# Management of End-of-life Flat Panel Displays through E-waste Compensation in Nigeria

## Feasibility study on options for developing environmentally sound recycling solutions in Nigeria


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## Abstract

The following study addresses the possibilities for responsible management of end-of-life flat panel displays in Nigeria. For this, it explores types of flat panel displays, their markets as well as responsible options for suitable recycling along their reverse value chain from collection, storage, de-pollution and dismantling to downstream solutions. A special focus is set on hazardous fractions such as mercury containing backlights and brominated flame retardents (BFR) in plastics. Furthermore, the study explores the implementation of the concept of ‘e-waste compensation’ (also called ‘offsetting’) in the context of flat panel screen recycling in Nigeria in practice. E-waste compensation is a concept where manufacturers and/or users of IT contribute to sustainable recycling of end-of-life devices. The study was carried-out under the project E-waste Compensation as an international financing mechanism in Nigeria (ECoN) with the project partner Closing the Loop organizing environmentally friendly and suitable collection, transport and final management together with the partners Verde Impacto Nigeria, Hinckley Recycling Ltd., in Nigeria. SRADev Nigeria and Oeko-Institut e.V. guide the project from a scientific and local policy perspective.

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The ECoN project team

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# 1 Background & structure of the study

This report was developed within the project *E-waste Compensation as an international financing mechanism in Nigeria (ECoN)*, which is funded under the PREVENT Waste Alliance. The ECoN project aims at advancing the concept of 'e-waste compensation', where international brands and users of electronic equipment can contribute to a sound management of equivalent e-waste volumes in developing countries by providing finances to an organization that organizes collection and environmentally sound management of e-waste on behalf of the brands and users. The project is conducted by Öko-Institut e.V. Closing the Loop, Hinckley Recycling, SRADev Nigeria and Verde Impacto Nigeria.

Unsound management of end-of-life electrical and electronic equipment (e-waste) is known to be a major environmental concern in waste management systems of many low- and middle-income countries. Within the West-African context, Nigeria is known as a country where challenges are particularly pronounced, which is – amongst others – due to the large size of her population and urban agglomerations, as well as the widespread informality of collection and recycling networks. While policy development is underway, implementation and enforcement are still fragmentary. In this situation, most observed management practices refer to extraction of valuable materials (mostly metals), while ignoring or dumping of residual and polluting fractions. While formal recycling exists, the sector still operates in a niche market. Furthermore, also formal recyclers have not yet managed to develop and implement full sustainable solutions for all e-waste fractions.

In this situation, both, national policymakers, as well as international players are about to develop solutions along the line of Extended Producer Responsibility (EPR), where producers and importers bear the responsibilities and costs for full sustainable collection and recycling. While such policy-development processes are currently ongoing in Nigeria, this process is also supported by the concept of e-waste compensation, which is explained in more detail in chapter 9. While e-waste compensation was so far already implemented for collection and management of end-of-life (EoL) mobile phones internaionally, the concept is to be expanded to more product groups, specifically product groups that are known to be negative value. Hence, this feasibility study aims to discover sustainable recycling paths for flat panel displays in Nigeria using e-waste compensation as a financing mechanism.

The reason for this is to enable environmentally friendly recycling of at least 10 tons of flat panel displays within the pilot project 'E-waste compensation as an international financing in Nigeria' (ECoN). By this, the study aims at elaborating suitable conditions for collection, transport, re-use and refurbishment, depollution, dismantling, sorting and further treatment and downstream options for fractions. At the same time, the study considers specific limitations of possible (pre-)processing steps of recycling in Nigeria. While currently, most of the e-waste management is in the hands of the informal sector in Nigeria, the ECoN pilot project aims at showing that EoL products can be handled with due care if supported by an effective financing mechanism (from national or international sources).

Furthermore, the financing mechanism of 'e-waste compensation' shall be extended to flat panel displays in the pilot project. Basically, this comprises the willingness of manufacturers and users of displays to (co-)finance sustainable recycling of 'equivalent amounts' of e-waste in terms of their new products placed on the market or used. Details of the financial mechanism of e-waste compensation are explained in the following chapter 2.

After this, chapter 3 defines the scope of the study and elaborates on indicative Bill of Materials (BoM) of the flat panel screens in scope. This is done in order to generate a profound understanding of the recycling tasks, and also to create data for decision-making on e-waste compensation criteria, in particular in relation to mass balances and the question from what point on a defined screen number or weight unit can be regarded as 'compensated'.

Chapter 4 provides brief insights on ever growing quantities of globally produced flat panel screens. This is followed by chapter 5 that structures the reverse value chain of end-of-life flat panel screens from collection, transport, storage, de-pollution, and sorting with a focus on guidelines of 'good practice'. A special focus is set on suitable de-pollution, health and safety.

Chapter 6 summarizes the resulting e-waste fractions from flat panel screens and chapter 7 provides insights on national and, if necessary, international downstream solutions. This is followed by an indicative business model of sustainable flat screen recycling using data from the ECoN project in chapter 8. This is finalized by general considerations of the role of e-waste compensation within the National Policy Framework of Nigeria in chapter 9.

Chapter 10 provides a summary of the conclusions and recommendations for flat screen recycling within the e-waste compensation scheme.

## 2 About e-waste compensation

The concept of e-waste compensation was developed by Closing the Loop (CTL) and builds upon the finding that many tech purchasers aim to procure electronics in a way that better aligns with their (personal) values. However, the purchased devices are often linked to environmental and health problems, due to unsound e-waste management in many low- and middle-income countries. Through a voluntary financial contribution, these purchasers can assign a third party to make sure a defined e-waste volume is collected in one or more target countries and consequently managed in an environmentally sound manner. The approach is used to compensate a purchase, it makes a new device 'waste-neutral'. Closing the Loop has set up and is operating such an e-waste compensation scheme for public and corporate customers (predominantly located in Europe). To do so, CTL cooperates with the local informal sector, as well as with e-waste recycling and management companies in various African countries who manage collection networks to make sure the requested amounts of e-waste is prevented from ending up in landfills or harmful recycling and channelled to their facilities for sound treatment. So far, these schemes were limited to mobile phones, tablets & notebooks and based on a 1-to-1 principle, where each customer finances the collection and management of a defined number of devices (this number commonly correlates with the number of devices brought onto a defined market in Europe). In that context it is important to note that e-waste compensation does not replace legal obligations for participating in an Extended Producer Responsibility (EPR) scheme in the country where the equipment is brought onto the market. E-waste compensation is a voluntary additional measure which delivers on the large and growing demand for green electronics procurement. It results in the support of collection and e-waste recycling systems in countries with widely unregulated e-waste landscapes. The logic for this is that many IT devices do not reach end-of-life in the market where they were originally introduced.

The concept of e-waste compensation was also taken up by the eco-labelling scheme TCO Certified: Companies applying for a TCO-edge certification for their mobile phones, tablets or notebooks must prove that 'for every manufactured unit of the product, the brand ensures take back of an equal amount of e-waste that already exists on the market in a country that lacks proper e-waste recycling capacity.' (TCO Development 2019; 2020a; 2020b). This shall be achieved by the following mechanism:

- 'The brand owner purchases offsetting from an approved collector, compensating for the potential e-waste of the certified product.
- The approved collector uses the fee to pay for the collection of the corresponding e-waste amount of end-of-life products that are no longer relevant for normal use. The collection takes place in regions where there is a lack of functional take-back systems.
- If responsible recycling is not possible locally, the approved collector must transport the e-waste to recycling facilities fulfilling high environmental standards.
- The offsetting for the certified product is continuously verified by an approved independent verifier.' (TCO Development 2019; 2020a; 2020b).

While this model is comparably new in the e-waste management field, similar approaches also exist for plastic and packaging waste (plasticbank; Plastic Fischer).

On the one side, e-waste compensation is a way to align (the purchase of new) electronic devices with organisations' values and ambitions. These can be commercial ambitions (such as employee engagement or company branding) as well as responsibility/moral ones (being a good corporate citizen). By providing organisations with a commercially interesting solution to make their IT consumption more sustainable, it allows these organisations to get started on the rather challenging concepts of sustainable procurement and sustainable operations.

On the other side, the concept aims at various objectives within the countries where e-waste is collected:

- To avoid that unsound handling, recycling and disposal of such products leads to pollution and adverse effects on human health and the environment;
- To open business opportunities for local waste management and recycling operators that comply with national regulations and that apply environmentally sound processes;
- To support the increase of local awareness, value-addition and investments in environmentally sound reuse and recycling.

To contribute to these objectives, the following additional principles implicitly apply:

1 | Local sourcing: E-waste compensation is aimed to manage waste from local consumption in the countries the collection takes place. It shall by no means stimulate any imports of e-waste to such countries and operators of compensation schemes shall take convincing measures to ensure that e-waste collected and processed under such arrangements comes from local consumption.

2 | Additionality: E-waste managed through compensation mechanisms should also come from a waste stream that would – without the scheme – most likely be managed in an unsound and polluting manner (e.g. open dumping, burning, crude recycling). It must therefore be avoided that compensation addresses waste volumes for which another player (e.g. the previous owner of the equipment) has already commissioned (and paid for) sound end-of-life management.

A further aspect that may need further discussion and public consultation is the question of what technical level the management processes shall comply with: While the first objective above (avoiding pollution) calls for a high ambition approach, the third objective might call for compromises in fields where highest recycling standards may – at least in the short term – only be realised through export of full devices to companies applying highest standards.

While this study cannot give an exhaustive answer to this question, the following chapters explore feasible and meaningful ways to manage end-of-life Li-ion batteries under e-waste compensation schemes in Nigeria.

# 3 Scope of the study

The scope of this feasibility study comprises electronical devices that make use of large flat panel displays. However, to narrow this scope to a feasible extent of the pilot project, the project team in a first step agreed to focus on flat panel computer monitors, flat panel televisions as well as flat panel screens of notebooks (see section 3.1). In a second step, as well in the course of the first pilot collection and dismantling exercises carried out on site in May/June 2021, the project team realised that including notebook screens into the scope would generate an incentive for collectors to take of screens from the rest of the notebook (computer and input unit), which would again motivate dismantling steps under uncontrolled conditions. Hence, the team decided to only focus on computer monitors and televisions. A second reason for this is that currently, the most important clients of Closing the Loop pay for compensation of computer monitors. An extension towards notebooks can be envisaged a later point in time.

## 3.1 General description

Generally, large flat panel display units (> 10 $cm^2$ as defined by the EU-WEEE Directive No. 2012/19/EU[1], recast) are mainly used in the following three consumer electronic product categories (see Figure 1):

- Flat panel televisions (left),
- Flat panel computer monitors (middle),
- Flat panel laptop screens (right, not in the scope of the pilot project finally).

Figure 1: Samples of end-of-life flat panel displays collected in Lagos, Nigeria

*Source: Oluwatobi Adegun (2021).*

Illumination of all three product categories can be either be realized by (1) LED lighting or (2) by cold cathode fluorescent lamps (CCFL). This leads to a matrix of 6 product categories that are in the scope of this project (see Table 1). Furthermore, especially computer monitors, and TVs can significantly be different in size.

[1] Flat panel displays smaller than 10$cm^2$ or tablets are not in the scope of this project.
EU WEEE Directive 2012/19/EU (recast), https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:02012L0019-20180704&from=EN

Hence, for e-waste compensation, also a size correction factor might be considered (see section 3.2).

Table 1: Product categories in the field of flat panel displays in the ECoN project

| Product categories for flat panel displays | 1 Mercury containing backlighting (CCFL) | 2 Non-mercury containing backlighting (LED) |
|---|---|---|
| A Televisions (left) | A1 | A2 |
| B Computer monitors (middle) | B1 | B2 |
| C Laptop screens (right) | C1 | C2 |

*Source: Own categorization.*

Figure 2: Cathode Ray Tube (CRT) screens are not in the scope of the pilot project

*Important Note: Cathode Ray Tube Displays (CRT) are not in the scope of the project (the very heavy big ones with a deep tube).*

*Source: Oeko-Institut e.V.*

### 3.1.1 Indicative Bill of Materials (BoM) of typical flat panel displays

Based on the categorization of flat panel displays in section 3.1, data collection was carried out in Nigeria. For this purpose, for each category (A) TVs, (B) laptop screens and (C) a sample of 3 collected screens was dismantled according to (Schluep et al. 2015). Hence, altogether nine devices were dismanteled and documented below.

Before dismantling, the weights of the screens as well as their diameter were measured. Also, the dismantling time in minutes was documented (see Table 2).

Table 2: Data collection and documentation of undismanteled screens

| Fractions (kg) | Average computer screen | Average laptop screen | Average television screen |
|---|---|---|---|
| Total weight (kg) | 4.33 | 0.87 | 9.00 |
| Average screen size (cm) | 43.50 | 38.67 | 60.00 |
| Average screen size in inch | 17.2'' | 15.2'' | 23.62'' |
| Dismantling time (mins) | 31.33 | 203.33 | 58.50 |

Source: own data collection and compilation in Nigeria

Furthermore, the products were de-polluted and dismanteled and the resulting fractions were documented in Table 3.

Table 3: Data collection and documentation of resulting fractions

| Fractions | Average computer screen% | | Average laptop screen | | Average television screen | |
|---|---|---|---|---|---|---|
| | kg | % | kg | % | kg | % |
| *A Printed Circuit Boards (PCB) & Cables* | | | | | | |
| 1 Low Grade PCBs | 0.0483 | 1.14 % | 0.0327 | 3.25% | 0.2860 | 3,23 |
| 2 High Grade PCBs | 0.2607 | 6.17% | | 0.00% | 0.4740 | 5.35% |
| 3 Cables and wires | 0.0227 | 0.54% | 0.0140 | 1.39% | 0.0690 | 0.78% |
| *B Plastic Fractions* | | | | | | |
| 1 ABS | 0.8340 | 19.75% | 0.2160 | 21.44% | 2.1560 | 24.32% |
| BFR plastics[2] | 0.2780 | 6.6% | | | | |
| Non-BFR | 0.5560 | 13.16% | | | | |
| *C Metal Fractions* | | | | | | |
| 1 Ferrous metals | 1.5980 | 37.84% | 0.0653 | 6.48% | 4.2375 | 47.81% |
| 2 Aluminum | 0.1980 | 4.69% | 0.0367 | 3.64% | 0.1550 | 1.75% |
| 3 Magnesium | | 0.00% | 0.1960 | 19.46% | | 0.00% |
| 4 Mixed scrap metal | | 0.00% | | 0.00% | 0.0320 | 0.36% |
| *D Background Lighting* | | | | | | |
| 1 LED backlights | | 0.00% | | 0.00% | | 0.00% |
| 2 Fluorescent back-lights | 0.0240 | 0.57% | 0.0097 | 0.96% | 0.0620 | 0.70% |
| *E Liquid Crystal Display & other Layers* | | | | | | |
| 1 LCD | 0.3843 | 9.10% | 0.2340 | 23.23% | 0.7110 | 8.02% |
| 2 Acrylate layer (PMMA) | 0.7120 | 16.86% | 0.1287 | 12.78% | 0.4085 | 4.61% |
| 3 Diffusion layer | 0.0873 | 2.07% | 0.0633 | 6.28% | 0.1445 | 1.63% |
| *F Other Fractions* | | | | | | |
| 1 Speakers | 0.0240 | 0.57% | | 0.00% | 0.0560 | 0.63% |
| 2 Unidentified/ Resi-dual | 0.0070 | 0.17% | | 0.00% | 0.0080 | 0.09% |
| 3 Screws | 0.0227 | 0.54% | 0.0030 | 0.30% | 0.0640 | 0.72% |
| **Total** | **4.2230** | **100%** | **1.0074** | **100%** | **8.8635** | **100%** |

Source: own data collection and compilation in Nigeria

[2] Estimations derived from the data set generated in the pilot project.

## 3.2 Size classification and correction

Apart from deriving a bill of material (BoM) in section 3.2, the project team also discussed and agreed upon a size classification for the collected flat panel screens. The threshold from S to M is based on the average size of a monitor screen (rounded up to 17”). The threshold level from M to L is larger than the collected samples of TVs as their size increased considerably over the last years. As laptop screens were decided not to be in the scope (see section 0), they are also not covered in the size classification scheme here.

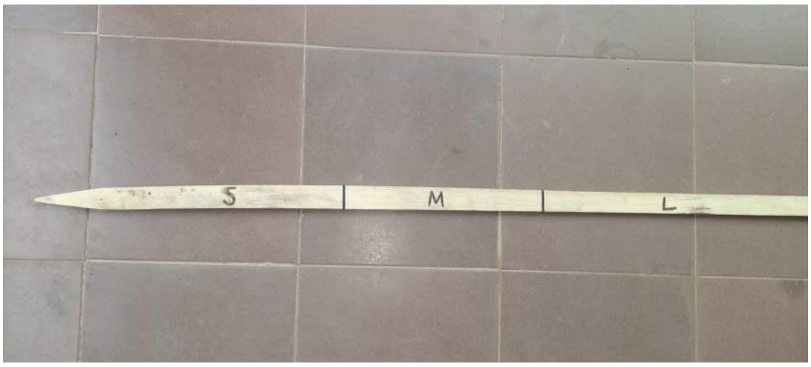
Table 4: Size classification of flat panel screens

| Size Class | cm | inch |
|---|---:|---:|
| S | <43.18 cm | <17” |
| M | 43.18 – 73.66 cm | 17- 29” |
| L | >73,66 cm | >29” |

*Source: Own classification*

Furthermore, data in section 3.1.1 shows that televisions are about two times heavier than computer monitors (9 kg vs. 4.33 kg) due to generally bigger sizes. Hence, from a weight perspective, one average television could compensate around two average computer monitors. Weight comparisons within the classes result in an additional weight of TVs of 138 % (based on the samples of section 3.1.1). Figure 3 shows a measurement stick that was introduced for an easy measurement of the size classes S, M, L. Especially, as workers might be rather uneducated, this allows for an easy and clear measurement.

Figure 3: Low threshold measuring of screens sizes in the ECoN project




*Source: Hinckleys Recycling Ltd.*

The aim of the above-described size analysis was to derive comparison criteria for e-waste compensation. The results will be published in a separate forthcoming report. After this initial analysis of the average weights it was agreed amongst the team to mainly focus on monitors.

# 4 Markets for flat panel displays

## 4.1 Flat panel computer monitors

After the technological transition from cathode ray tubes (CRT) monitors during the first two decades of the century, by the year 2021, practically all new computer monitors are based on the liquid crystal display (LCD) technology. This technology enabled significantly increased displays sizes as well as higher energy efficiency[3] and better ergonomics.

According to (Mordor Intelligence 2022), in 2021 the most relevant global brands are Samsung products (market share of 10.1 %), TPV (10.6 %), Dell (21.5 %), HP (10.1 %) and Lenovo (11.9 %) (IDC 2021). Most of them are produced in Asia including China, Taiwan and Malaysia where labour is comparably cheap leading to a comparative advantage for mass production.

On the consumption side, regional growth rates for computer monitors are highest in North America and South-East Asia followed by Europe, Middle-America and Australia. Also, the Covid-19 pandemic caused the demand for monitors to rise considerably because most people were working from home using these monitors. However, growth rates for 2022-2027 are lowest in South-America and on the African continent (Mordor Intelligence 2022).

Altogether, during the second quarter of 2021 (Q2/2021) a total of more than 35 Million units were sold and shipped globally (IDC 2021). As compared to the second quarter of 2020 (Q2/2020), this means an increase of 11.2 % (ibid.).

## 4.2 Televisions

During the year 2020, global sales of televisions was around 217 Million units (Statista 2022). Rapid technology developments such as smart TVs, better LED and OLED (organic light emission diode) and ever better resolutions such as 4k and 8k drive the markets.

Data from 2019 (T4 2022) shows market shares of 30.9 % of the Samsung Group, 16.3 % by LG, 9.4 % by Sony and 6.4 % of TCL and Hisense each (Others: 30.6 %).

## 4.3 Local market in Nigeria

Even if no exact market data on the number of domestically used screens in Nigeria are available, recent trends and estimates show a rapid increase in digizalsation in Nigeria. Worldbank data from 2020 shows that 36% of the Nigerian population has access to internet with an approximate 2% increase per year. (Worldbank 2022). Furthermore, Nigeria is far the largest IT market on the African continent (ITU 2021). According to the latest e-waste monitor, this translated into 461.3 kt of e-waste per year in 2019 (Forti et al. 2020).

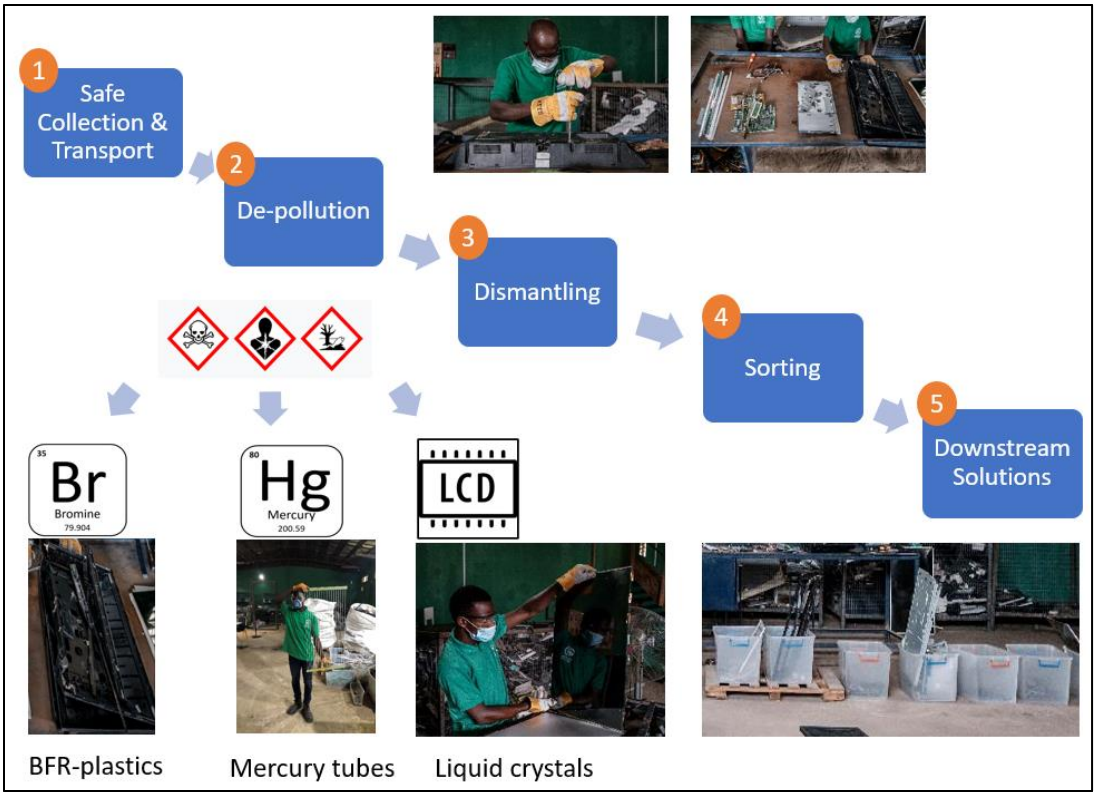
[3] However, there are observations that efficiency gains are eaten up by larger screen sizes (so called rebound-effect, https://www.energysufficiency.org/).

# 5 Collection, transport, storage, de-pollution and dismantling of flat panel displays

## 5.1 Overview: Flow chart of de-pollution, dismantling and sorting

This section summarizes the overall process in a flow chart.

Figure 4: Summarizing flow-chart of flat panel screen treatment




*Source: Own illustration.*

Figure 4 summarizes the five key steps of safe and sustainable flat panel screen treatment in Nigeria:

1 | Collection, transport & storage (see section 5.2),
2 | De-pollution of bromine containing BFR-plastics, mercury containing light tubes and liquid crystal containing LCD glass layers (see section 5.5),
3 | Dismantling, see (Schluep et al. 2015),
4 | Sorting and resulting fractions (see section 6),
5 | Transfer of fractions to safe downstream solutions (see section 7).

## 5.2 Collection, transport & storage

### 5.2.1 Typical situation in Nigeria

By the time of this report, in Lagos (Nigeria), end-of-life flat panel displays were most commonly collected by informal players and networks from (1) repair shops, (2) from households directly (door-to-door collection) or even from (3) makeshift dumps[4]. Screens were collected by the informal collectors who seek a daily livelihood by selling to informal recyclers (subsistence). Informal sector recyclers dismantle and seek picking valuable components to earn a small living. By this, dismantling takes place under considerable health risks and non-valuable or hazardous components (e.g. mercury containing lamps) are neglected, dumped, or burnt. Typically, flat panel displays are assessed physically before accepted and collected (e.g. scratches, broken display, etc.). While functional screens are resold to repair shops, dysfunctional ones are passed-on to dismantling (mostly informal).

### 5.2.2 Collection in the project

In the ECoN project, only complete screens are collected by agents and bought from the informal sector. However, most of the screens are damaged, some are without the plastic cover, others have cracked screens (see Figure 5). In major markets for second-hand goods in Lagos, repair shops and dealers of electronic products are organised in associations. Some of these associations created spots where their members can drop off obsolete and non-reparable devices from where they are picked by informal collectors. Beyond, waste pickers are often organized in networks and some engage with colleagues in other cities and states for collection.

Figure 5: Screens at a typical collection point of an Electronics Association in Nigeria

*Source: Oluwatobi Adegun (2021).*

Most (almost 90 %) of the collected screens are computer monitors. Typical prices for a flat panel display from the beginning of the pilot collection were 905 ₦ (~1,80 € for a complete computer monitor, for more prices, see section 8). The ECoN project collaborates with Verde Impacto that buys the devices from informal collectors or collection spots of Electronics Associations. It is important to

[4] Reportedly, most screens that are offered to collectors still are Cathode-Ray-Tubes (CRT) screens, that are not in the scope of this project, however.

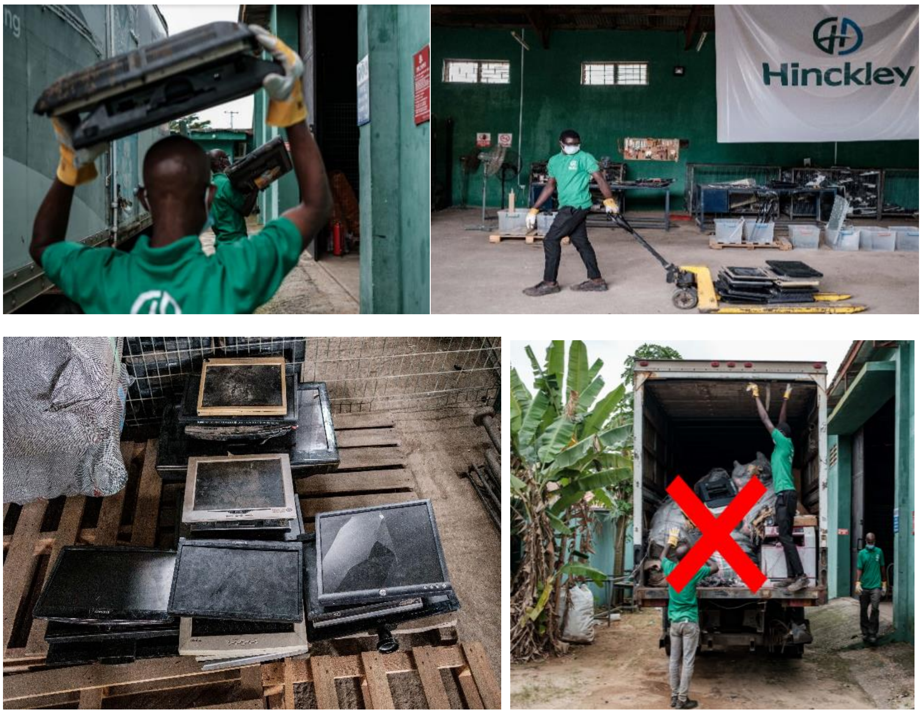
note that these prices are not sustainable and do not reflect the intrinsic value of the monitors. The project will also seek to sensitise workers in understanding the value of these devices.

### 5.2.3 General guardrails for responsible collection & transport

For the purpose of this pilot project, certain minimum requirements for collection, handling and transport of EoL screens were defined. This included:

- Collection of complete end-of-life flat panel computer monitors, and televisions[5]
- Screens should not be exposed to physical force (e.g. during loading and unloading from a transport vehicle),
- Should be handled with due care at any time (also during transport),
- Shall not be stacked too high so that they can fall over (ideally metal crates are used for interim storage),
- Shall be stored in metal crates (or similar containers) when transported to avoid movements and crashes on the road (compare Figure 6).
- Generally wearing personal protection Equipment such as gloves when picking flat panel screens.

Figure 6: From collection to handling and transport




*Source: ECoN Project (Closing the Loop, Hinckley Recycling Ltd.).*

The delivery of the screens must be carried out with sufficient care. They must not be thrown and only stacked carefully so that the screen side does not break.

[5] Parts of flat screens are not accepted as prior dismantling shall not be incentivized.

In any case, they should be stored temporarily on a concreted floor. In the best case, they should be stored in metal crates.

### 5.2.4 Challenges and recommendations for storage

#### *5.2.4.1 Challenges*

Besides collection and transport, also storage of e-waste and resulting fractions needs to follow due care and caution. Typical challenges and dangers are illustrated in Figure 7.

Figure 7: Careless storage and overcrowding of crates with e-waste fractions

*Source: © Oeko-Institut e.V.*

Figure 7 shows a dismantling workshop where fractions are just thrown on a pile regardless of the risk of a collapse and possible injuries of workers. The picture on the right shows overcrowding of crates with metal fractions so that they cannot be moved safely anymore.

Also, during storage, special attention must be set on hazardous fractions such as mercury containing lamps (see 5.6.1). The following Figure 8 shows how mercury lamps must not be stored (left) as compared to careful storage (right).

Figure 8: Unsafe storage of broken (!) mercury lamps (left) compared to handling with due care (right)

*Source: Oeko-Institut e.V.*

Breaking of lamps must be avoided. In case lamps are broken, they need to be taken to a safe airtight container to prevent mercury emissions harming workers and the environment.

#### *5.2.4.2 Recommendations*

Collection and storage shall be implemented with boxes and other means of transport that are safe, both, in terms of human health and the environment. For storage of flat panel displays and fractions, certain boxes and containers are suitable. Therefore, the table below provides and overview of the recommended safe means of transport and storage. In any case, the boxes and barrels need to be clearly labelled. Especially hazardous fractions need to be labelled according to international risk classifications (e.g. mercury lamps).

Table 5: Recommended means of transport and storage

| Device or fractions | Means of transport and/or storage |
|---|---|
| Complete end-of-life screen | Metal crates (avoid movement and damage) |
| Different plastic fractions | Big bags |
| Ferrous metals | Big bags |
| Aluminium | Big bags |
| Printed Wiring Boards (PWBs) | Big bags |
| Small batteries from PWBs | Plastic barrels (embedded in dry sand) |
| Cables and wires | Big bags |
| LED backlights | Wooden box |
| Florescent backlights | Wooden box with safety foam material inside<br>(to allow safe transport without breakage to pre-processing, see section 5.6). |
| CD display layers | Wooden box |

*Source: Closing the Loop, Oeko-Institut e.V.*

*Note: Especially, the mercury containing lamps need to be handled with due care. The wooded box with safety foam is only meant for intermediate storage until they are further processed in the so-called 'bulb eater' (see section 5.5.1).*

Also, for any dismantler, it is highly important to make sure the type of box or container is well coordinated with the downstream off taker of the fraction (e.g., plastic fraction). This also holds for the degree of pre-sorting of fractions. This avoids additional efforts of re-packaging and, hence, reduces efforts and possibly further risks (e.g., in case of the mercury lamps).

## 5.3 Re-use options

### 5.3.1 Re-use screening

Prior to the following processes of (1) de-pollution, (2) dismantling and (3) sorting, the devices should be considered for re-use. However, this shall not be done by trying if devices are still functional by plugging them in due to the risk of an electric shock during dismantling.

Figure 9: No re-use screening via plug-in and function test

*Source: Oeko-Institut e.V.*

Hence, re-use screening shall be made based on the visual impression of the device. If the device is considered for re-use, it shall be completely taken out of the process for a check. However, if the device is not functional anymore, it must be stored at least four weeks before dismantling to avoid the risk of a fatal electric shock of the workers.

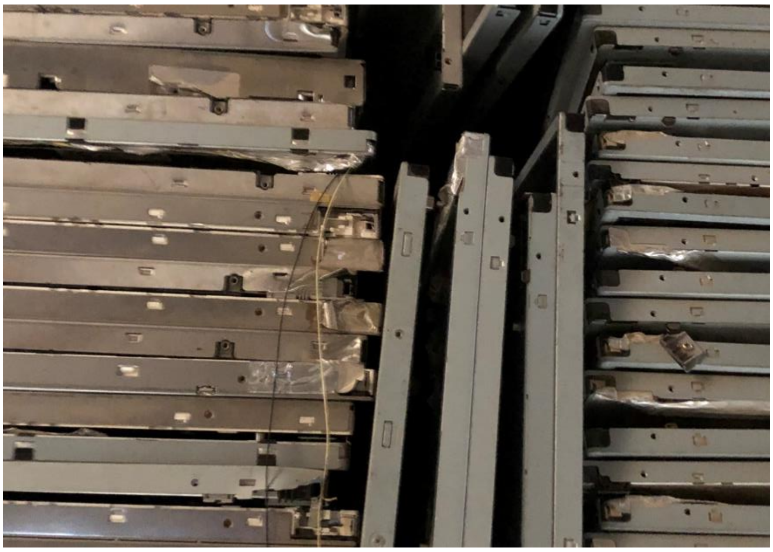
Generally, re-use options for flat panel displays, may not only focus on the reuse of full devices, but also on the re-use of components for repair/refurbishment of other equipment, or for other suitable application. In that case, all non-reusable parts shall be channelled to sound recycling.

*Note: Regarding the ECoN pilot project, however, it can be assured that devices are indeed at their end-of-life due to the collection price which would be considerably too low to allow for functioning devices on the Nigerian market.*

### 5.3.2 Possibilities for re-use of components

A prominent possibility of re-use of components of flat panel screens, is re-use of an intact display unit. By this, the use value of intact display units is exploited which is expected to be much higher as compared to the resource value for recycling.

Figure 10: Intact display units for re-use in new televisions.



*Source: Electrorecycling Ltd. Ghana*

Already, in other countries than Nigeria, the business model of re-using intact display units is realized and fully refurbished televisions using a second life display units are available on the market. However, this downstream path is currently out of the scope of the ECoN pilot project.

## 5.4 Pre-treatment options of flat panel displays in Nigeria

### 5.4.1 Guardrails for safe dismantling of flat panel displays

This section aims at a hands-on practical description of flat panel display dismantling in the context of the ECoN project. In the context of Nigeria, this means a practical methodology that considers strengthening the local generation of added value. Accordingly, the project recommends manual dismantling of all types of flat panel categories (see section 3.2) as illustrated by (Schluep et al. 2015).

In this way, manual dismantling creates jobs locally and results in more local valuable addition compared to shipment of whole devices for recycling abroad. Beyond, according to (Buchert et al. 2012) better recycling rates can be reached as compared to automated recycling (e.g. shredding) of whole devices.

However, manual dismantling needs to follow very distinct guardrails and guidelines to guarantee that

1 | Due diligence is set on health and safety of the workers,
2 | Pollutants are not released to the environment (see section 5.4.5) and
3 | Devices are dismantled into fractions and sorted carefully for downstream recyclers.

The latter is key to achieve a comparatively good price for local operators and to create added value for the Nigerian economy.

In the following, this study provides the most important steps for manual dismantling of flat panel displays.

### 5.4.2 General challenges

Primarily, the most important requirement for safe dismantling and other e-waste management steps, is an adequate organisation of all processes. For example, during storage of components, the organisation and structure of the processes should be organised in a way that the probabilities for accidents (e.g. head injury caused by falling components) are minimized (e.g. parts are stored close to the ground level).

Secondly, based on a due organisation of the process as described in (Schluep et al. 2015), health and safety is key for manual dismantling of any e-waste device. Health and safety measures (such as PPE) are important for the last protection of workers in the event of an accident, as described on (Burns et al. 2019). Hence, additionally to a clear and adequate organisation of all works, a focus must be set on health and safety.

### 5.4.3 General health & safety

As already mentioned in section 5.3.1, first of all, any testing of electric or electronic equipment prior to dismantling must be avoided due to the risk of a fatal electric shock. Due to the importance of this, this requirement shall be repeated here in Figure 11.

Figure 11: No re-use screening via plug-in and function test

*Source: Oeko-Institut e.V.*

Secondly, a complete and up to date first aid kit needs to be near the work site. It needs always to be checked periodically. A well organised safety policy sets clear rules for periodic checks and documentation.

In case any chemicals reach the eyes, it is important that workers do have fast access to an eye wash station (Figure 12).

Figure 12: Emergency eye wash station


*Source: © Oeko-Institut e.V.*

All general health and safety measures need to be explained regularly to all workers by regular health and safety training. The training also must contain general first aid measures as well as behavioural advice in case of an accident (avoidance of gaping).

Documents on the dates and contents as well as participants and trainers need to be safely stored and accessible to the facility manager at all time.

### 5.4.4 Personal protective equipment (PPE) and tools

As flat panel screens need to be dismantled in a safe manner, workers need to be protected by personal protective equipment (PPE) as illustrated in Table 6.

Table 6: Personal protective equipment (PPE) for manual flat panel dismantling

| | |
|---|---|
|  | ▪ Gloves protect the labourer from cutting his hands by sharp objects or splints.<br>▪ Optimal gloves are tight so that the labourer is not handicapped in executing his work |
|  | ▪ Protective goggles should be worn whenever a hammer is applied. |
|  | ▪ Protective shoes contain steel bars and protect the worker in case of heavy components drop. |
|  | ▪ When backlights are broken, an appropriate mask should be worn to avoid inhalation of mercury. |

*Source: (Schluep et al. 2015).*

Beyond PPE, manual flat panel display dismantling needs the use of appropriate tool that are compiled in Table 7.

Table 7: Tools for manual flat panel display dismantling

| | |
|---|---|
|  | ▪ Screw drivers are the most used tools.<br>▪ Considering all different devices, all different sizes and shapes (flat, torx, star etc.) are required. |
|  | ▪ Beside opening screws, a flat screwdriver can be used to release labels, rubber mountains etc. from plastics surfaces and open small casings (e.g. mice). |
|  | ▪ A side cutter is required wherever the scissors is not<br>▪ strong enough, e.g. to cut off power cables |
|  | ▪ Pliers are applied very frequently to remove components that are glued. |
|  | ▪ Strong industrial scissors are mainly used to cut cables and wires. |
|  | ▪ An industrial scale is required to quantify the<br>▪ recovered material. |
|  | ▪ A fine balance is needed to weigh smaller fractions accurately. |

*Source: (Schluep et al. 2015).*

### 5.4.5 Suitable workspace

Flat panel displays need to be dismantled with due care and without major damage of the workers' health (injuries) and the resulting fractions. Most importantly, devices are dismantled at a suitable work bench. Also, organization of tools in a tidy toolbox is very important. The following guardrails need to be followed when dismantling flat panel screens:

- Wear personal protection gear (see above),
  - Nitrile gloves
  - Safety goggle
  - Heavy boots
  - Dusk mask (Type FFP2/N95)

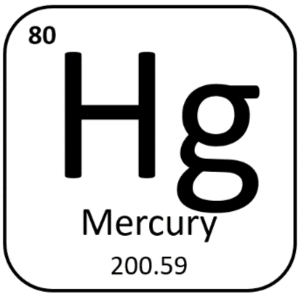
- Wear long sleeve (e.g. a coverall or at least robust trousers),
- Clean work bench policy: Clean your work bench before dismantling screens
- Work with your own tools: we provide you with tools and you are responsible, check your tools if working properly, always put tools back in your own box
- Install emergency eye wash stations
- Keep doors barrier free
- Always work with due time and not stressed
- Well aerated workplace (e.g., using a fan)
- Wet cleanable workplace to avoid accumulation of dust

## 5.5 Focus: De-pollution during dismantling

When dismantling a screen, the most critical fraction refers to the lighting element. Older screens make use of mercury containing fluorescent tubes (in TVs very often as backlights behind the screen; in laptops and monitors typically under the screen).

### 5.5.1 Mercury containing tubes

The most critical step in de-manufacturing a flat screen monitor or TV is the removal of the mercury containing fluorescent backlights (Fluorescent Lamps, FL).




Mercury (chemical sign Hg) is the only metal that is liquid under normal temperature conditions. In the human body, it can have an impact on the function of enzymes and structural proteins. The symptoms of mercury poisoning vary depending on the substance or compound. However, impacts on the nervous system are most common. The most relevant entry point of elemental mercury is the inhalation of mercury vapours as around 80 % of them are retained in the lung from where mercury can enter the bloodstream.

Inorganic mercury can cause severe burns of the oral cavity, pharynx and oesophagus as well as nausea and bloody vomiting when ingested orally. Within the gastrointestinal tract, inorganic mercury compounds can lead to circulatory collapse, shock and death. The smallest lethal amount in the human body is about 3 - 15 mg per kg of body weight (Böni and Widmer 2011).

First generation flat panel screens were always backlighted by fluorescent lamps that contain mercury whereas second and third generation devices make use of LED lighting today. However, still today, screens with mercury containing fluorescent lamps enter the markets.

In the fluorescent lamps, mercury is added in gaseous form. Typically, it can be assumed that new fluorescent lamps for screens contain 3mg (computer monitors) and 5 mg (TVs). Mercury ionised by electricity emits UV light, which is converted into visible light by the luminescent layer. However, over time, the mercury amalgamates on the inside of the tubes. Both, lifetime and brightness of the lamps depend on the amount of mercury. According to (Böni and Widmer 2011), end-of-life mercury lamps for screens still contain 1.33 – 2.63 mg of mercury vapour.

Hence, as mercury is added in gaseous form to the fluorescent lamps, breakage has to be avoided during manual dismantling. To make sure that workers are sufficiently protected, it needs to be guaranteed that the workplace is well aerated. The best solution is a ventilation system that deducts potential emissions directly away from the exposed workers. However, due to the small amounts of mercury, also a well-ventilated working space (open hall, windows, fans etc.) would be acceptable.

In the following Table, de-pollution of a screens from mercury backlighting units is summarized according to (Schluep et al. 2015).

Table 8: Stepwise depollution of the mercury containing light tubes

| | | |
|---|---|---|
| **Step 1** | Remove the cover that protects the layers by releasing the cover with a screwdriver and pre-check if the display is illuminated by mercury containing fluorescent lamps or LEDs. |  |
| **Note** | Typical mercury containing backlights (tubes)<br>  | |
| | Less critical: LED backlights<br>In case LED are identifed, remove them and sort them out. |  |

| | | |
|---|---|---|
| Step 2 | Remove the cover, and other fractions that need to be removed before able to safely remove the lamps. Make sure that mercury lamps are not broken! |  |
| Step 3 | Remove the backlights carefully with a screwdriver, take them aside and remove them carefully from the fixings. |   |
| Step 4 | Store the lamps in a closed box or container which disposes of a mechanism preventing the release of air.<br>If a lamp is broken it should be placed immediately into the container. |  |

*Source: Own compilation after (Schluep et al. 2015).(c) Photographies by Closing the Loop, Hinckley Recycling Ltd. and Oeko-Institut.*

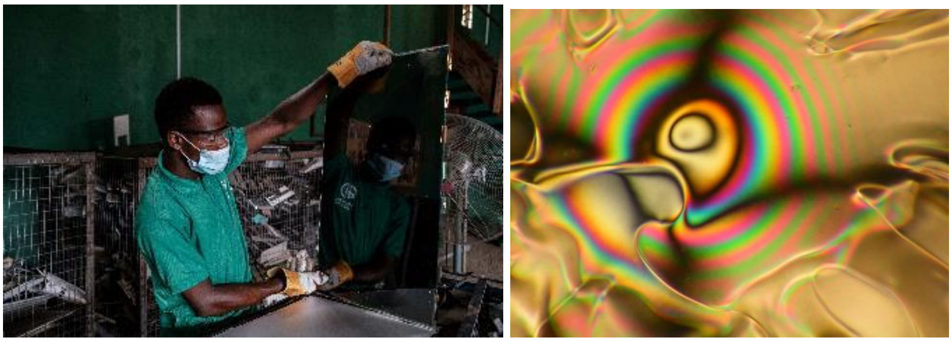
It is important to make sure that the workplace is well ventilated (e.g. by ventilators). The best option would be a ventilation system for the workplace. Under no circumstances de-pollution shall take place in small rooms without windows.

*Note: FFP2 masks are only suitable to protect workers from dust, not from gases such as mercury emissions.*

### 5.5.2 Liquid crystal display (LCD) glass

A second fraction that needs to be depolluted with due care are liquid crystal display layers (see also section 6.5). The organic liquid crystals are located between a glass layer and an indium tin oxide layer (ITO). The impacts of liquid crystals are unknown. Possibly they are carcinogen (Huijun 2018). Hence, the glass should be handled with care to avoid breakage and injuries of workers.

Figure 13: Liquid crystal display (LCD) glass



*Source: Hinckleys Recycling Ltd. & © Wikimedia Commons.*

Also, the LCD glass layer shall not be shredded or broken to make sure that the liquid crystals are spread. Regarding downstream options see section 7.

Also, the LCD glass layers shall be stored safely as illustrated in section 6.5.

### 5.5.3 Small batteries on printed circuit boards (PCBs)

Printed circuit boards (PCBs) in flat panel screens often contain small battery cells. According to the literature (Schluep et al. 2015), these kind of batteries shall also be depolluted which means manually taking them off the PCB and storing them separately.

Figure 14: Example of button batteries on PCBs.

*Source: Own photography.*

However, in scope of this project the PCBs are treated in a safe manner (e.g. smelting at very high temperature in a refinery) they can be treated together with the PCBs depending on the smelting facility.

*Note: This does not hold for larger batteries, such as Li-ion batteries from mobile phones. For these product group the parallel feasibility study in the ECoN project needs to be considered.*

### 5.5.4 Plastic fractions

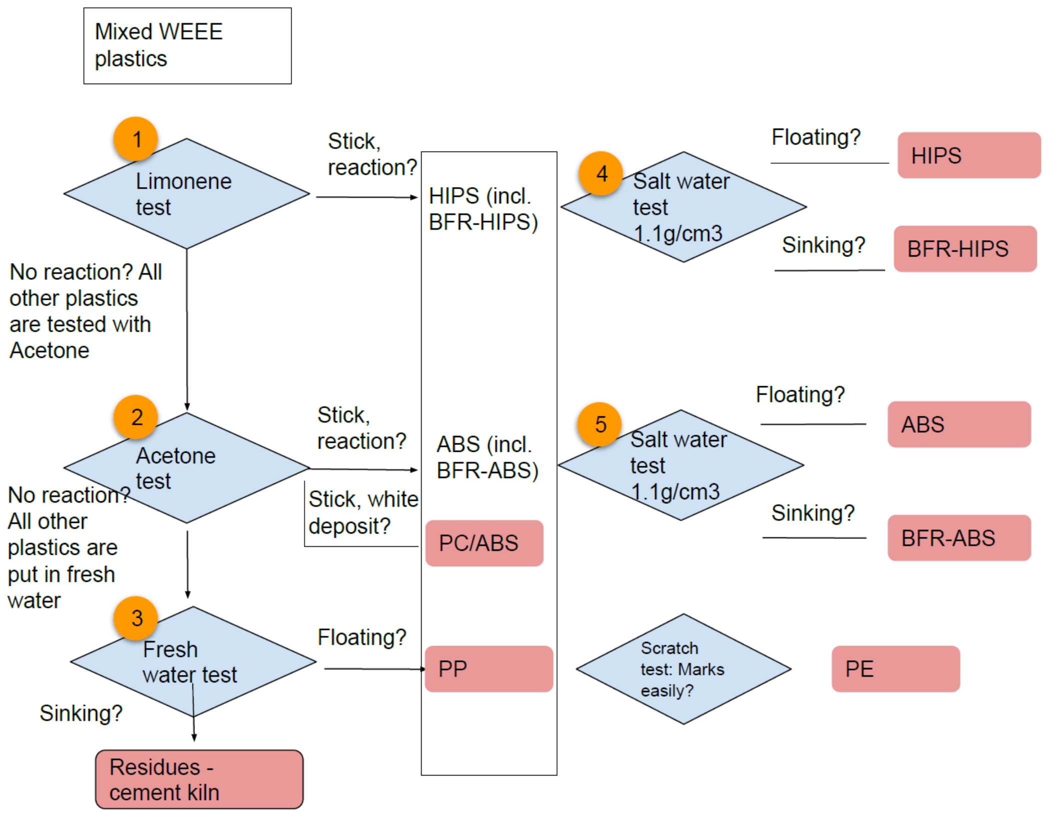
The most important de-pollution of the plastic fraction is related to Brominated Flame Retardants (BFR) in heat resistant plastic parts (see also section 6.2).

Bromine (Br) is a nonmetallic liquid and a member of the halogen elements. The element got its name from the heavy smell and is irritating to the skin, eyes, and respiratory system. Exposure to concentrated bromine vapor, even for a short time, may be fatal (Encyclopedia Britannica 2022).


In WEEE, Bromine is used as additive for BFRs. Some of them, such as polybrominated biphenyls (PBBs), polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecane (HBCD) are classified as Persistent Organic Pollutant (POP) under the Stockholm Convention because of their persistent, bioaccumulative and toxic (and long range transport properties (Haarman et al. 2020). Hence, the Stockholm Convention requires to sort out BFR plastics and channel them to safe final treatment such as co-processing in the cement industry.

In this chapter, however, identification of BFR plastics shall be explained. Therefore, the flow chart in Figure 15 shall provide orientation.

Figure 15: Flow chart for de-pollution and sorting of plastics from flat panel screens




*Source: Hannah Jung, Closing the Loop, based on (Bill 2019).*

Figure 15 provides an overview of a set of simple tests to easily identify the relevant types of plastic used in flat panel screens as well as if they contain BFRs (Bill 2019). It is recommended to conduct them in a stepwise approach as follows:

1 | **Lemonene-Test**: Lemonene is a natural orange concentrate that potentially reacts with HIPS. In case concentrated limonene is put on HIPS the plastics dissolves and becomes sticky. Hence, all plastics that dissolve with limonene are HIPS (including BFR-HIPS).

2 | **Acetone-Test**: Acetone is a widely spread chemical (e.g. high-quality nail polish remover) that reacts with ABS plastics. Hence, in case a plastic part becomes sticky in contact with Acetone, it is ABS (including BFR-ABS).

3 | **Fresh-Water Test**: Plastics from flat panel screens that do not react neither with Acetone nor Limonene should be tested in a 'sink-float' test with fresh water (density 1 g/cm3). Floating plastic parts ca be generally identified as Polypropylene (PP) or Polyethylene (PE). PE parts can be identified if a scratch is left on the surface if scratched, e.g. with a knife. Plastic parts that sink in fresh water shall be regarded as residues and send to safe final treatment, e.g. co-processing in the cement industry.

4 | **Saltwater sink-float test for HIPS**: A simple, key test to identify if BFRs are added to HIPS plastics is a sink-float test in salt water with a concentration of 1.1 g/cm2. In case the HIPS plastic pieces sink in such as saltwater solution, it is contaminated with BFR. Floating pieces are BFR-free (Bill 2019).

5 | **Saltwater sink-float test for ABS**: In parallel to the sink-float test for HIPS, ABS plastic pieces can be tested using this method. In case the ABS plastic pieces float in a saltwater solution of 1.1 g/cm3, it is BFR-free. In case is sinks, it can be assumed that they are contaminated in with BFR.

Summarizing, the illustrated simple tests can be used to easily identify types of the most used plastics of end-of-life flat screens as well as BFR contamination.

## 5.6 Further mechanical pre-treatment options of fractions

### 5.6.1 Mercury backlight lamps

After careful manual de-polluting the screens of the mercury containing backlight units (see section 5.5), the lighting tubes can be further processed and de-polluted in Nigeria: Therefore, an installation that is called 'bulb eater' can be used. At least two recycling facilities in Nigeria have a such an installation at their disposal.

Figure 16: Filtering of mercury lamps in a ‘bulb-eater’


*Source: Own photography at a recycling facility in Nigeria.*

In a first step, a mechanical ‘bulb eater’ crushes the bulbs under an inert atmosphere so that no mercury can evaporate to the environment. The lamps, however, need to be fed manually by a worker who needs to wear suitable personal protective equipment (PPE) such as safety boots, workwear (e.g. coverall), oxygen supply and helmet. FFP2 masks are not suitable to protect workers against mercury dust.

They second key processing step of the ‘bulb-eater’ is the absorption of the mercury in active carbon filters. The system is designed in a way that not only the mercury fumes are sucked into the filter, but also powder and some glass dust from crushing. Thus, the filter is likely to get blinded quickly without absorbing much mercury. Hence, it needs to be exchanged regularly, otherwise the system turns ineffective in terms of mercury capture.

However, as the backlighting tubes from screens are much smaller as compared to compact fluorescent lamps or linear fluorescent lamps for room lighting, the expected quantities from the pilot project are low. According to (Revolve 2016) the amount of mercury per flat panel display depends very much on its size and the number of backlight tubes, ranging from 4 tubes for 14’’ monitors up to 20 tubes for big TVs. According to (Böni and Widmer 2011) the typical range of mercury content per tube in PC monitor screens is between 1.33 – 2.63 mg. Assuming an average size of the collected screen of 23’’ (class M, 17’ - 29’), as most of the collected screens are computer monitors, see section 3.2, according to (Revolve 2016) we can assume 10 tubes per device. Based on an average weight of the screens of 4.33 kg/pieces (see section 3.1.1), the target value of 10t of collected screens translates into 2’310 pieces.

Accordingly, Table 9 provides an estimate of the overall amount of mercury in screens collected in the ECoN project.

Table 9: Estimated amount of mercury in the collected screens in the ECoN project

| | | Source / Assumption |
|---|---|---|
| Number of collected screens in ECoN | 2’310 | 4.33 kg/piece |
| Assumed average size of the screens | 23’’ | Average of class M (see section 3.2) |
| Average number of tubes per device | 10 | (Revolve 2016) |
| Mercury content per tubes | 1.33 – 2.63 mg | (Böni and Widmer 2011) |
| Range of mercury content in collected screens of ECoN project | 30.7 – 60.8 g | |

*Source: Own estimate based on (Böni and Widmer 2011; Revolve 2016).*

It is estimated that the between 30.7 – 60.8 g of mercury are in the backlighting units[6] [7]. Hence, as compared to the larger lighting applications such as in linear fluorescent lamps the amount of mercury in screens is rather low. It is, however, recommended to exchange the active carbon filter in the bulb eater according to its specific mercury abortion capacity.

Finally, the de-polluted lamp glass is recovered in a drum (see red drum in Figure 16) and can be transported to further downstream processes.

### 5.6.2 Shredding of de-polluted and sorted plastics

Based on de-pollution and sorting of plastics (see section 5.5.4), it is recommended to shred them in order to meet the requirements of downstream plastic recyclers.

[6] Under the assumption that all screens contain mercury lamps.

[7] According to the European ROHS-2018 directive, maximum allowed contents for linear lamps for room lighting applications are between 5 mg (triphosphor) and 10 mg (halophoshate). Hence, the mercury of the collected screens equals the estimated maximum allowed mercury amount of 300 – 600 linear fluorescent lamps (tubes).

Figure 17: Mechanical shredder for de-polluted and sorted e-waste plastics


*Source: Closing the Loop, Hincklyes Recycling Ltd.*

This can be done mechanically (see Figure 17). In case, a mechanical shredder is not available, plastics can also be crushed manually, e.g. with a machete. However, in any case personal protective equipment (PPE) needs to be worn and due care must be exercised to avoid risks for workers.

# 6 Resulting fractions of dismantled flat panel screens

## 6.1 Printed circuit boards & cables

As illustrated in section 3.2, printed circuit boards (PCB) make up a considerable part the products categories in the scope of the project. In general, there are two categories of PCB that are relevant for recycling: (1) Low grade PCBs and (2) High grade PCBs (Schluep et al. 2015).

Low grade PCBs typically contain a lower amount of precious metals such as gold and are found in power supplies of the devices. Accordingly, prices for low grade PCB fractions are low. Therefore, they are often not collected by the informal sector but just dumped. Their typical colour is brown or yellow. In turn, high grade PCBs are the ones where high-performance processes of electronic devices take place (such as the central processing unit, PCU). Hence, they need to contain more precious metals such as gold, tin and others. As compared to low grade PCB, high grade PCB fraction reach higher prices (see also section 8).

Depending on the category (A: Computer Monitors, B: Laptop Screens and C: Televisions screens), the amount of low-grade PCB range between 1.14 % - 3.25 %, whereas the range of high-grade PCB is between 5.35 % - 6.17 % (however, notebook screens do not contain high grade PCBs as the processing unit is in a different part of the product). Apart from the PCBs, the fraction of cables makes up to 0.54 % - 0.78 % of the flat panel displays product categories in scope (see 3.1.1).

## 6.2 Plastic fractions

A big share of the resulting fractions is made of plastics (see also section 5.5.4). Around, 20% of the average weights of the collected computer screens consist of plastic parts (see section 3.1.1). In screens, most of them are ABS plastics (Acrylonite Butadiene Styrene). As an exemption, also HIPS (High Impact Polystyrene) can be found, however, HIPS are rather used in refrigerators and other white household appliances.

The most relevant pollutant of plastics in screens are so called brominated flame retardants (BFR) that are used to prevent the plastics from overheating or even catch fire (Bill 2019). Hence, BFR plastics are typically used where heat is expected in the device. The Bromine content of BFR plastics is typically 2-5 %[8].

Elementary Bromine, however, is a halogen that is highly toxic for both, human health, and water organisms. Hence, BFR plastics muss not be treated in a way that the Bromine is released to the environment (e.g. open fire). According to the Stockholm Convention (UNEP 2019), BFR plastics shall be taken out of waste stream to avoid the release of Persistent Organic Pollutants (POPs).

[8] Expert judgment by EMPA, Switzerland.

Figure 18: Samples of ABS plastic fractions containing brominated flame retardants (BFR)

*Source: © Oeko-Institut e.V.*

Regarding specific practical test methods for the identification of BFR plastics, see section 5.5.4.

## 6.3 Metal fractions

### 6.3.1 Ferrous metals

Dismantling leads to several ferrous metal fractions (Figure 19). They can be easily identified by using a magnet. Besides housing parts, typically also screws are made of ferrous metals and shall be collected and sorted.

Figure 19: Ferrous metal fraction from dismantled flat panel screen

*Source: © Oeko-Institut e.V.*

From an environmental due diligence perspective of recycling, local downstream markets are relatively uncritical. Hence, it is recommended to sell ferrous metals on the local recycling markets in Nigeria.

### 6.3.2 Aluminium

Similar to ferrous metals, flat panel screen dismantling also result in an aluminium fraction. Aluminium is much lighter as compared to ferrous metals and non-magnetic.

Figure 20: Aluminium fraction from flat panel screens

*Source: © Oeko-Institut e.V.*

Also, for aluminium, in Nigeria, there is an established recycling industry. The sorted fraction can be channelled back to the local smelting industry.

## 6.4 Background lighting

As illustrated in section 5.6.1, background lighting is a fraction of environmental and health concern of flat panel screen if mercury fluorescent lighting is used. For details see section 5.6.1.

## 6.5 Liquid crystal display (LCD) layer

A fraction that needs special notice are the liquid crystal display layers. They mainly consist of glass, however, are coated with a thin layer of indium tin oxide (ITO). In between the glass and the ITO layer, there are organic liquid crystals (LCs).

Figure 21: Liquid Cristal Display Layers

*Source: © Oeko-Institut e.V.*

It is key that the LCD layers are handled with due care during dismantling, storage and transport as they easily break and can cause cuts or other injuries. Secondly, possibly adverse impacts of LCs on the human health are mainly unknown (Huijun 2018). Hence, in order to mitigate these risks for human health, safe final treatment is recommended. This means that a treatment should be carried out which breaks organic compounds completely, such as incineration at sufficiently high temperatures. Another possibility is to use it in processes that involve very high temperatures, such as cement production (co-processing).

*Note: The LCs are bound in a kind of paste. Therefore, the LCD glass should not be shredded. Otherwise, the crystals are dispersed and can no longer be collected and disposed of safely.*

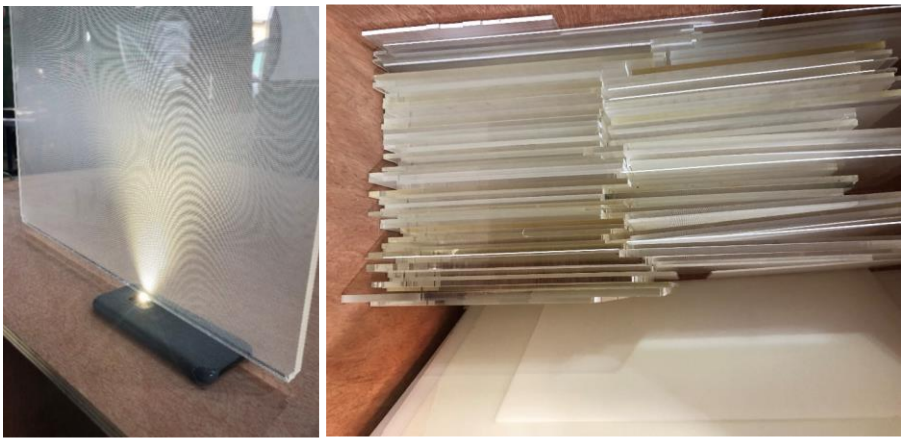
From data of the pilot project itself, it is estimated that 10t of displays would result in ~ 910 kg of LCD displays (~9 % of the mass of a full computer screen).

For more information on downstream options, see section 7.

## 6.6 Acrylate layer

Beyond LCD glass layers, flat panel screens contain a thick Polymethyl methacrylate (PMMA, trade name German: ‘Plexiglas’) layer that channels the light from the backlighting to the LCD unit. The layer has a thickness between 0.5 – 1.0 cm (see Figure 22). PMMA is a polymer that can be regenerated to its monomeric state by thermal depolymerisation.

Figure 22: Polymethyl methacrylate (PMMA) layers in flat panel displays



*Source: © Oeko-Institut e.V.*

Due to its good quality and robustness, it is recommended to channel PMMA layers into possible re-use options, such as:

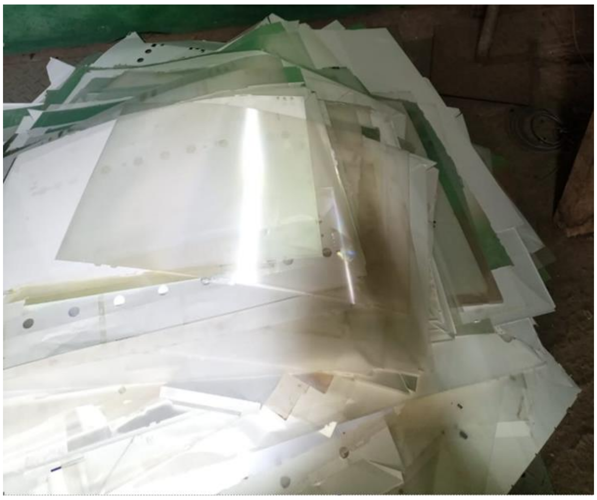
- Transparent separations of working spaces for Covid-19 protection,
- Illumination,
- Artwork,
- Others local re-use options in Nigeria.

In case local re-use options cannot be identified, is it possible to also shred the PMMA layers and sell them to international recycling markets. Solid PMMA sheets can be broken down again into their original building blocks by chemical recycling to make new sheets, tubes, rods with virtually unchanged product quality (Roehm 2018).

## 6.7 Polarization filters and other layers

Beyond the LCD layers, screens also contain a certain set of other diffusion layers such as polarization filters. They typically consist of plastic films such as polyvinyl alcohol (PVA). Some layers such as reflection layers can be metal coated as well.

Figure 23: Other diffusion layers such as polarisation filers



*Source: © Oeko-Institut e.V.*

Volume estimates from the ECoN pilot project range around ~207 kg from the collected 10t of screens (0.207 % of the mass balance).

# 7 Downstream and export options of fractions from Nigeria

## 7.1 The approach of due diligence

For all downstream re-use and recycling solutions of resulting fractions, the approach of 'due diligence' shall be applied. Similar to the approach for primary resources (OECD 2016), due diligence shall be conducted on secondary resources by private companies along the value chain in terms of environmental and social risks. By this, both, human rights and environmental issues shall explicitly not only be the responsibility of national regulators, but also private business shall need to care.

A related applied risk assessment is related to an identification and knowledge of environmental risks by targeted research of (reverse) value chains. As 'risk' is a factor of 'probabilities' and related possible 'damage', appropriate due diligence needs to especially focus on those sectors and fields where either the potential damage itself is high (e.g. severe human health impact) or probabilities for human rights or environmental damage is high (e.g. mercury emissions of broken fluorescent lamps).

Hence, for private recycling actors along the chain, it is important to use reasonable, targeted efforts on downstream due diligence by focusing on high pollutants and other high risks (e.g. working conditions). Regarding the recycling of flat panel screens, the following fractions and risks are in the focus and addressed in a targeted manner:

- Working conditions at collection, transport, pre-processing (de-pollution and sorting),
- Special safe treatment and safe disposal of mercury containing FL backlighting,
- Sorting and special treatment of BFR plastics,

However, in case of minor risks, e.g. where neither environmental nor human rights issues are at high risk (e.g. recycling of ferrous metals), follow-up risk assessment activities shall be executed at reasonable effort.

## 7.2 Priority on local value creation

The ECoN project follows a recycling approach that focusses on local value creation in Nigeria. This means that materials shall first of all be treated, recycled and re-used within the country. Only in case sustainable recycling of fractions and materials is not possible in Nigeria, for example if there is a lack of safe and sustainable recycling industry, the project team considers international shipping of fractions.

For the following fractions, local recycling or treatment is recommended:

- Ferrous-metals and aluminium fractions to be channelled to local recycling industry,
- Non-BFR plastic fractions to be channelled to local plastic recyclers (both ABS and HIPS),
- LCD glass, polarization filters and residual fraction as co-processing fuel for local cement industry (possibly also BFR-plastics),

- Diffusion layers
- Cables
- Other residues

Especially, for plastic fractions, the project team identified a possible downstream recycler located in Nigeria, that can recycle both, HIPS and ABS (see Figure 24).

Figure 24: Impressions from a local plastic recycler in Lagos

*Source: © Oeko-Institut e.V.*

According to the Stockholm Convention, BFR-plastics shall be channeled out of value chains. However, as long as new products are marketed containing brominated flame retardants, the project team would regard it as an acceptable solution if also BFR-plastics were recycled locally, if the resulting product requires flame or heat resistance, thus substituting the use of new BFR-plastics. Hence, if a local recycler produces heat resistant plastic parts e.g. back cover of car lighting, local recycling of BFR-plastics can be considered as well.

*Note: At the time of this report, the project team is still in search of other solutions. The research is not completed yet.*

## 7.3 Treatment and export of hazardous fractions

The most critical fraction in term of toxicity in devices using flat panel displays (see section 0) is the mercury containing backlighting (see also section 6). This backlighting technology is not used in every device as during the past 10 years, global markets have experienced a major technological and economic breakthrough of LED lighting technologies. LED lighting is not as hazardous as mercury containing discharge lamps, however, also classified as e-waste. However, still today for some screen applications mercury containing discharge lamps are used as background lighting. Also, older screens (>10 years) that are also collected in Nigeria, typically use mercury lamps. Hence, the project aims at international shipping and sustainable recycling overseas of mercury contaminated active carbon filters from the recycling of fluorescent lamps (see section 5.6.1).

# 8 Business model of screen recycling in e-waste compensation

Screen recycling, no matter if computer monitors or television screens are not a profitable business model per se. The reason for this is that the revenues for resulting scrap fraction do not meet the costs for collection, dismantling, de-pollution, transport, and safe disposal costs.

This shall be illustrated in the following. The Table below shows possible revenues of screen fractions based on the most relevant fractions. Revenues are market in green while negative value fractions are market in red.

Table 10: Revenues of positive and negative value fractions in typical business model for sustainable screen recycling in Nigeria[9]

| | | **Computer monitor** | |
|---|---|---|---|
| Fractions | Reference price in EUR/kg | Average monitor in kg | EUR/ monitor |
| Average weight | | 4.223 | |
| High grade PCB | 11.55 | 0.261 | 3.01 |
| Low grade PCB | - | 0.048 | |
| Cables and wires | 7.35 | 0.023 | 0.17 |
| Ferrous metals | 0.63 | 1.598 | 1.01 |
| Screws (ferrous metals) | 0.63 | 0.023 | |
| Aluminium pieces | 1.42 | 0.159 | 0.23 |
| Aluminium layer | 1.42 | 0.039 | 0.06 |
| LCD layer | - | 0.384 | |
| PPMA layer (Polymethyl methacrylate) | - | 0.712 | |
| Other diffusion layers | - | 0.087 | |
| Mercury lamps (gate fee in Germany, without transportation) | -1.20 | 0,024 | -0.03 |
| Plastic Fractions (ABS) | - | 0.834 | |
| Speakers | | 0,024 | |
| Mixed metal scrap | | 0,000 | |
| Other residual waste | | 0,007 | |
| **Total** | | | **4.44** |

*Source: Closing the Loop, Oeko-Institut e.V.:*

The Table above shows that the revenues of the most relevant fractions itself could exceed the considered negative value fraction. However, revenues or costs are not only related to the values of the resulting e-waste fractions. Also,

[9] In this report an exchange rate of 1 € = 500 ₦ was used.

collection, processing, and transportation costs need to be taken into account (see Table below).

Table 11: Cost of collection, processing and transportation

| | Reference price in EUR/kg | Average monitor in kg | EUR/ monitor |
|---|---|---|---|
| Collection price per device - flat fee in pilot project | | | -8.00 |
| Estimated processing costs (without transportation costs) | -0.50 | 4.223 | -2.11 |
| PAYMENTS | | | -10.11 |

*Source: Closing the Loop, Oeko-Institut e.V.*

Note: At this point, it must be mentioned that in the cost compilation above, transportation costs, as well as notification costs for international shipment of some fractions (mainly PCBs and active carbon from mercury lamp pre-treatment) were not taken into account. Hence, the cost compilation is systematically underestimated, and we expect additional costs of 4-5 Euro per monitor due to estimated shipment costs of 0.9 €/kg (Manhart et al. 2022).

Anyway, without any additional funding such as a compensation fee, sustainable screen recycling itself is not a viable business model (see red color in the Table below).

Table 12: Balance of costs and revenues of screen recycling in the pilot including a compensation fee

| | |
|---|---|
| Revenue/costs fraction sale +/- | 4.44 |
| Costs for collection and processing - | -10.11 |
| Balance without compensation | -5.67 |
| Compensation fee from the ECoN pilot project + | 5.00 |
| BALANCE WITH COMPENSATION | -0.67 |

*Source: Closing the Loop, Oeko-Institut e.V.*

In the model above as well as in the pilot project, a compensation fee (green) was selected to be five euros (5 €) per screen. However, even this compensation fee does not lead to a positive result and breaking even. Hence, it is recommended to increase the compensation fee to allow the business model to break even.

# 9 E-waste compensation within the national policy framework of Nigeria

E-waste compensation as an international financial mechanism in Nigeria is not an independent system per se. Moreover, it is embedded in a national policy framework in Nigeria. In case Nigeria implemented an effective EPR scheme channelling financial means from the ‘polluters side’ (importers, manufacturers, users) towards sustainable recycling in Nigeria, e-waste compensation would withdraw and fully hand over to a Nigerian EPR system. Also, in case additionality was implemented in Nigeria, e-waste compensation could withdraw. Otherwise, e-waste compensation would lead to a situation of ‘double accounting’ of e-waste quantities.

A national EPR system is meant to take ‘polluters’, in the case of flat panel screens this could be manufacturers and importers, up on their promise to guarantee sustainable recycling and avoid pollution and health risks that are related to the product in question and its end-of-life.

Currently, the development of Nigerian EPR policy for e-waste is advancing.  The process has already started with the *National Environmental (Electrical/Electronic Sector) Regulation* of 2011 (Nigerian Federal Ministry of Environment 2011), which included provisions for an Extended Producer Responsibility Programme. Nevertheless, a financing system through an EPR mechanisms is just being built up, supported by a recently published *Guidance Document for the Implementation of the Extended Producer Responsibility (EPR) Programme for the Electrical /Electronics Sector in line with Circular Economy* (NESREA 2021). In this document, TV sets are listed as one out of five product groups to be of immediate priority and to be addressed by short term collection and recycling activities. Screens and monitors are included as own category to be addressed by middle and long-term collection and recycling targets.

A Producer Responsibility Organisation (PRO) for environmentally sound end-of-life management of e-waste is in the process of being established but is not yet fully operational and no EPR fees are raised yet. The PRO is named Environmental Producer Responsibility Organization Nigeria (EPRON) and its membership base comprises some of the biggest producers. Additionally, EPRON has registered collectors and recyclers, which are supposed to provide sound end-of-life management once EPR implementation goes beyond registration. A standard defining minimum criteria for sound management, and for benchmarking collectors and recyclers, is currently being developed. Additionally, EPRON works on a set of differentiated fees, covering the costs which arise from sound end-of-life management of different types of e-waste. Furthermore, a software supporting the PRO´s administrative processes is under development.

At this point of time, PRO-driven collection and recycling activities are limited to pilot testing, and participating producers do not yet pay EPR fees for their product volumes placed on the Nigerian market. Thus, the e-waste EPR system is still in a quite initial stage with no established routines in fee collection, administration and organisation and monitoring of collection and end-of-life management of e-waste.

An additional challenge described by EPRON is to keep track of the amounts of goods brought to the Nigerian market. They are working on suitable tracking solutions together with Nigerian customs, the Standard Organization Nigeria (SON)[10] and the responsible enforcement authority (NESREA).

Summarizing, this means that there is not yet any functioning structure that fully finances environmentally sound management of end-of-life flat panel screens. In this situation, end-of-life flat panel screens are still subject to unsound management as costs for full responsible management are not covered.

In this context, piloting the concept of e-waste compensation in Nigeria was welcomed by various stakeholders engaged in the development of the mentioned policies and EPR systems. While it is clear that e-waste compensation cannot replace any binding national policies and financing mechanisms, it can serve as a first case where (monetary) contributions enable fully responsible collection, handling and management of EoL flat panel screens. With this, collection networks, recyclers and responsible authorities gain practical insights in developing high standard management, from a technical, logistical, and a financial perspective. However, the aspect of additionality needs to be respected carefully to avoid double accounting of collected and managed volumes in particular when national EPR schemes become operational in Nigeria (see section 2).

Experts involved in the set-up of EPR systems expressed their high interest to receive an overview of practical learnings from piloting e-waste compensation for flat panel screens in Nigeria and stressed the importance to continue coordination efforts from both processes in the future.

In this context, a basic role of the ECoN pilot project is to showcase that sustainable recycling of flat panel screens is feasible in Nigeria, once the regulatory gap by enforced standards is bridged by additional funds for formal recyclers. Without additional funds, formal recyclers cannot compete against a ‘cherry picking’ informal sector. Until a functioning EPR scheme is in place, e-waste compensation can pave the way and facilitate its implementation.

[10] SON has developed standards, which include requirements for new products coming to the Nigerian market. Currently, these SON standards do not cover used products.

# 10 Conclusions & recommendations

The preliminary outcomes of the ECoN pilot project led to the following conclusions:

- Without additional financial engagement such as waste compensation, sustainable recycling of flat panel screens is not financially viable. The business model estimations (see section 8) clearly show that the expected revenues resulting from channelling fractions to downstream solutions for recycling do not pay off costs of collection, pre-processing, de-pollution and sustainable end-of-life treatment of hazardous fractions such as mercury containing lamps. Any claim that sustainable recycling of flat panel displays would be a financially viable business in itself without financial support of a financial mechanism, are not justified from the results and experiences of the ECoN project team.
- Vice versa, however, the ECoN project could prove that by using an additional financial incentive for collection, sustainable pre-processing, de-pollution and sustainable downstream solutions, sustainable recycling of flat panel displays is possible in Nigeria. The financial mechanism that was used is 'E-waste compensation' (see section 2) with a temporary compensation fee per device of more than 5 Euro. This compensation fee could almost balance the costs of sustainable recycling, however, breaking even would require a higher fee.
- As TVs are, on average, more than two times larger than computer monitors, the ECoN team mostly collected and processed computer monitors (87.7 % related to a number of 2,344 EoL-devices). Only a share of 12.3 % (330 devices) of the collected screens were televisions. As at the beginning of the project, the project team realized that integration of notebook screens would result in prior damaging and splitting of notebooks, screens from notebooks were taken out of scope. The main reason for this was not to incentive damaging or splitting of devices before suitable processing.
- For e-waste compensation efforts (or similar financing schemes), it is recommended to introduce comparison criteria allowing to account the collection and recycling of one screen type for compensations paid for another. This may either be done on a weight base (as in many EPR schemes), or on the base of accounting factors (e.g. 1 TV screen accounts for 2 monitor screens).[11]
- The project team showed that under robust guidelines, flat panel screens can be suitably de-polluted and dismantled in Nigeria so to prevent harm to the environment and human health. Following clear guidance on collection, transport and storage (see section 5.1) and depollution during dismantling (5.4), and pre-treatment (5.6), flat panel screens can be processed in a way that markets for valuable fraction can be explored and served, and sustainable solutions for hazardous negative value fractions paid.

[11] Under work package 4 of this project, the team will make a proposal for comparison criteria.

- The ECoN project shows that e-waste recycling does not have to be organized in a way that all valuable fractions are exported from Nigeria while hazardous negative value fractions remain in the country polluting the environment and harming human health. The prior principle of the project was local sourcing (see section 2) to reduce any imports of e-waste of end-of-life devices as well as local recycling if possible. Local recycling options were identified for ferrous metals, non-ferrous metals, non-BFR plastics (local plastic industry), BFR-plastics (either co-processing for cement industry or local re-use for heat resistant plastic parts), LCD glass (co-processing in cement industry), polarization filters and other thin plastic layers and residual waste (ibid.).
- However, as currently there is no sustainable recycling possibility for Printed Wiring Boards in Nigeria, the ECoN team decided to export this fraction to international smelting for recovery of the metals. As shown in section 8, the revenues of the international sales of PWB do not compensate for the related costs.
- Regarding the most critical hazardous fractions of flat panel screen recycling, the solutions in terms of local final treatment differ. While mercury containing fluorescent lamps from backlighting can only be pre-processed in Nigeria (see section 5.6.1), BFR plastics can either be remoulded to new heat resistant plastics in Nigeria or finally disposed-off as an alternative fuel in the local cement industry (feasibility still to be tested and verified). Presumably, liquid crystal containing glass fractions can be safely channelled for co-processing as an alternative fuel to the local cement industry.
- Currently, Nigeria is preparing a fully-fledged EPR scheme for e-waste (see section 9) that should guarantee that responsibility for sustainable recycling is taken over. The financial mechanism of e-waste compensation shall not represent an additional burden or parallel system but pave the way towards an effective EPR scheme in Nigeria. In the course of developing an effective EPR system in Nigeria, lessons from e-waste compensation (e.g. level of compensation fee) can be taken over. Once a national EPR scheme is up and covering a significant part of the e-waste landscape, e-waste compensation should be phased-out to avoid parallel system and double counting of recycling achievements. In that sense, e-waste compensation shall always be regarded as a pioneering effort that can fill financing and management gaps in situations where effective systems on national level are not yet in place.
- However, EPR as a system, is very much limited on a national scale while e-waste compensation can potentially channel financial means from international actors (e.g. manufacturers in Asia or users in Europe) into Nigeria to financially enable sustainable recycling. Until sustainable recycling standards are effectively implemented, and conformity enforced, additional funds are needed to make sure that sustainable recycling can compete with sub-standard polluting recycling practices in Nigeria. E-waste compensation can bridge this financial and regulatory gap until recycling standards and an EPR scheme is implemented.

Based on the conclusions above, the ECoN project team can formulate the following recommendations for recycling of flat panel screens within the e-waste compensation system:

- In case, the compensation fee is high enough (significantly above 5 €), e-waste compensation can lead to sustainable recycling of flat panel computer monitors. As televisions are bigger (at least factor 2, see section 3.2), also the compensation fee should be adopted accordingly. Notebook screens shall only be taken into account in combination with the CPU and the rest of the device to avoid prior splitting or dismantling of notebooks and incentivizing 'cherry picking' (focus in the selection of valuable parts and pollution due to negative value hazardous fractions). Flat panel computer monitors, and TVs can be taken into the e-waste compensation system.
- In case, flat panel screens are taken into account for e-waste compensation, the identified guidelines for collection, health and safety, transport, storage, depollution, sorting and channelling towards sustainable recycling or disposal options (see chapters 5, 6.7 and 7) should be applied.
- Especially mercury containing backlighting lamps must be depolluted with due care, channelled to safe pre-processing as well as safe final disposal including a recognized disposal certificate (e.g. safe sulfurization process and safe final disposal).
- Brominated flame retardant (BFR) containing plastics parts shall be identified based in easily implementable tests (see section 5.5.4). According to the Stockholm Convention (UNEP 2019), BFR plastics shall be channelled to hazardous waste disposal. In case this is not feasible locally, other options can be examined (e.g. cement industry if emission control and co-processing process is suitable or possibly to local plastic recycling, if heat resistant plastic parts are re-produced and BFR-plastics are not mixed with non-BFR plastics).
- Any extension of e-waste compensation to flat panel screens should follow the principle of 'local sourcing' and 'local value creation'. No directly imported e-waste shall be processed nor fractions shipped if a sustainable solution is available in Nigeria.

# 11 References

Bill, A. (2019): Processing of WEEE plastics. With M. Gasser, A. Haarman and H. Böni. Available online at https://www.sustainable-recycling.org/wp-content/uploads/2020/04/Plastic-Handbook-Final_cc-by-sa.pdf.

Böni and Widmer (2011): Entsorgung von Flachbildschirmen in der Schweiz. Schlussbericht. EMPA, Swico recycling. Available online at https://www.swico.ch/media/filer_public/1c/4d/1c4d7923-7c18-4023-a514-3377fc95f99a/entsorgung_von_flachbildschirmen_in_der_schweiz.pdf.

Buchert, M.; Bleher, D.; Manhart, A.; Pingel, D. (2012): Recycling kritischer Rohstoffe aus Elektronikaltgeräten. Available online at http://www.lanuv.nrw.de/uploads/tx_commercedownloads/30038.pdf.

Burns, K.; Sayler, S.; Neitzel, R. (2019): Stress, health, noise exposures, and injuries among electronic waste recycling workers in Ghana. Available online at https://www.researchgate.net/publication/330291940_Stress_health_noise_exposures_and_injuries_among_electronic_waste_recycling_workers_in_Ghana.

Encyclopedia Britannica (2022): Bromine. Available online at https://www.britannica.com/science/bromine.

Forti, V.; Baldé, C. P.; Kuehr, R.; Bel, G. (2020): The Global E-waste Monitor 2020. Quantities, flows, and the circular economy potential. Hg. v. United Nations Univerisity & International Telecommunication Union. Available online at https://ewastemonitor.info/wp-content/uploads/2020/11/GEM_2020_def_july1_low.pdf, last checked on 19.05.2022.

Haarman, A.; Magalini, F.; Courtois, J. (2020): Study on the Impacts of Brominated Flame Retardants on the Recycling of WEEE plastics in Europe. Sofies. Available online at https://www.bsef.com/wp-content/uploads/2020/11/Study-on-the-impact-of-Brominated-Flame-Retardants-BFRs-on-WEEE-plastics-recycling-by-Sofies-Nov-2020.pdf, last checked on 26.01.2022.

Huijun (2018): Persistent, bioaccumulative, and toxic properties of liquid crystal monomers and their detection in indoor residential dust. With Huijun Su, Shaobo Shi, Ming Zhu, Doug Crump, Robert J. Letcher, John P. Giesy, and Guanyong Su. Available online at https://www.pnas.org/content/116/52/26450, last checked on 25.01.2022.

IDC (2021): Quarterly PC Monitor Tracker. Available online at https://www.idc.com/getdoc.jsp?containerId=prUS48252421, last checked on 28.01.2022.

ITU (2021): Digital trends in Africa 2021. Information and communication technology trends and developments in the Africa region 2017-202. Hg. v. International Telecommunication Union. Available online at https://www.itu.int/dms_pub/itu-d/opb/ind/D-IND-DIG_TRENDS_AFR.01-2021-PDF-E.pdf, last checked on 19.05.2022.

Manhart, A.; Betz, J.; Schleicher, T.; Hilbert, I. Smit, R.; Jung, H.; Adogame, L. (2022): Management of End-of-life Li-ion Batteries through E-waste Compensation in Nigeria. with support of Israel Olagunju and Adrian Clews (Hinckley Recycling Ltd.) comissioned by PREVENT Waste Alliance.

Mordor Intelligence (2022): Computer Monitor Market - Growth, Trends, COVID-19 Impact, and Forecasts (2022 - 2027). Available online at https://www.mordorintelligence.com/industry-reports/computer-monitor-market, last checked on 28.01.2022.

NESREA (2021): Guidance Document for the implementatin of the extended producer responsibility (EPR) programme for the electrical / electronics sector in line with circular economy, 2021.

Nigerian Federal Ministry of Environment (2011): National environmental (electrical / electronic sector) regulations 2011.

OECD (2016): OECD Due Diligence Guidance for Responsible supply Chains of Minerals from Conflict-Affected and High-Risk Areas. Available online at https://www.oecd.org/daf/inv/mne/OECD-Due-Diligence-Guidance-Minerals-Edition3.pdf, last checked on 28.01.2022.

Plastic Fischer: Take Action. Available online at https://plasticfischer.com/take-action, last checked on 06.07.2021.

plasticbank: Partnering for the Regenerative Society. Available online at https://plasticbank.com/business-partnerships/, last checked on 05.07.2021.

Revolve (2016): Informative piece on mercury. Available online at http://revolvproject.eu/wp-content/uploads/2018/03/ReVolv-project_Educational-piece_mercury.pdf, last checked on 26.01.2022.

Roehm (2018): UMWELT-PRODUKTDEKLARATION - PLEXIGLAS® Solid sheets. Available online at https://www.plexiglas.de/files/plexiglas-content/pdf/sonstige-dokumente/Umwelterkl%C3%A4rung-EPD-PLEXIGLAS-Massivplatten-de.pdf, last checked on 28.01.2022.

Schluep, M.; Spitzbart, M.; Balser, F. (2015): Dismantling Guide for IT-Equipment. World Resources Forum in cooperation with Dismantling-and Recycling-Centre(DRZ), Vienna & Institute for Materials Science & Technology (Empa), St. Gallen. Available online at https://www.sustainable-recycling.org/wp-content/uploads/2020/09/2015_Schluep_et_al_SRI_DismGuide_IT_Equipment.pdf, last checked on 22.06.2021.

Statista (2022): Television unit shipments worldwide from 2015 to 2021. Available online at https://www.statista.com/statistics/276238/television-shipments-worldwide-forecast/.

T4 (2022): Global TV Market Shares by Sales Volume 2019. Available online at https://global-uploads.webflow.com/5d71c5b5ed21579fe7c3535a/5f391bf6598ce62112099811_tv-market-share.png, last checked on 28.01.2022.

TCO Development (2019): TCO Certified Edge, Version 1, for tablets. Available online at https://tcocertified.com/files/certification/tco-certified-edge-version-1-for-tablets.pdf, last checked on 06.07.2021.

TCO Development (2020a): TCO Certified Edge - Version 1, for smartphones. Available online at https://tcocertified.com/files/certification/tco-certified-edge-version-1-for-smartphones.pdf, last checked on 06.07.2021.

TCO Development (2020b): TCO Certified Edge - Version 2, for notebooks. Available online at https://tcocertified.com/files/certification/tco-certified-edge-version-2-for-notebooks.pdf, last checked on 06.07.2021.

Ugbor, Terseer (2022): Interview covering the Nigerian EPR system for batteries and insights into the activities of the PRO 'Alliance for Responsible Battery Recycling' on the 11.02.2022. Interviewer Inga Hilbert.

UNEP (2019): Stockholm Convention on persistent organic pollutants (POPs). Revised in 2019. Available online at *http://www.pops.int/TheConvention/Overview/TextoftheConvention/tabid/2232/Default.aspx*.

Worldbank (2022): The World Bank in Nigeria. Online available: https://data.worldbank.org/country/nigeria, last checked on 19.05.2022.