastics.

If crushing of lamps is done with a drum top crushing machine, then the drum must be of the correct UN specification for crushed lamps and the drums must be labelled correctly (see *Figure 57*). Examples of incorrect storage practices are given in Figure 58.

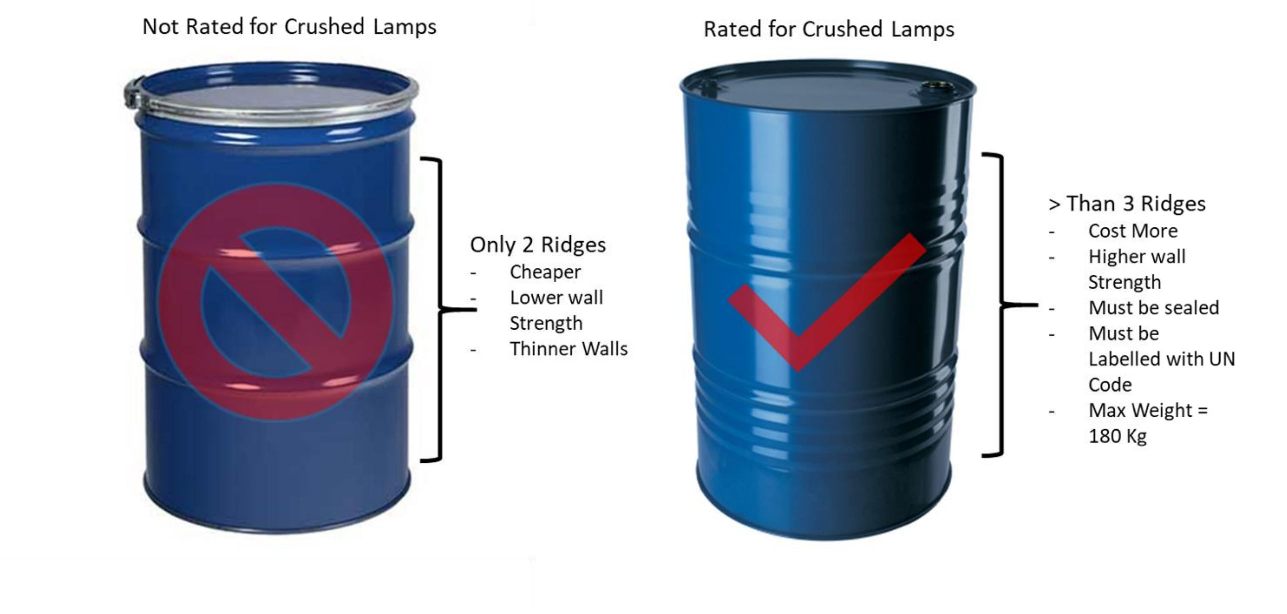

Figure 57: Correctly rated drums for crushed lamps (Reclite SA (Pty) Ltd 2019)

Figure 58: Examples of incorrect storage practices (Reclite SA (Pty) Ltd 2019)

Further storage requirements for lead acid batteries

1) For the vented type of batteries market, special care must be taken to avoid leakage or accidental spillage of the acid, especially if the vent cap is broken off or missing. Always check that the vent caps are sealed tightly.
2) Store containers in a cool dry place
3) An eyewash fountain and safety shower should be located in or near the storage areas for lead acid batteries or acid containers. Such area should be equipped with acid proof floors and sump to collect, neutralise and bag spills for correct disposal.
4) When diluting acid always add acid to water, not water to acid as this will cause a violent reaction. Small quantities of water may be added to battery acid safely.
5) Handle lead acid batteries and containers of acid carefully to avoid spilling the acid.
6) Batteries must be labelled accordingly. The label identifies the battery type and handling requirements. All lead acid batteries must always be packed or stored upright as the label indicates. An example of the correct label is shown below.

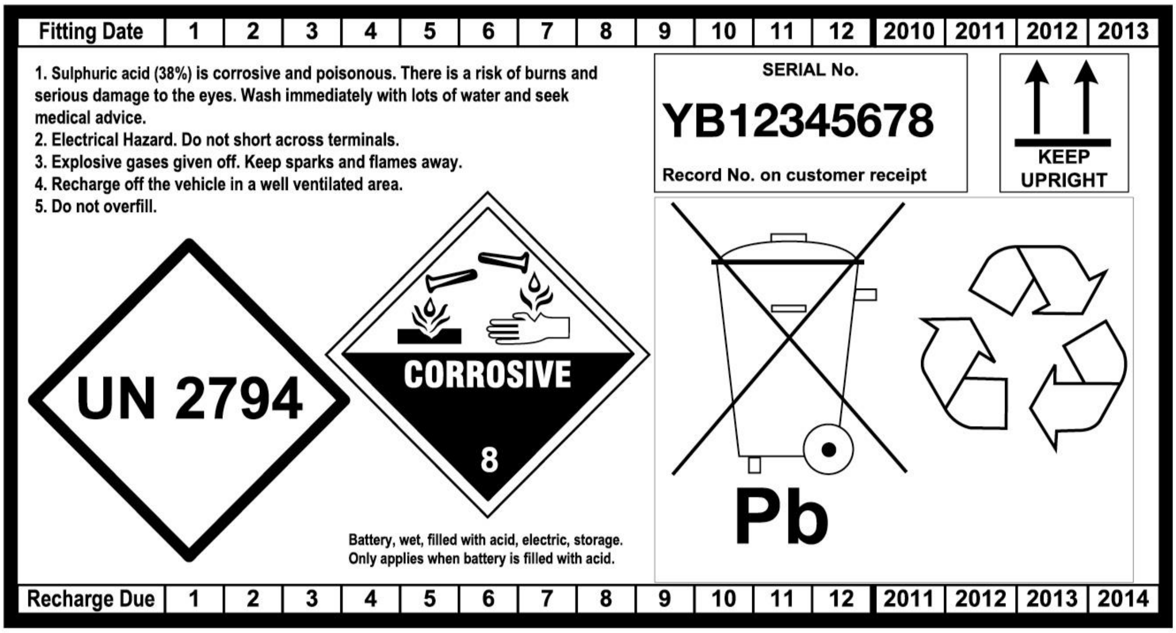

Figure 59: Correct label which should be on each battery (yuasa.co.uk (accessed 31.10.2019))

Heat, moisture and incompatibles are conditions to avoid. Prevent smoking, fires and any other sources of ignition around lead acid batteries. Battery electrolyte will react with water to produce heat. Can react with oxidising or reducing agent.

Water, potassium chlorate, potassium perchlorate, potassium permanganate, sodium, lithium, bases, organic material, halogens, metal acetylides, oxides a hydride, metals, strong oxidising or reducing agents are all incompatible materials to lead acid batteries.

Vented lead acid batteries release little or no gas until the battery is recharged to approximately 80% of its capacity. They create no gas escape unless stored in extreme heat. They are vulnerable to overheating if voltage and/or ambient temperature exceed recommended levels.

Lead acid batteries should be packed correctly, on a suitable pallet or drainage tray with carboard sheets placed between the layers.

When transporting almost any types of battery ensure to protect all terminals against short circuits that can result in fires. Terminals must be protected by completely covering them with an insulating, non-conductive material such as the carboard layer, using electrical tape or enclosing each battery separately in a plastic bag), or packing each battery in fully enclosed inner packaging to ensure exposed terminals are protected.

Different rules apply when shipping damaged batteries. A lead acid battery is considered damaged if there is a possibility of leakage due to a crack or if one or more caps are missing. In these cases, extra care must be taken, and these batteries must each be placed in an individual plastic bag and transported on a lead acid battery spill tray.

In general, try to avoid using flimsy wooden pallets as the battery acid can cause the wood to fail in strength if there are any leaks or spills. If wooden pallets are used, make sure they are sturdy and check them often for integrity and discard pallets with acid spills on them in the correct manner. If possible, use acid resistant plastic pallets or spill trays.

The storage room of facility should always have the following signage up to be visible to all.

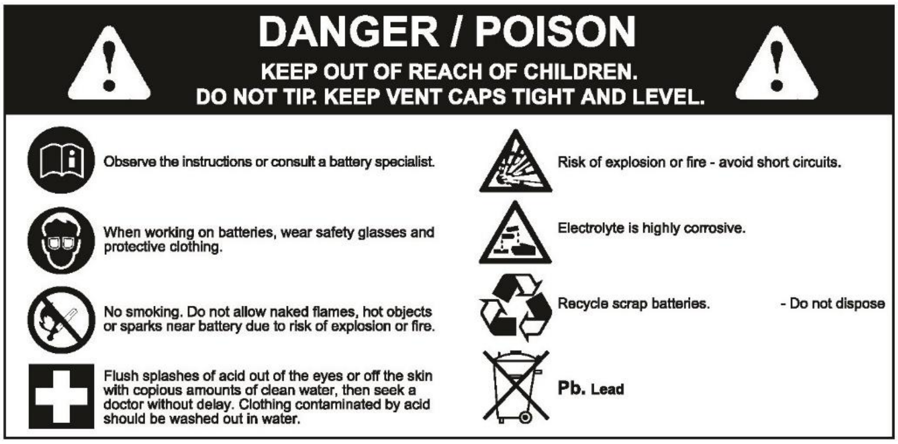

Figure 60: Required signage for lead acid battery storage facilities (First National Battery - South Africa (accessed 31.10.2019))

Annex 2.2: Transportation of WEEE

Light delivery vehicles can be used to transport small volumes. For screens, screen stands should be removed at this point if possible, so as to maximise the volume on the vehicle. The vehicles should be registered according to local hazardous transport regulations and should be satellite tracked 24/7.

Large trucks should be used to transport large volumes, such as the large containers from the storage consolidation site to the treatment facility. The trucks are normally used for long distance transport. The trucks need to be hazardous load registered with stabilisation controls on the axles to avoid swaying or an unbalanced load. The vehicles should be registered according to local hazardous transport regulations and should be satellite tracked 24/7.

Figure 61: Sample transport truck with transport containers for hazardous products made from recyclable cardboard; maximising volume on long distance trucks (Reclite SA (Pty) Ltd 2019)

Truck loading and unloading requirements

Containers must be labelled showing that they contain waste together with the UN code.

If lamps are crushed on site with mechanical drum top crushing equipment the drums must sealed with clamp seals and be stored appropriately with labels and the UN code. Containers must be stacked no more than 3 high and drums no more than two high if palletised. Otherwise, drums should just be single stacked. Loading and unloading rules are summarized as follows:

Loading

1) Before loading any vehicles, assess the specifications of the vehicle being loaded, pay close attention to the vehicles maximum loading capacity, vehicle tire pressure, and the vehicles empty centre of gravity.

2) All items must be weighed prior to be loaded to ensure the maximum loading capacity of the vehicle is not exceeded and to allow for even weight distribution.

3) All items weighing more than 30kg must be loaded using a forklift, only a licensed forklift driver may operate the forklift, and the forklift's maximum carrying capacity should not be exceeded.

4) At least one person must be a dedicated spotter for the forklift driver.

5) Care must be taken when loading the vehicle to ensure the vehicle does not sustain any damages, any damages must be reported to your manager immediately.

7) Containers, pallets must be carefully loaded using a forklift, containers can be stacked no more than three high depending on condition and weight. Drums can be loaded either loose, or palletised, strapped together and no more than 4 drums per pallet, if drums are loaded loose, do not double stack, only boxes can be evenly loaded on top of the drums, if the drums have

been palletised, double stacking of drums is permitted (but need to be secured to the truck body).

8) Loose boxes must be carefully loaded and bonded together to not allow for any movement during transport.

9) Once the vehicle has been fully loaded, ensure all items are tied down with the appropriate straps/tie downs to keep the load secure during transport.

10) Photos of the load must be taken before the vehicle leaves.

Unloading

1) Ensure the vehicle parks in a suitable area for unloading.
2) The vehicle must be off and stop blocks must be utilized on the tires of the vehicle before unloading commences.
3) All items weighing more than 30kg must be unloaded using a forklift, only a licenced forklift driver may operate the forklift, do not exceed the forklifts maximum carrying capacity.
4) At least one person must be a dedicated spotter for the forklift driver.
5) Before removing any straps/tie downs, asses the load for any shifting that may have taken place during transport, inspect for any unstable stacks, all possible unstable stacks must be unloaded first, the forklift must be in place to lift the top item of the stack before removing the strap/tie down to prevent the stack from falling.
6) Once all unstable stacks if any have been unloaded, all other straps/tie downs must be removed.
7) Unloading can commence once straps/tie downs have been removed, care must be taken when unloading to ensure the vehicle does not sustain any damages, any damages must be reported to your manager immediately.
8) Once the vehicle has been unloaded, the vehicle must be swept and cleaned of possible broken glass and rubbish if any.

Receiving waste at the treatment facility

1) Waste is inspected to make sure the waste can be accepted or rejected
2) Waste acceptance criteria:
    - Waste label must match content
    - Waste must be in a state where it can be safely handled
    - Waste must be free of contaminates to prevent contamination of the recyclables
3) If waste is accepted it is weighed on a trade rated scale with all parts removed for ease of transport efficiency's
4) The waste is then entered into the inventory system
5) Admin dept. will receive one copy of the, waste manifest document (delivery/collection note) and a weight sheet in order to generate recycling/destruction certificate.

6) Office copy of the waste manifest and/or transfer note will be kept with the administrator.

RECLITE (PTY) LTD P.O. BOX 2970, Alberton, 1450 Tel: +27 (0)11 825 0336 Email: admin@reclite.co.za Reg.No: 2009/008620/07	RECLITE RECYCLING THROUGH INNOVATION	**WASTE MANIFEST Number:**

Waste Generator Details		**Transporter Details**	
Company Name		Company Name	
Contact Name		Contact Name	
SAWIS Reg. No.		DEA registration	
Phone		Phone	
FAX		FAX	
Email		Email	
Generation Address		Transporter Address	
Order Date		Consolidation Address	
Intended Receiver	Reclite (Pty) LTD		
Applicable SDS			
PO No. / Quote No.		PO No. / Quote No.	
Comments		SAWIS registration No	

Recycler Details / Final Destination			
Recycler Company Name	RECLITE (PTY) LTD	WML No.	12/9/11/L44253/3
Recycler Site Name	Reclite Gauteng	DEA No.	GPR-03-154
Recycling Site Address	Unit 4, 15 Monte Carlo Place, Raceway Industrial Park, Germiston	Weighing / Entry Number	
Recycling Instructions	Recovery / Recycling	Site Classification	H:H

Consignment Details		
Item	**Quantity**	**Comments**
Total Weight / Volume (kg / tonnes / no. items)		

EXAMPLE

Comments / Special Instructions:	

Generator Declaration: The Generator hereby declares that the content of this consignment is fully and accurately described, classified, packed, marked and labelled, and in all respects in proper condition for transportation in accordance with the applicable laws and regulations.
Transporter Declaration: The Transporter hereby declares to have received the consignment as herein described.
Recycler Declaration: The Recycler hereby declares to have received the consignment as declared herein and to manage the content according to relevant legislation.

	Generator	**Transporter**	**Recycler**
Name			
Signature			
Date			

Blue – Client / Transporter Copy Yellow – Office Copy White – Book Copy

Figure 62: Example of waste manifest (Reclite SA (Pty) Ltd 2019)

Further information on the transport of lamps

Figure 63 shows a high-volume transportation container that has been filled with linear waste lighting tubes which were transferred from the smaller collection containers brought into the storage facility. These high-volume transportation containers will be labelled and sealed ready for loading onto a truck for transportation from the storage and consolidation facility to the treatment facility. This method ensures efficient and safe transportation.

Figure 63: High-volume transportation container with linear waste lighting tubes. (Reclite SA (Pty) Ltd 2019)

Crushed lamps can be transported in drums. According the UN transportation regulations, loose drums must be transported as depicted in Figure 64.

Do Not Double-Stack Single-Stack Only

Figure 64: Transportation requirements for loose drums containing crushed lamps. (Reclite SA (Pty) Ltd 2019)

Annex 3: Additional information on processing steps for CRT and FDP

Preparation and processing

- Waste is stored in the production que for processing.
- Waste is stored for no longer than one week before processing.
- Fractions are weighed and recorded in the inventory/mass balance system.
- This is processed according to health and safety procedures and machine operating parameters.
- All fractions go to authorised final advanced processing treatment and recyclers either internally or externally.

Documents and certification

- A waste manifest (see *Figure 62*) must be handed to the generator upon collection/receipt of waste.
- A weight slip is generated upon receipt of lighting waste.
- A recycling/destruction certificate will be generated after processing.

Copies of documents and certificates must be kept safely for a minimum of 3 years.

Annex 4: Economic Value

Due to the nature of the electronic recyclable components a recycler should try and cover a larger segment of electronic waste recycling with a modular semi-automated recycling chain that allows a continues recovering of high-quality recyclables from various types electronic waste. This then results in a higher utilisation of resources and sharing of CAPEX cost between various electronic waste streams. Where possible an “in-house”, or at least in close proximity manufacturing of new products from the recycled material tends to increase the profitability for the both the recycling of waste and manufacturing of new items.

Annex 4.1: CRT and FDP

CRT and FPD recycling can under the right circumstances (optimal volume, high efficiency etc.) cover all operational costs, however a gate fee (charge raised for the treatment of waste, paid by waste generators, i.e. the clients) would still be required to ensure future re-investments.

CRT Monitors have high copper content and can generate high revenue, however at the same time the leaded glass is a cost item that depending on the countries infrastructure and available recyclers can be expensive to further treat/dispose of correctly. If possible, a specialised glass smelter should be constructed to separate the lead from the glass and therefore allowing a full recycling of the CRT Monitor. This does require a substantial capital investment and should only be done if there is sufficient feedstock available bearing in mind that CRT's are no longer being manufactured.

Additionally, BFR plastics can sent for energy recovery at a cost or landfilled. It is possible to perform spot checks on BFR content to develop an understanding of BFR concentration in the casing and separate as per BFR content. The mixed plastics with BFR content below the threshold can then be sold as mixed recyclable plastics and create additional revenue for the recycler. The below table is an outline of what type of plastics can be mixed together for this purpose.

Table 13: Plastic mixing table (Reclite SA (Pty) Ltd 2019)

Main plastic	Contaminant																
	ABS	EP	HIPS	PA	PBT	PC	PE	PET	PMMA	POM	PP	PS	PUR	PVC	SAN	PC+ABS	PC+PBT
ABS	G	O	Y	R	O	G	R	O	O	O	R	R	Y	Y	R	G	Y
EP	Y	G	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
HIPS	Y	Y	G	R	R	R	R	R	R	R	R	O	R	R	R	R	R
PA	R	R	O	G	O	R	R	O	R	R	R	O	O	R	R	R	R
PBT	O	R	R	O	G	G	R	R	R	R	R	R	O	R	R	O	G
PC	G	O	O	R	G	G	R	G	G	R	R	R	O	O	G	G	G
PE	R	R	R	R	R	R	G	R	R	R	G	R	R	R	R	R	R
PET	O	R	O	O	R	G	R	G	R	R	R	O	O	R	R	O	R
PMMA	O	R	O	R	R	G	R	Y	G	O	R	O	O	G	G	G	R
POM	R	R	R	R	O	R	R	R	R	G	R	R	R	R	R	R	R
PP	R	R	R	R	R	R	O	R	R	R	G	R	R	R	R	R	R
PS (HI)	R	R	O	R	R	R	R	R	R	R	R	G	R	R	R	R	R
PUR	Y	R	O	Y	O	O	O	O	O	O	O	O	G	Y	O	O	O
PVC	Y	R	R	R	R	R	R	R	G	R	R	R	O	G	G	O	R
SAN	G	O	R	R	R	G	R	R	G	R	R	R	Y	G	G	G	O
PC+ABS	G	O	G	R	G	G	R	Y	G	R	R	G	Y	O	G	G	G
PC+PBT	G	O	R	O	G	G	R	Y	R	R	R	R	O	R	G	G	G

G	Good compatibility (properties stay good even if >5% contamination)
Y	Reasonable compatibility (properties stay good only if contamination <5%)
O	Limited compatibility ((properties stay good only if contamination <2%)
R	Bad compatibility (properties are bad even if contamination =1%)

(Bicerano, 2006; Hepp, 2013; Peeters et al., 2014)

Below a representation of the cost versus value retrieved from the process is shown (*Figure 65*). The red blocks are the cost and the green blocks is the value. Depending on the local available offtake partners, small profits could be possible, however for the purpose of this process we assume worst case scenario in which the costs outweigh the value generated. Some of the fractions need to be re-processed in other plants to create products of value. This is where the fraction value would increase, and the process can be become profitable.

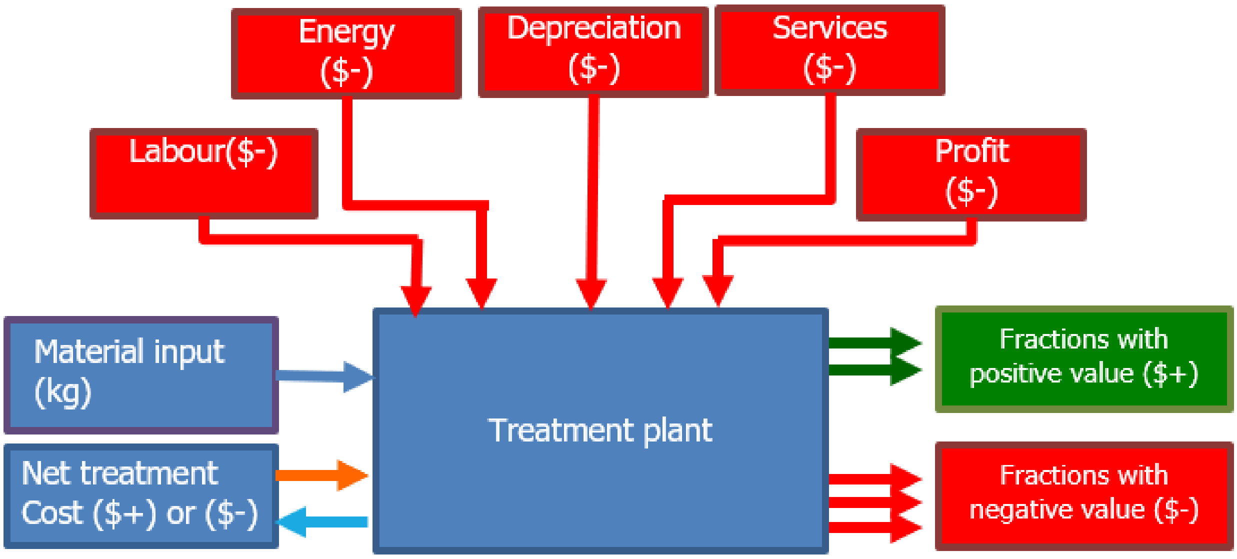

Figure 65: Recycling cost versus value recovered for CRT and FDP (Reclite SA (Pty) Ltd 2019)

As shown in the figure above the commercial value recovered from the recycled fractions is low without further advanced processing of these fractions and does not cover the total operational and administrative costs of the recycling facility, therefore an upfront recycling cost will always apply. This is termed as a negative waste stream. However, the environmental value recovered is high. This should always be considered when establishing the treatment facility.

Annex 4.2: Cables

The main components of cable and wire products have a positive value.

The red section in *Figure 66* below illustrates the value of the copper fractions from waste cabling as being high.

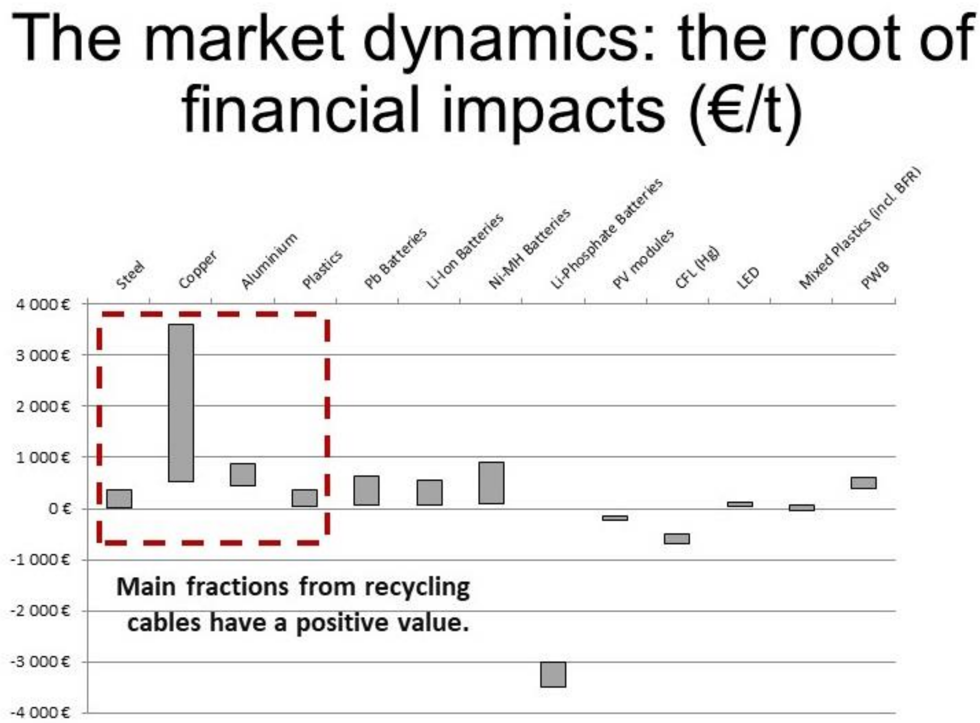

Figure 66: Graphic Illustration of the recoverable value from cable waste (in €/t) (Reclite SA (Pty) Ltd 2019)

Below is a representation of the cost versus value retrieved from the process. The red blocks are the cost and the green blocks is the value. It can be seen from this that the value outweighs the cost.

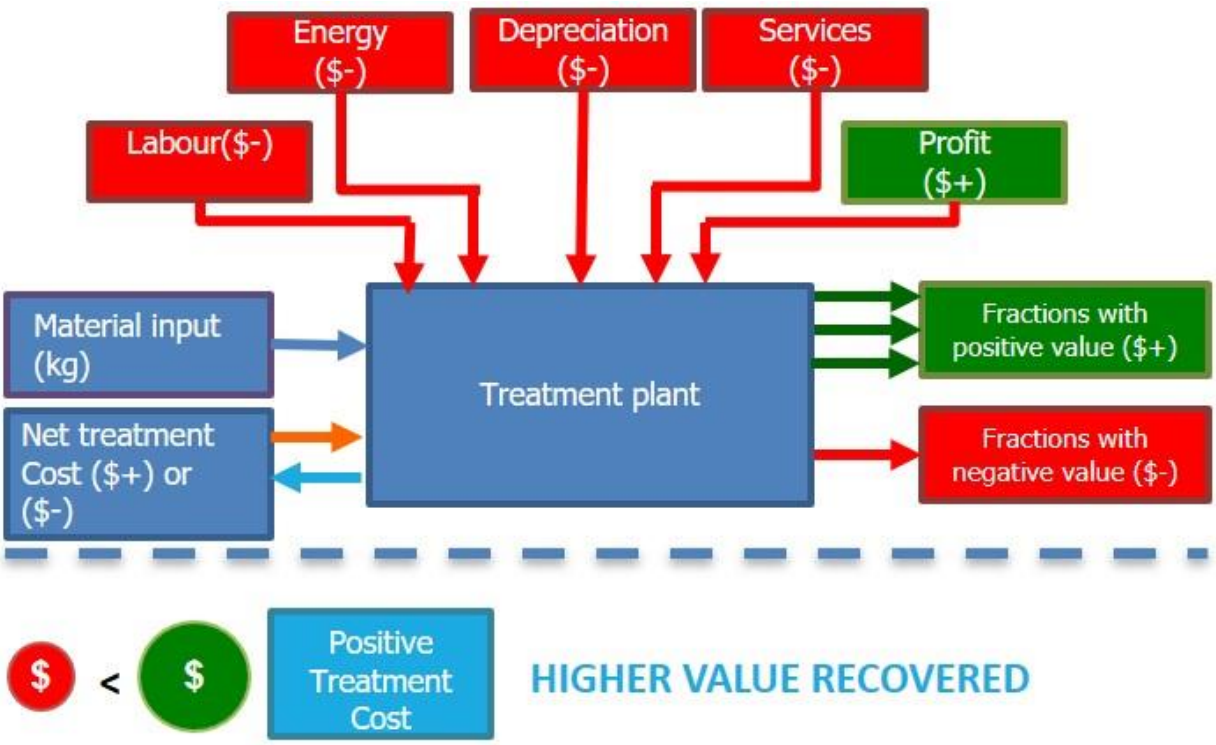

Figure 67: Recycling cost versus value recovered from cables (Reclite SA (Pty) Ltd 2019)

Annex 4.3: Lamps

The main components of lighting products have a negative value. The red section in Figure ??? below illustrates the value of fractions from fluorescent lighting and from LED lighting as being negative or very low.

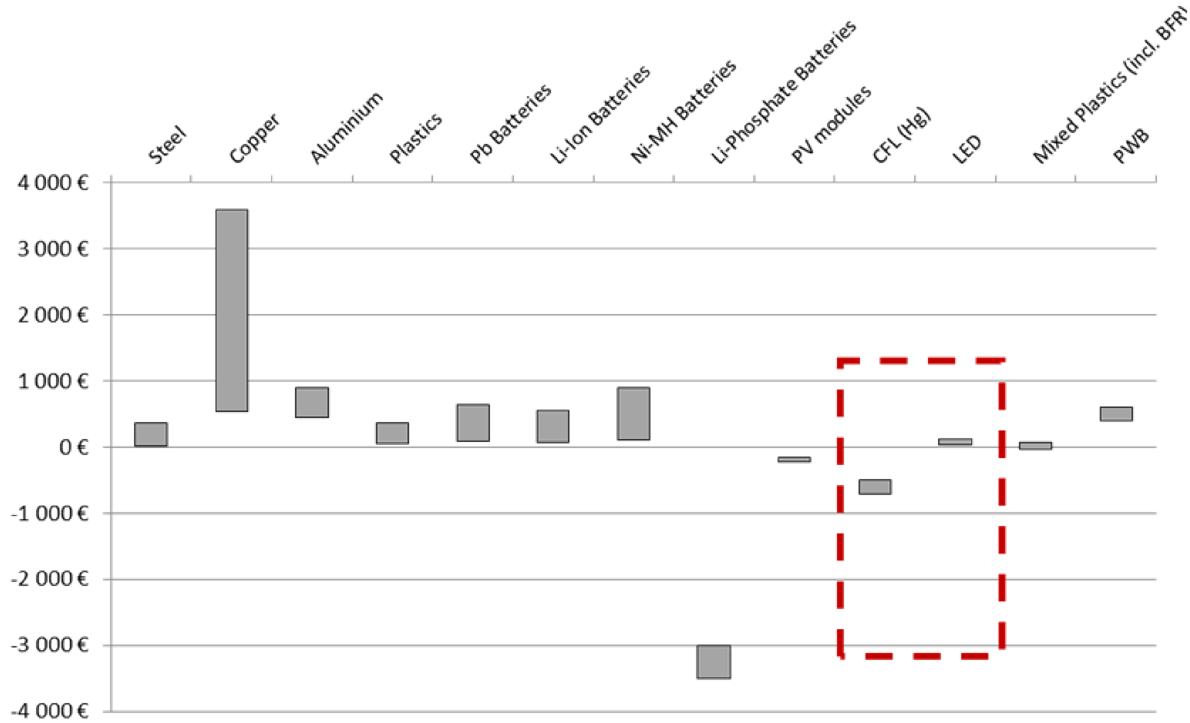

Figure 68: Graphic Illustration of the recoverable value from lighting waste (in €/t), highlighted by the dotted red section Recycling cost versus value recovered (Reclite SA (Pty) Ltd 2019)

Figure 69 visualizes the cost versus value retrieved from the process. The red blocks are the cost and the green blocks is the value. It can be seen from this that the costs outweigh the value. Some of the fractions need to be re-processed in other plants to create products of value. This is where the fraction value would increase.

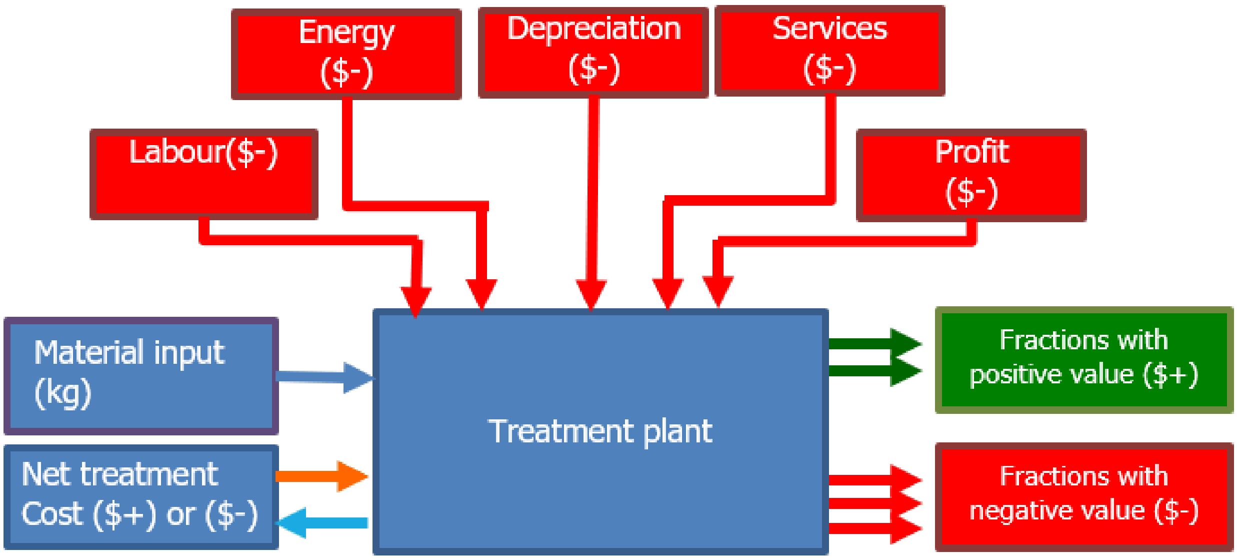

Figure 69: Recycling cost versus value recovered from lamps recycling (Reclite SA (Pty) Ltd 2019)

In South Africa, the treatment or gate fee on the LP 400's plant's full capacity is $463,27 per metric tonne. This will be higher if less feedstock is available. The operational costs can vary and are dependent on local energy and labour costs etc.

The income generated will be determined by the profit margin added onto the gate/treatment fee by the treatment operator.

Creating value from recovered fractions

Further investment is needed to for advanced treatment or beneficiation to create value from the fractions recovered as separate standalone income generating processes. The fractions recovered from lamp processing would serve as feedstock for the advanced treatment. This investment can yield a high return on value, but it is crucial to have the volume of lighting waste to substantiate the investment, known as sufficient access to waste. An overview of volumes and economic value of fractions, before and after treatment is given in table 14.

Table 14: Comparison of the economic value of fractions before and after advanced treatment (re-processing for beneficiation) (Reclite SA (Pty) Ltd 2019)

Lighting type	Volumes in % of Total	Glass	Ferrous Metals	Non-Ferrous Metals	Mixed Plastic	PC-Boards C Grade	Powders	Mercury	
Fluorescent tubes	50,0%	85,00%	3,00%	11,34%	0,00%	0,00%	0,60%	0,06%	100,00%
CFL's	8,0%	70,00%	4,67%	14,00%	11,00%	0,00%	0,30%	0,03%	100,00%
CFL-i's	20,0%	63,40%	5,27%	16,00%	10,00%	5,00%	0,30%	0,03%	100,00%
HID	5,0%	74,90%	15,00%	10,00%	0,00%	0,00%	0,00%	0,10%	100,00%
LED tubes	10,0%	50,00%	5,00%	25,00%	15,00%	5,00%	0,00%	0,00%	100,00%
Led lamps	2,0%	50,00%	5,00%	25,00%	15,00%	5,00%	0,00%	0,00%	100,00%
Integrated LED Fittings	5,0%	0,00%	5,00%	25,00%	65,00%	5,00%	0,00%	0,00%	100,00%
	100,0%	56,19%	6,13%	18,05%	16,57%	2,86%	0,17%	0,03%	100,00%
Before re-processing	*Value Potential in $ per ton*	*-$35,00*	*$92,00*	*$1 080,00*	*$75,00*	*$360,00*	*$0,00*	*-$7 300,00*	
Fluorescent tubes	$ / ton feed from above	-$29,75	$2,76	$122,47	$0,00	$0,00	$0,00	-$4,38	$91,10
CFL's	$ / ton feed from above	-$24,50	$4,30	$151,20	$8,25	$0,00	$0,00	-$2,03	$137,22
CFL-i's	$ / ton feed from above	-$22,19	$4,85	$172,80	$7,50	$18,00	$0,00	-$2,03	$178,93
HID	$ / ton feed from above	-$26,22	$13,80	$108,00	$0,00	$0,00	$0,00	-$7,30	$88,29
LED tubes	$ / ton feed from above	-$17,50	$4,60	$270,00	$11,25	$18,00	$0,00	$0,00	$286,35
Led lamps	$ / ton feed from above	-$17,50	$4,60	$270,00	$11,25	$18,00	$0,00	$0,00	$286,35
Integrated LED Fittings	$ / ton feed from above	$0,00	$4,60	$270,00	$48,75	$18,00	$0,00	$0,00	$341,35
After re-processing	*Value Potential in $ per ton*	*$240,00*	*$92,00*	*$1 080,00*	*$75,00*	*$380,00*	*$35 000,00*	*$55 000,00*	
Fluorescent tubes	$ / ton feed from above	$204,00	$2,76	$122,47	$0,00	$0,00	$210,00	$33,00	$572,23
CFL's	$ / ton feed from above	$168,00	$4,30	$151,20	$8,25	$0,00	$105,00	$15,29	$452,04
CFL-i's	$ / ton feed from above	$152,16	$4,85	$172,80	$7,50	$19,00	$105,00	$15,29	$476,60
HID	$ / ton feed from above	$179,76	$13,80	$108,00	$0,00	$0,00	$0,00	$55,00	$356,56
LED tubes	$ / ton feed from above	$120,00	$4,60	$270,00	$11,25	$19,00	$85,00	$0,00	$509,85
Led lamps	$ / ton feed from above	$120,00	$4,60	$270,00	$11,25	$19,00	$85,00	$0,00	$509,85
Integrated LED Fittings	$ / ton feed from above	$0,00	$4,60	$270,00	$48,75	$19,00	$0,00	$0,00	$342,35
Value Gained									
Notes:									
All the above is based on averages and are subject to market fluctuations both positive and negative									
Value creation from plastic not calculated									

Figure 70 compares the economic value of fractions before (treatment by the lamp processor only) and after advanced treatment (after re-processing for beneficiation and/or product manufacturing). The values are based on averages and variances can be experienced in differing economies and based on supply and demand principles.

Fractions after treatment before Beneficiation/Product Manufacturing

- Steel – **Low**
- Aluminium – **Medium**
- Other metals – **Medium**
- Plastics – **Low**
- Glass – **None**
- Phosphor Powder – **None**
- Mercury – **None**
- Electronics – **Medium**
- Diodes - **None**

Fractions after Beneficiation/Product Manufacturing

- Plastics – **Medium**
- Glass – **High**
- Mercury – **High**
- Phosphor Powder – **High**
- Aluminium – **High**
- Electronics – **High**
- Diodes - **Medium**

Figure 70: Value before advanced treatment vs. value after advanced treatment (beneficiation) (Reclite SA (Pty) Ltd 2019

Annex 4.4: Lead acid batteries

The main components of lead acid batteries have a positive value.

The red section in *Figure 71* below illustrates the value of the lead and plastic fractions from waste lead acid batteries as being positive.

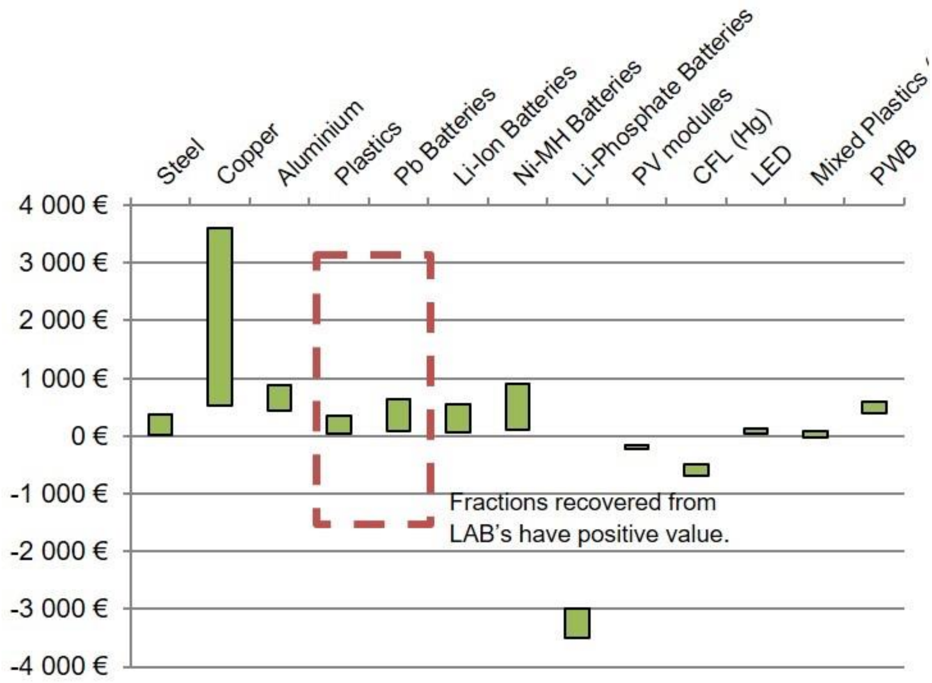

Figure 71: Graphic illustration of the recoverable value from lead acid battery waste (in €/t) (Reclite SA (Pty) Ltd 2019)

Below is a representation of the cost versus value retrieved from the process. The red blocks are the cost and the green blocks is the value. It can be seen from this that the value outweighs the cost.

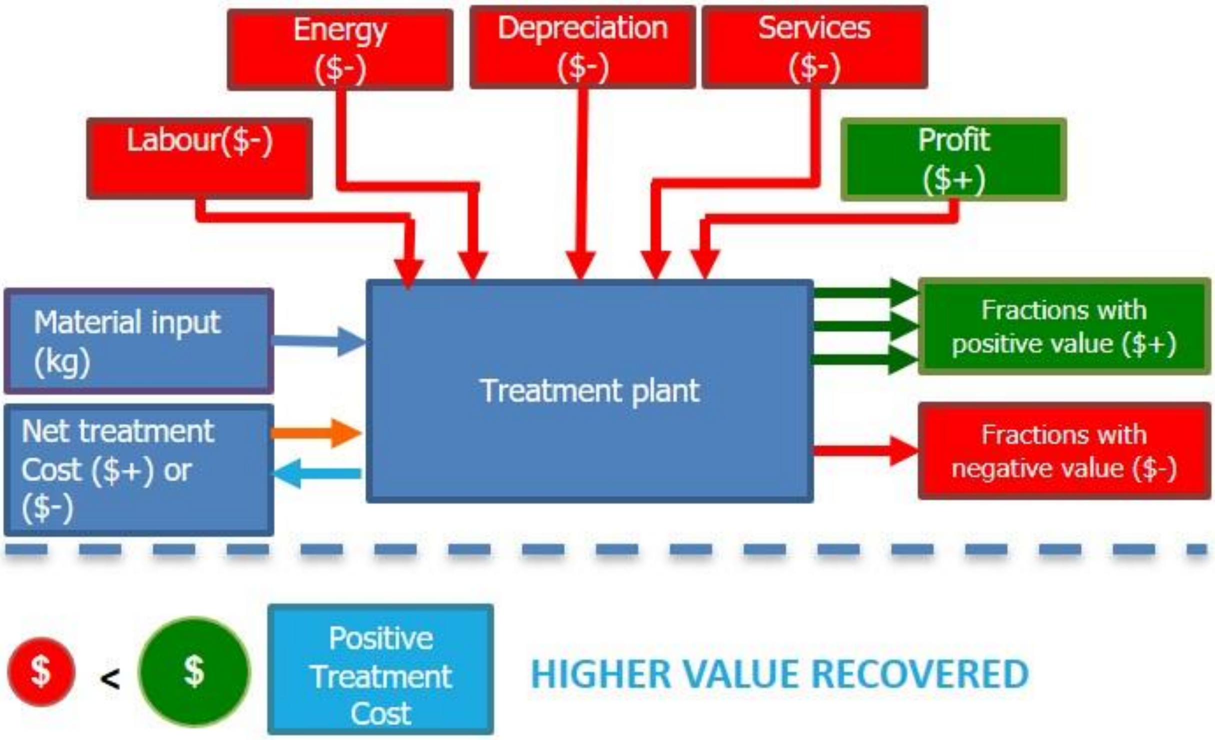

Figure 72: Recycling cost versus value recovered from lamps recycling (Reclite SA (Pty) Ltd 2019)

Value from Recovered Fractions per ton

The below table is to show the fractions in lead acid batteries. The analysis is based on industry averages and will differ from market to market. Adjustments will be necessary to ensure market distribution and fraction concentration is correct.

Table 15: Fraction content of Lead acid batteries and potential value per ton (Reclite SA (Pty) Ltd 2019)

Battery Components	Volumes in %	Value potential in $/ton
Lead Chips	30,0%	2 000,00
Electrode Paste	43,0%	2 000,00
Sulphuric Acid	13,0%	-100,00
Polypropylene	6,5%	240,00
Other Plastics	5,0%	-80,00
Ebonite	2,0%	-40,00
Others-Waste	0,5%	-40,00

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