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Recycling options for WEEE plastic components

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Ghana

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%	Per cent
BFR	brominated flame retardent
CRT	Cathode Ray Tube
EEE	Electrical and Electronic Equipment
EoL	End of life
FR	flame retardent
g	gram
PBB	Polybrominated biphenyls
PC	Personal Computer
PCB	Polychlorinated biphenyls
POP	Stockholm Convention on Persistent Organic Pollutants (POP)
POP-PBDE	Polybrominated Diphenyl ethers listed and (restricted) under Stockholm Convention on Persistent Organic Pollutants (POP)
SVHC	Substances of Very High Concern
w/o	without
WEEE	Waste electrical and electronic equipment

1. Introduction

The following document describes the findings regarding recycling possibilities for thermoplastics from WEEE within the project “Global circular economy of strategic metals - best-of-two-worlds approach (Bo2W)”[1]

Practically each electric or electronic equipment (EEE) contains plastic parts. Beside the plastic used for printed wiring boards, the most relevant fraction are plastics forming the housings or casing for EEE. The polymer types used for EEE are thermoplastics (in the case of printed wiring boards: thermoset material). Thermoplastics not only give the product shape and appearance but also fullfill the function to protect from environmental impacts, lowering the weight and restistance against heating.

The technical requirements lead to the development of a broad variety of different thermoplastic types. From a consumer point of view, the innovations in thermoplastics brought lighter, smaller and more durable products. In contrast, e-waste management faces serveral challenges with a proper handling of post-use thermoplastics. First, post-use thermoplastics have low values but these are not comparable to metal scrap. This makes collecting, sorting and processing more unattractive. Second, the broad variety of polymer types makes it unsuitable to differentiate properly without using special technical equipment. Third, thermoplastics contain serious amounts of flame retardents in order to prevent the risk of catching fire.

This report tackles the challenge and shows possible solutions based on literature and desktop research as well as numerous interviews with company representatives from the related recycling sector.

2. Thermoplastics, specifications and the current situation

The analysis focusses on thermoplastics form housings/casings from post-use cathode ray tube (CRT) appliances as this thermoplastic fraction is considered as most relevant regarding mass flow in combination with ecological damage potential.

Within the Bo2W project, the average composition of a CRT TV and monitor was defined. The definition is based on (Wecycle 2009), a research that measured the weight of nearly 1.900 CRT appliances and on (Parson 2008) and (Lee 2002) for the weight of containing components. Table 1 shows the mass balance of CRT appliances as used for the entire Bo2W project.

[1] See: http://www.resourcefever.org/project/items/global_circular_economy_of_strategic_metals.html)

Table 1 **Mass balance of average CRT appliances and containing thermoplastics**

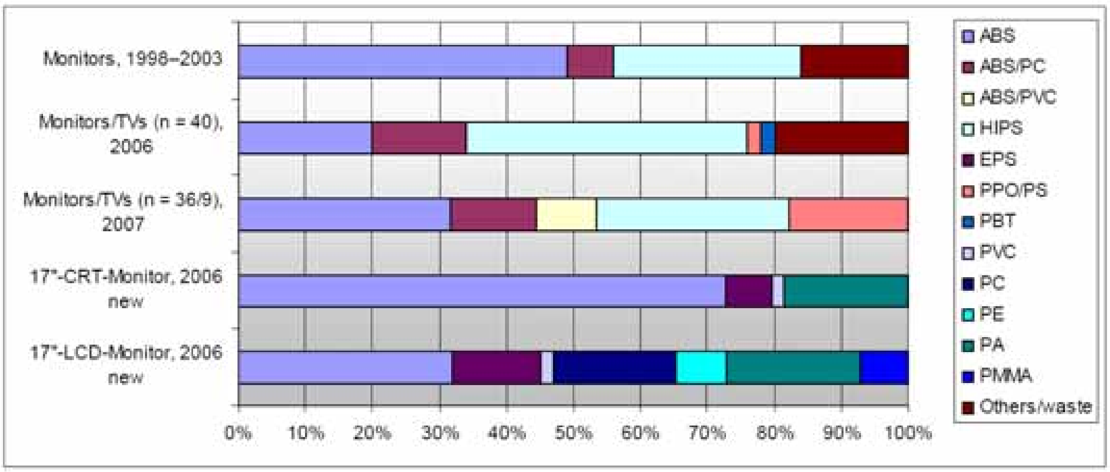
	Total appliance (kg)	Thermoplastic for housing (kg)	Share of total (%)
CRT Monitor	14,2	2,5	17,4
CRT TV	24,1	4,2	17,4

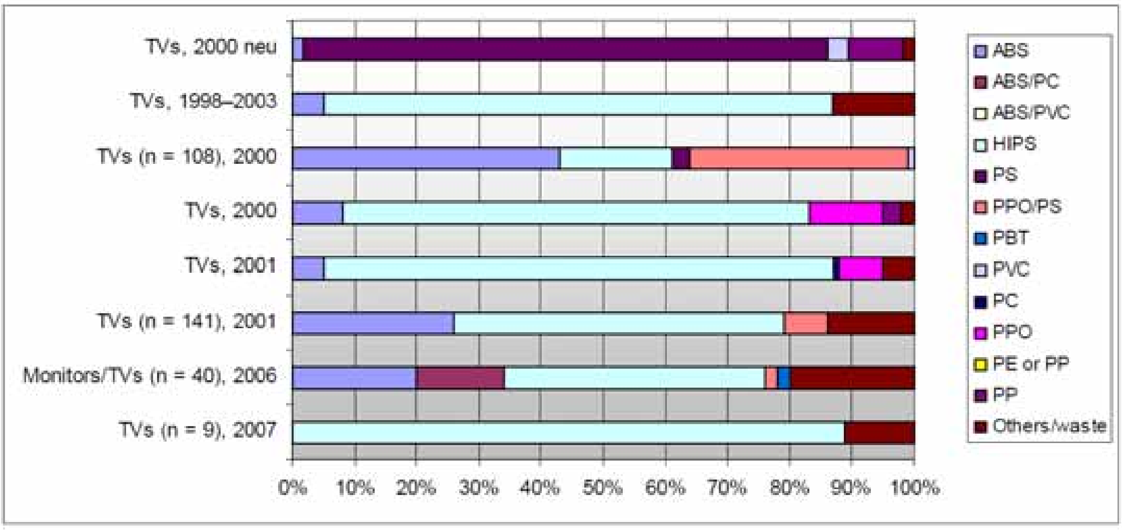
Source: Lee 2002; Parsons 2008; Wecycle 2009; baseline calculation for the Bo2W project

The term thermoplastic includes the following polymers: Acrylic, Nylon, Polybenzimidazole, Polyethylene, Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC) and Teflon. Mainly PS but also PP polymers are used in EEE. In order to improve the product performance of PS regarding hardness and durability, two or more monomeres are mixed in the polymerization process leading to so called copolymers. The most relevant PS-copolymers for EEE are: ABS (Acrylonitrile butadiene styrene), HIPS (High Impact Polystyrene) and the copolymer blends ABS/PC (Polycarbonate/Acrylnitril Butadien Styrol) and PPO/PS (Poly(p-phenylene oxide).

Studies show the varying share of polymer and copolymers used in EEE (Waeger et al. 2010). Regarding CRT monitors and CRT TVs, the most relevant plastics are ABS, HIPS and ABS/PC but it seems not possible to estimate the composition of used plastics by only knowing framework data like for example year of manufacture (see Figure 1).

Figure 1 **Composition of plastic types forming monitor and TV housings**

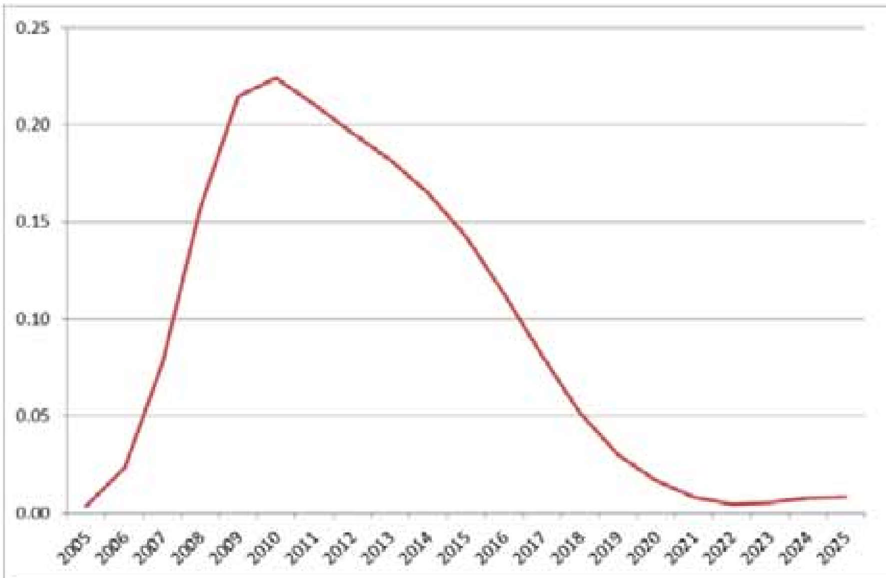




Source: Waeger et al. 2010

The Figure 2 shows the projected number of CRT TVs reaching each year the EoL (end of life) phase in Ghana. The amount of waste thermoplastics is evolving correspondingly. It is projected that the nummer of annual EoL CRT appliances reached its maxium in 2010/2011 with around 220 000 waste CRT TVs. As LED and plasma TVs gain relevant market shares quickly, the CRT technology is phasing out while a waste stock of thermoplastics is currently building up very fast.

Figure 2 **Projection of number of EoL CRT- TVs per year in Ghana 2000-2025 [in million]**



Source: Manhart et al. 2014

In countries with lacking recycling structures, like in the Bo2W partner countries Ghana and Egypt, WEEE thermoplastics are uncontrolled dumped in the landside or beeing burned in open fires to remelt other materials (see Figure 3). A way to handle this waste flow has to be found urgently.

Figure 3 Current situation dealing with thermoplastics in Ghana

Source: Andreas Manhart, Öko-Institut

3. Health and environmental concerns associated with thermoplastics from WEEE

Plastic forming polymers are generally very persitant and hereby withstand desintegration when dumped in the landside. In the case of thermoplastics for WEEE additional problems arise as these plastics typs are often added with flame retardents to increase the resistance to ignition and delaying the spread of fire. Traditionally, flame retardents in WEEE contain hazardous substances like chlorine or bromine. Flame retardents containing chlorine or bromine are named either as polychlorinated biphenyls (**PCB**), polybrominated biphenyls (**PBB**) or Polybrominated Diphenyl ethers (**PBDE**). The spectrum of flame retardents and especially brominated flame retardents is very broad and will be discussed more profoundly in the follwing chapter.

Problematic from an health and environmental point of view is that PCB, PBB and PBDE once released into environment are very persitant (=resitant against degradation) and consequently accumulate in living organisms (“bioaccumulative”). By doing so, the substances reach the human nutrition chain and accumulate in the human body. Several studies indicate adverse health effects by uptaking PCB, PBB or PBDE (see e.g. Morf et al. 2005).

The introduced hazardous substances are released into environment at different stages along a products life phase:

- Release during the production

- Release during the use-phase (e.g. outgasing and emission from FR containing furniture to indoor air).
- Release as a result of inappropriate waste treatment. Especially the uncontrolled buring of plastics form highly toxic dioxins and furans that are very persistant have carcinogenic effects. Furthermore, hazardous substances may also be released through leaching processes e.g. when dumped into landside (UNEP 2009).

Even not all flame retardents have the same harmfull effects on the environment and human health, flame retardents are adressed by diverse national and international regulations and restrictions which are more detailled discussed in the follwing chapters.

4. Variety of BFR and content in EEE

Polychlorinated biphenyls (PCBs), are a group of 209 different congeners that have formally been added as flame retardent in the production of transformers, capacitors or fluorescent light blasts (see EPA 2008). It is not apparent, that PCB have been used in thermoplastics for EEE housings. According to (ISQ 2011) PCB have been phased out in the production of capacitors.

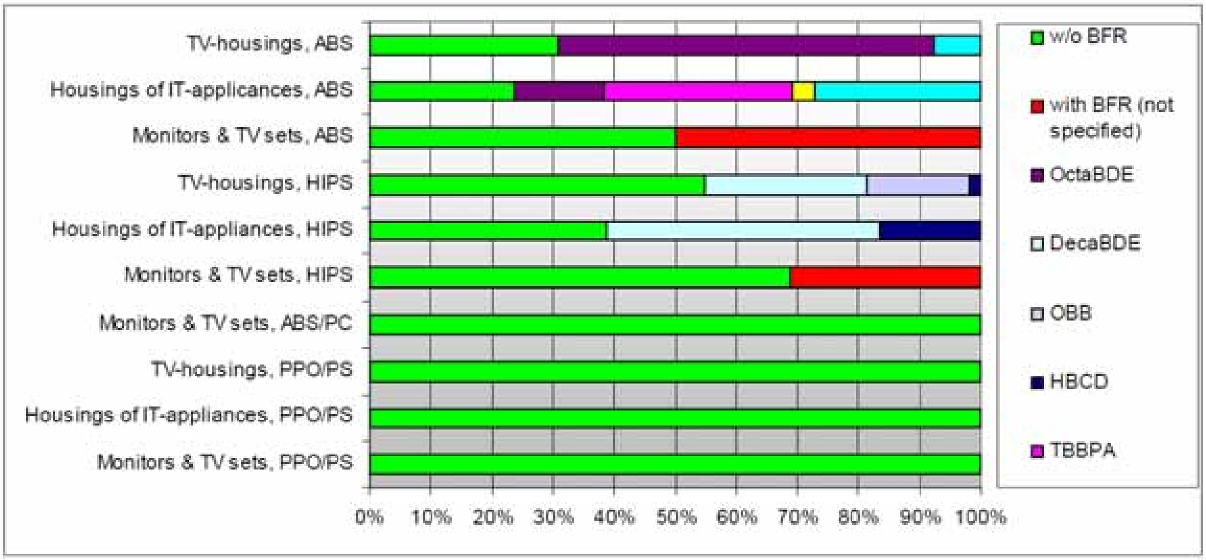
More relevant additives in the production of thermoplastics are bromine containing flame retardents (BFR). These compounds can widely be found in EEE, furniture and office equipment, paints and textiles. BFR can be dividied in the following four main groups with corresponding sub-groups (see Freer 2005):

- Polybrominated biphenyls (PBB's)
- Hexabromocyclododecane (**HBCD**), mostly addet to PS foams and used in textile, furniture and building applications (isolation material). Less common for EEE.
- Polybrominated Diphenyl ethers (**PBDE**'s), differentiated into a subgroup with low bromine content (tetra-BDE, Penta-PDE and hexa-BDE) and a subgroup with higher bromine content (including **Octa-BDE**, Nona-BDE and **Deca-BDE**). Deca-BDE is added to either ABS, HIPS, PP or PE and very common in EEE.
- Tetrabromobisphenol-A (**TBBPA**). TBBPA is added to ABS polymers and very common in EEE (for housings as well as printed wiring boards).

It becomes obvious that different types of BFRs are used in EEE. But it is difficult to predict which type of BFR is mostly applied for housings of TVs or monitors as being the subject of this study. Waeger et al. 2010 displays the testing results regarding the occurance of different BFR types in housings from two other investigations (see Figure 4). Obviously, the greatest variety of used BFR occures in housings made out of ABS and HIPS polymers. In contrast, TV and monitor housings made out of PPO/PS apparently are not added with bromine containing FR (phosphorous based FR may be used in this case). This shows that bromine free alternatives exist and are already applied (UBA 2008).

The database for the investigation shown in Figure 4 are 149 samples (35 TV housings and 114 monitor housings). Around 70% of the plastics were added with BFR. In 45% of the samples a bromine concentration between 6% and 10% by weight was found, 12% of the samples even had a bromine content of >10% by weight. These measured BFR concentrations are comparable to information on BFR concentration given from Freegard et al. 2006.

Figure 4 **Different type of BFR found in TV and monitor housings**



Source: Waeger et al. 2010

Studies like Sindiku et al. 2011 and 2012 that investigated the BFR content of WEEE in Nigeria come to the same conclusion: thermoplastics from waste TV or monitor housings mostly contain BFR. Thus, no correlation between production country / brand / year of manufacture and type and concentration of used BFR is possible.

5. Current regulation for BFR

Due to the negative health and environmental effects, the use of brominated flame retardent is restricted under diffferent regulations. Table 2 gives an overview about the current situation.

Stockholm Convention on Persistent Organic Pollutants (POP) is an international environmental treaty that aims to eliminate or restrict the production and use of persistent organic pollutants. 178 states plus the European Union[2] have jet ratified the Convention and committed to comply with the requirements of the Convention. Listed **POP-PBDE** substances shall either be eliminated (listed under Annex A), restricted (listed under Annex B) or controlled against unintended production (listed under Annex C). Since 2009, Octa-BDE and Penta-BDE are listed under Annex A and C and therefore restricted for the production and shall be monitored to prevent unintended production like for example due to dilution. The

[2] Relevant non-ratifying states include the United States, Israel, Malaysia and Italy

restriction in production seems unproblematic as producers already phased out Penta-BDE and Octa-BDE since 2004 (BSEF 2013). Consequences resulting from the listing under Annex C will be discussed in the following chapter.

In 2013, Norway proposed to add Deca-BDE under Annex A. The POP Review Committee is currently developing a risk profile of Deca-BDE as a basis for decision making.

Since May 2013, HBCD is listed under Annex A (elimination) but giving a 1 year exemption for HBCD used in insulation sheet applications.

Table 2 Overview regulations for the use of BFR

	International treaty	European Legislation		
	Stockholm Convention on Persistent Organic Pollutants (**POP)**	**RoHS**	**REACH**	**WEEE Directive**
Deca-BDE	proposed to be added	Ban for use in E&E applications (apart July 2008) if concentration >1% from product weight	registered in Sept. 2010, since Dec. 2012 on SVHC list (producers and importers have to notify and inform)	separation prior to recovery and recycling
Octa-BDE	listed since 2009			
Penta-BDE	listed since 2009			
TBBPA			registered since Oct. 2010. Intention to put on SVHC list .	
HBCD	listed since 2013 (1 year exemption for insulation sheet applications)		registered since Oct. 2010. Part of SVHC list. Apart Aug. 2015 only authorized uses	

Source: BSEF 2013, own calculation

RoHs is the short term for “Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment”. All PBB and PBDE flame retardants are restricted and banned in a concentration more than 1% from an EEE product weight. As RoHs is an european directive, the restriction of the named substances is only applicable for the European Union.

According to REACH, producer, importers and following users have to register applied chemicals and are responsible for a proper handling. This also includes instructions regarding information routines for customers. Selected substances of very high concern (SVHC) need for specific registration requirements before put on the market.

Deca-BDE, TBBPA and HBCD are registered substances under REACH. Deca-BDE and HBCD are furthermore listed as SVHC. As Octa-BDE and Penta-BDE are already being phased out in the production, these substances are not in the discussion for a regulation under REACH. In the case of HBCD, the 21^{st} August 2015 is defined as “sunset date” apart of this day, the production and commercialization of HBCD is completely banned.

The European Directive (2012/19/EU) on waste electrical and electronic equipment (“WEEE-directive) does not list single materials but defines that hazardous substances have to be separated prior to recycling and/or recovery.

All above introduced regulations indicate, that brominated flame retardents become more an more restricted. TBBPA remains as the most relevant non-restricted BFR for housing thermoplastics.

With regard to the focus of this study it has to be remarked, that even on the production side, many BFRs are phased out, these substances will still occur in EoL appliances as they are of specific interest of the Bo2W project.

5.1. Best practice treatment according to Stockholm Convention

The Stockholm Convention (SC) published recommendations and best practice examples how to treat EoL materials containing restricted POP-PBDEs (UNEP 2012 and SC Work programme POPRC-6/2). Basic intention is that not only the elimination at the production side has to be regarded but also the recycling side needs specific attention. As the hazardous potential lies in the persistance of the substances, POP-PBDEs from EoL appliances can return into a product (and use-phase) through material recycling. This rebound effect either occurs from unintended dilution (new product contains POP-PBDE through cross contamination) or in products were flame retardency is a basic characteristic (like e.g. in children’s toys). Brominated diphenyl ethers should not be diluted since this would not reduce the overall quantity in the environment. In consequence, the formulation of a sound recycling approach must avoid the rebound effect but still complying with the principles of the waste management hierachy (material recycling prior to recovery/incineration/disposal).

The Stockholm Convention calls for a separation and elimination of brominated diphenyl ethers from the recycling stream as soon as possible before recycling. For developing countries this means the introduction of screening techniques to separate BRF-materials. This will also reduce the exposure of workers in dismanteling operations. Separated POP-PDBE containing plastic fractions shall not be exported except for the purpose of an environmentally sound disposal in the importing country.

As the recovery of bromine from POP-PBDEs containing material is (in a full-scale facility) jet not possible, an appropriate treatment of POP-PBDE fraction can be discribed as follow: recovery by substituting fossil fuels or in incineraton plants with energy recovery. Further downstream treatment is incineration (w/o energy recovery) and destruction of pollutants followed by a responsible disposal.

6. Process optimization in Ghana/Egypt

In the previous chapters, the type of applied plastics for TV and monitor housings were identified and the problems arising from the added flame retardents explained. This chapter applies the obtained information regarding the current situation in the Bo2W partner countries Ghana and Egypt. This compendium is supplemented with information given from several plastics recyclers in the EU which have been contacted during the research for this paper.

- All reasearch done on plastics from WEEE indicate that the waste stream of TV and monitor housings accumulating in Ghana and Egypt contains an unpredictable composition of plastic types and applied flame retardents.
- A reliable separation in plastic type and BFR content is only possible with technical equipment. UNEP 2012 gives an comprehensive overview above screening technologies, including handheld instruments like x-ray based technologies but also automatic separation techniques like the sink and float process.
- Without such technical equipment, dismantling facilities in Ghana or Egypt are not able to separate plastic type and flame retardent in order to increase the added value in the downstream recycling process.
- The only pre-separation step that can be done without technical assistant is the differentend collection of black TV plastics that are mostly formed of PS plastics and white Computer plastics which are mostly made of ABS plastic. This pre-separation step would reduce the downstream separation effort and potentially increase the achieved prices for the dismantling/recycling company. Pure ABS/PC plastic is the most valuable plastic fraction with achievable market prices around 400 Euro per tonne.
- The overall impression from interviews with recyclers in the EU is that recycling of thermoplastics is – in contrast to the recycling of CRT glass (see Bleher 2014) - technically feasible and economically rather attractive.
- Most recyclers show interest in the Bo2W project and the intention to cooperate with dismantler/recycler from Ghana or Egypt and taking back waste thermoplastics.
- Dealing with waste thermoplastics is different to waste CRT glass as the material composition is more complex and diverse. European plastic recycler need more detailed information regarding the amount and quality (composition) of available material to determine price conditions within a possible business cooperation.
- For such a cooperation, baling or shredding of the material needs to be organized.
- The shipment of thermoplastics from e-scrap must not be notified if the plastic content as at least 90% of weight (Geyer 2013).

- The shipment of unsorted plastic can be an option as European plastic recyclers have the technique to separate by polymer type and BFR content. A pre-separation in countries like Ghana or Egypt is not strictly nescessary.

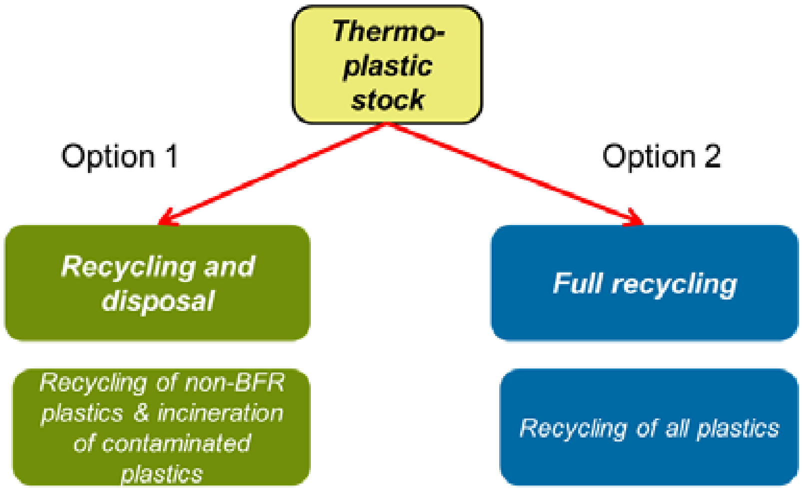
As the Bo2W project pursues an ecological holistic approach, the question of which output products can be processed with the material from Ghana or Egypt is of certain interest. This is especially because of the environmental and health damage potential combined with containing BFR. Plastic recyclers are reluctant with information on what happens to BFR containing output materials. Obviously, not all plastic recyclers find customers for recycling output containing BFR substances and so incineration or landfilling is common practice.

The question how to deal with BFR containing plastics is therefore a central aspect in the proposed recycling options in the following chapter.

7. Proposed recycling options for Bo2W project

Based on the presented findings, the Bo2W team proposes two options for an appropriate recycling of waste thermoplastics from TV and monitor housings in the partner countries Ghana and Egypt (see Figure 5).

Figure 5 Proposed recycling solutions for WEEE thermoplastics



Source: own illustration

Both recycling options differ to question how to handle BFR containing plastics. Option 1 implies the exporting (shipment) of the thermoplastic stock to appropriate facilities overseas with material recycling of the non-BRF containing fraction and incineration of contaminated plastics in state of the art installations. Option 2 implies a shipment and full recycling of waste thermoplastics from Ghana or Egypt.

Recycling and disposal (Option 1)

Option 1 focusses on the environmental best practice treatment of BFR containing plastics. Alongside with the UNEP 2012 guidance, all BFR substances are taken out of the system and an uncontrolled dissemination/dilution is avoided. Specifically this means that dismantling companies from Ghana or Egypt exclusivly cooperate with plastics recyclers that assure a qualified separation and treatment of BFR fractions. The environmental sound treatment of BFR fractions is either a recovery in form of substituting fossil fuels (co-generation) or a recovery in incineraton plants with energy recovery.

Based on a set of assumptions[3], the Bo2W-team calculated the costs for transportation and shipment with around 60 Euro-Cent per average, unsorted housing from an CRT TV. Break even price to achieve a slight net profit of 20 Euro-Cent per TV housing would be a net-price of 200 Euro per tonne of average thermoplastic.

Following this apporoach, the question arises, who pays if transportation and shipment costs exceed the achieved price?

<u>Sub Option</u>

Alternativly to the BFR separation at the designated plastic recycling facility, a BFR separation step at the dismantling sites in Ghana or Egypt may be implemented. Among the range of available screening technologies, UNEP 2012 proposes a certain technology as most favourable for FR detection and plastic separation in developing countries. The sliding spark technology is able to detect all kind of BFR. Costs for a single handheld equipment are around US$ 6,000 (UNEP 2012). Furthermore, the equipment can be combined with a near infrared sensor (extra costs: US$ 33,000) which allows to determine the polymer type. As a result, clean BFR and polymer fractions can be produced. The method is quite labour intensive but thus can be attractive to be done in developing countries in order to compete succesful with a separation done in industrial countries with higher wages.

The approach to generate clean BFR and polymer fractions in the Bo2W partner countries leads to another setting of the proposed recycling option. It would be thinkable that the dismantling facility sells all non-BFR fractions on the global market and simultaneously becomes supported for an environmental sound management of the hazardous fraction (qualified co-generation or incineration with energy recovery). This support may be reached by a proper utilisation of funds raised through an extended producer responsibility (EPR) scheme.

From the Best-of-2-worlds perspective, the above described sub option should only be allowed if any risk arising from an inappropriate treatment of the (separated) BFR-containing fraction is excluded.

[3] 425kg per bale , 42 bales in a 40 foot container -> 101 housings per bale, 4,254 housings per container.

Full recycling (Option 2)

The full recycling option describes an approach to cooperate with a plastic recycler who is able to process and re-sell all plastic fractions. It should then be taken into account that BFR containing plastics are diluted with other plastics to a certain percentage in order to undercut legal limits (e.g. 0,1 % of weight to be RoHs compliant). An oversea export of BFR containing fraction to countries with less strict regulations is also thinkable. The uncontrolled dissemination of brominated flame retardents in recycling products is inevitably linked with this option. Thus, the ideal of an environmental best recycling is backed up by accepting that any material recycling is a significant improvement to the uncontrolled dumping of thermoplastics as it is the current situation. The advantage compared to the above presented option 1 is that probably higher added values can be achieved as no disposal costs push prices and profits down. Neverthelss, the shipment costs and breake-even prizes are the same as in option 1.

8. Conclusion

The research on recycling possibilities of thermoplastics from TV or monitor housing shows that several obstacles have to be overcome. Various polymer types have been applied and it is not possible to accuratly predict the specific polymer type without technical equipment. Additionally, distinctive flame retardents are added to the polymers of which most are persistent organic pollutants and therefore hazardous. A very dynamic process of international restrictions regarding the production of BFR can be observed at the moment. Nevertheless, a broad spectrum of BFR in the end-of-life waste stream in the Bo2W partner countries Ghana and Egypt must be expected for today and the next years. The identification of BFR content is –same as polymer type- without technical equipment not possible.

Nevertheless, a recycling solution for WEEE thermoplastics seems to be more promising than the recycling of waste CRT glass. This is mainly because some polymer types (especially ABS-PC plastics) have a reasonable economic value.

As no recycling facility specialized on plastic recycling (plastics from WEEE) was found to be located in West-Africa, an export of WEEE thermoplastics is necessary. The proposed recycling options differ in the question how to handle the BFR-containing fraction.

Option 1 represents a cooperation with a recycling company in Europe that assures an environmental sound handling of this fraction. The proper disposal of the hazardous fraction leads to additional costs and therefore reduced net profits for the supplier. A brake even price from around 200 Euro per tonnes is calculated to compensate expenditures for shiping and to generate at least a low net benefit.

A sub option to this option 1 might be the equipment of BFR and plastic type screening technologies for the dismantling facilities in Africa. This would allow the production of BFR containing plastic and clean plastic type sorted fractions. The dismantler than should be responsible for the export and/or safe disposal of the hazardous fraction (qualified co-generation or incineration with energy recovery). In this sub option the dismantler would be able to sell the attractive non-contaminated plastic fraction on the global recycling market.

In contrast, in option 2 higher revenues might be obtained by not insisting on environmental best management solutions. Then, a cooperation with a recycling company in Europe which is able to process and re-sell all types of plastic and flame retardent content is recommendable. This option accepts a dissemination and dilution of persistant BFR contents in recycling products but still represents an significant improvement to the current situation in Ghana or Egypt.

Practically, the most challenging problem is that the concrete mixture of the already accumulated thermoplastics at the dismantling facilities in Ghana or Egypt is unknown and any prize estimation therefore vague. A business partner needs to be identified who is willing to receive and process a test shipment. Company talks indicate that a test shipment needs to have a weight of at least 50 tons (Wilkinson 2013).

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