Environmental Footprint and Material Efficiency Support for Product Policy

Report on benefits and impacts/costs of options for different potential material efficiency requirements for Electronic displays

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**Executive Summary**

The scope of the present report is the analysis of resource efficiency measures for electronic displays and potentially related Ecodesign requirements. In particular the objective is to provide scientific support to help assess the benefits of the extraction of key components from electronic displays, and assess their benefits and environmental impacts.

The analysis is based on three phases:

- Literature review, to identify available scientific studies that are relevant to the analysis;
- Campaign of measurement of the time for dismantling electronic displays carried out in an Italian electric and electronic equipment waste recycling plant;
- Identification and assessment of suitable thresholds for the time taken to extract key components and their implementation as potential Ecodesign requirements.

The analysis focused on two types of key components in displays: Printed Circuit Boards (PCB) and Thin Film Transistor (TFT) panels. The analysed products are electronic displays (TVs and monitors) with Liquid Crystal Display (LCD). Plasma TVs were not considered due to their low representativeness in the market (less than 5% by 2011), and also because few devices are currently recycled and are expected to be phased out in a few years.

The extraction of the PCB and TFT panels has some common steps. Therefore, the setting of a single time threshold for the extraction of both of these components together would imply less uncertainty. Moreover, the introduction of a requirement about the combined extraction of PCB and TFT panel would leave to greater flexibility as regards the design of products that are compliant with the expected thresholds.

The analysis has identified several possible thresholds for the total time taken to extract key components (differentiated according to different sizes of devices). It must be noted that the present analysis refers to displays currently at their end of life (EoL) but that have been designed in the past 5-8 years. According to manufacturing associations, modern displays have a significant lower mass and also their design for dismantling purposes has been improved.

The most suitable option for a potential ecodesign requirement involves time thresholds with which at least 50% of displays with comply with the ecodesign time threshold extraction requirements described in this report.

The potential requirement for the extraction time of key components in electronic displays is the following:
For electronic displays smaller than 25 inches or 63.5 cm (diagonal screen size), the time for the extraction of Printed Circuit Boards (PCB) assembly that are larger than 10 cm², film conductors and TFT panels embedded in electronic displays shall not exceed 260 seconds.

For electronic displays equal to or larger than 25 inches or 63.5 cm (diagonal screen size), the time for the extraction of Printed Circuit Boards (PCB) assembly that are larger than 10 cm², film conductors and TFT panels embedded in electronic displays shall not exceed 480 seconds.

Finally, the report discusses potential benefits and impacts of the proposed Ecodesign requirement. It is estimated that the improved extractability of key components will help optimize the End of Life treatments of electronic displays, increasing the recovery rate of some rare, precious and critical raw materials. The implementation of the proposed requirement would allow the recovery of about 86-261 tonnes of copper, 7-15 tonnes of silver, 2-5 tonnes of gold, 0.5-1 tonnes of palladium and 5.5-11 tonnes of indium. The potential economic benefit of recovering such amount of metals is from 58 to almost 144 million €, and corresponds to about 7-14% of copper, 17-33% of silver, 14-28% of gold, 15-29% of palladium and 16-32% of indium contained in the TV sold in the EU in 2012. This implies also the reduction up to 30% of various life cycle impact categories (e.g. related to human toxicity, ecotoxicity and resource depletions).

Furthermore extracting PCBs and TFTs will reduce the risk of contamination of other waste fractions by potentially hazardous substances (contained into PCB and TFT).

The proposed requirement will also contribute to reduce the costs of the recycling of electronic displays (due to the improved extractability of key valuable parts and reduced labour costs) and would also increase revenues (due to the improved recyclability of some display parts).

No significant negative impacts are expected. The costs of re-designing new devices in order to comply with the proposed requirements are furthermore estimated to be negligible compared to other product's costs, especially considering that the requirement will affect the design of new devices in the next years. Manufacturers will have therefore the sufficient time to adapt the new models to the thresholds for extraction.
Abbreviations

EC – European Commission
EoL – End of Life
EEE – Electric and Electronic Equipment
ErP – Energy Related Product
EuP – Energy Using Product
ITO - Indium tin oxide
JRC – Joint Research Centre
LCD – Liquid Crystal Display
PCB - Printed Circuit Boards
PGM - Platinum Group Metals
PDP - Plasma Display Panel
TFT – Thin Film transistor panel
TV- Television
WEEE – Waste of Electric and Electronic Equipment
Benefits and impacts/costs of different potential material efficiency requirements for Electronic Displays

1. Introduction

A recently concluded study on material efficiency\(^1\) analysed a method for the identification and assessment of "hot-spots"\(^2\) for End-of-Life (EoL) treatments of Waste Electric and Electronic Equipment (WEEE) including television, washing machines and imaging equipment [Ardente and Mathieiuex, 2012]. Among various possible product’s measures, the study identified that a special focus on some key components rich in some relevant substances can increase the recovery yields at the recycling plants. In particular, the improvement of extractability of these components could represent a potential suitable Ecodesign requirement for some EU Ecodesign policies\(^3\).

Currently the Ecodesign implementing measures for televisions\(^4\) are under revision\(^5\), including the discussion also upon potential resource efficiency requirements for electronic displays\(^6\).

The present report is intended to provide scientific support for the development of measures to improve the extraction of key components from electronic displays, and assess their benefits and environmental impacts. The report includes first, a summary of key findings in the scientific literature. Successively, the results of the disassembly time measurement campaign in a recycling plant. Finally, the potential requirements on the extraction time of key components are assessed and discussed.

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\(^1\) Project — Integration of resource efficiency and waste management criteria in European product policies - Second phase (Administrative Arrangement n° 070307/2010/580887/CI; July 2011 – December 2012).

\(^2\) ‘Hot spots’ are those product’s components and characteristics that are relevant for some criteria for the considered EoL processes.

\(^3\) For example, the EU Ecolabel or the implementing measures under the Ecodesign Directive (2009/125/EC).


\(^5\) See the “Discussion paper on the review of the Ecodesign and Energy Labelling Regulations for televisions and on the draft Regulation on electronic displays, including computer monitors” discussed at the Ecodesign Consultation Forum meeting of 8 October 2012.

\(^6\) www.eceee.org/ecodesign/products/televisions/Television%20Review%20proposal%20on%20end%20of%20life.pdf (access July 2013)
2. Relevance of the extraction of key parts for EoL treatments of electronic displays

Electric and Electronic Equipment (EEE) contain a wide range of substances, some of which are valuable, some of which are toxic or otherwise hazardous and some are both [Hagelüken, 2006]. Components using these harmful substances (which would impair recycling) or valuable substances (which retain their high value only when treated separately) should be used in such a way that they can be extracted and recycled [Wimmer and Züst, 2003]. Table 1 illustrates the content of plastics, iron, aluminium, copper and precious metals, namely silver, gold and palladium in several electronic devices.

One task of WEEE treatments at the recycling plant is to ensure that materials enter the appropriate recovery processes. In particular, some pre-processing phases of waste can be carried out manually (manual disassembly), mechanically (for example material shredding and automatic sorting) or with combining manual and mechanical technologies [Chancerel et al., 2009].

<table>
<thead>
<tr>
<th>weight-%</th>
<th>Fe</th>
<th>Al</th>
<th>Cu</th>
<th>plastics</th>
<th>Ag [ppm]</th>
<th>Au [ppm]</th>
<th>Pd [ppm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TV-board</td>
<td>28%</td>
<td>10%</td>
<td>10%</td>
<td>28%</td>
<td>280</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>PC-board</td>
<td>7%</td>
<td>5%</td>
<td>20%</td>
<td>23%</td>
<td>1000</td>
<td>250</td>
<td>110</td>
</tr>
<tr>
<td>mobile phone</td>
<td>5%</td>
<td>1%</td>
<td>13%</td>
<td>56%</td>
<td>1380</td>
<td>350</td>
<td>210</td>
</tr>
<tr>
<td>portable audio</td>
<td>23%</td>
<td>1%</td>
<td>21%</td>
<td>47%</td>
<td>150</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>DVD-player</td>
<td>62%</td>
<td>2%</td>
<td>5%</td>
<td>24%</td>
<td>115</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>calculator</td>
<td>4%</td>
<td>5%</td>
<td>3%</td>
<td>61%</td>
<td>260</td>
<td>50</td>
<td>5</td>
</tr>
</tbody>
</table>

The technology used for pre-processing influences the material efficiency (i.e. quantity and quality, including the mechanical properties) of the processed materials in the output and thus the further separation steps. For example, Printed Circuit Boards – PCB contain most of the valuable metals and also most of the toxic metals in EEE [Meskers et al., 2009]. These metals are however dispersed when electronic components are shredded during pre-processing and thus dissipated [Chancerel et al., 2009]. The dissipation of valuable metals during mechanical pre-processing has been also confirmed by a comparative study of different pre-treatment plants in Europe and Japan [Peeters et al. 2013]. The study concluded that shredding recovers less than 10% of precious metals in PCBs while manual disassembly recovers more than 90% of these metals [Peeters et al. 2013].

"When separating several major materials (like Fe, Al, plastics) in subsequent processing steps from a complex feed material, the unintended co-separation of 'minor' metals can add up
substantially. In the concrete case of electronic scrap this means that the mechanical separation of iron, aluminium and plastics always bears the risk of inevitably losing precious metals in these streams” [Hagelüken, 2006]. Furthermore, mixing different qualities in collection/pre-processing can negatively influence recycling returns (dilution, technical constraints) [Hagelüken, 2006].

The recovery of scarce metals can improve significantly if PCBs are separated during the pre-processing of WEEE before shredding. Scarce metals can be easier to separate by appropriate design of the product, which facilitate the pre-sorting of WEEE according to their material composition [Chancerel et al., 2011].

For example, Table 2 shows the recovery yields of different precious metals by mechanical and manual dismantling. The recovery yield by manual dismantling is higher and therefore more effective than for mechanical shredding. For copper and silver it is 95% whereas for other precious metals like gold and palladium is 97% and 99% respectively [Meskers et al., 2009].

Table 2  Recovery yields of metals contained in PCBs by mechanical and manual dismantling(adapted from [Chancerel et al., 2009; Meskers et al., 2009]

<table>
<thead>
<tr>
<th>Recovery [%]</th>
<th>Copper</th>
<th>Silver</th>
<th>Gold</th>
<th>Palladium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery after mechanical processes (shredding)</td>
<td>60%</td>
<td>12%</td>
<td>26%</td>
<td>26%</td>
</tr>
<tr>
<td>Recovery after manual dismantling</td>
<td>95%</td>
<td>95%</td>
<td>97%</td>
<td>99%</td>
</tr>
</tbody>
</table>

Analogously to PCB, also other components should be extracted preventively before shredding. For example Thin-Film-Transistor (TFT) panels of electronic displays, for the potential recovery of indium. In fact, according to recent studies in the literature:

- Indium based compounds are immensely used in TFT panel [Chou et al., 2009]. More than 80% of indium produced in the world is for indium tin oxide (ITO) coatings used in Liquid Crystal Displays (LCD) [Park et al., 2009].
- Indium is mainly used together with arsenic, phosphorous and tin. Arsenic is classified as "toxic" and "dangerous for the environment" under the directive 67/548/EEC. Indium arsenide (InAs) and indium phosphate (InP) semiconductors and indium tin oxide (ITO) are potentially hazardous and have the potential to cause lung disease and cancer [NTP, 2001; Chou et al., 2009; Lim and Schoenung, 2010]. As Components containing indium compounds requires therefore specific EoL treatments.
- To reduce the environmental impacts of the EoL treatment of displays, on-going research focuses on determining the optimal degree of disassembly for different product configurations, considering the limitations and low recovery of indium after shredding treatments [Peeters, 2013].
- Most effective Indium recovery processes require TFT panel to be extracted [Yang and Ekberg, 2013]
- The recovery of indium from un-shredded TFT panel is technically and economically feasible [Li et al., 2009; Takahashi et al., 2009; Peeters et al., 2013].
3. Scope and objective of the report

“As disassembly accounts for a great part of recycling costs it is imperative to minimize work input for this stage. Thus, minimizing time for disassembly is a prerequisite for the recyclability of parts and components” [Willems et al., 2006]. The design for disassembly in most cases will also reduce assembly time and costs for the product [Wimmer and Züst, 2003].

Furthermore, it has been estimated that large-scale disassembly can be profitable and optimal when a substantial disassembly time reduction is achieved, in particular for medium-and large-sized EEE and in products rich of valuable substances [Willems et al., 2006].

The need of easy disassembly/dismantling of TV and the extraction of key components have been also highlighted in various environmental labelling schemes, standards and scientific publications, as e.g.:

- “The manufacturer shall demonstrate that the television can be easily dismantled by professionally trained recyclers using the tools usually available to them, for the purpose of: undertaking repairs and replacements of worn-out parts; upgrading older or obsolete parts, and separating parts and materials, ultimately for recycling” [EC, 2009].
- “The appliance shall be so designed and as to allow an easy and quick disassembly for the purpose of separating resource-containing components and materials. This means that corresponding connections must be separable by the use of universal tools and connections must be easily accessible; plastics should consist of only one polymer or plastic parts greater than 25 g in mass must be marked according to ISO 11469 to allow for a sorting of plastics by type and disassembly instructions must be made available to end-of-life recyclers or treatment facilities in order to recover as many valuable resources as possible” [der Blaue Engel, 2012].
- The television shall be designed for ease of disassembly within the recycler’s processes, as follows. “Ease of disassembly shall include, among the others, the following disassembly steps in a “total of at most 10 minutes for products weighting less than 50 lb; and at most 10 min plus 1 min per each additional 5 lb of total product weight, for products weighting 50 lb or more [...]” [IEEE, 2012].

As previously introduced, a research of the JRC analysed possible policy strategies and potential measures to improve material resource efficiency of some product groups, including flat screen TV [Ardente and Mathieux, 2012]. The study concluded that including design for dismantling measures for the separation of some key components in electronic displays as TV, for instance PCBs and the TFT panel could significantly affect the end-of-Life treatments of the waste and, therefore, the environmental impacts of the overall life cycle. Among these measures, the setting of thresholds of the extraction time of key components has been identified as potentially relevant requirement to implement, also in line with the Ecodesign Directive [EU, 2009]. Setting

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The terms disassembly and dismantling of a product (or its parts) are generally used as synonym. However there is a nuance between the two: the former refers to the removal/extraction of the part with some care (e.g. for substituting or repairing), while the latter refers to the removal/extraction of the part without particular care to destroy the functional integrity of the device or equipment.
up dismantling time thresholds for electronic displays requires a more detailed analysis of dismantling electrical and electronic devices.

The present report provides further scientific evidences about the benefits of including a threshold for extraction of PCB and TFT panel of electronic displays in ecodesign implementing measures. Data on extraction time are based on “on-site” measurements at a recycling plant.

4. Method for the analysis

The analysis has four steps:

1. Review of scientific literature which is relevant for the scope of the analysis.
2. Measurement of the dismantling times of electronic displays (TV and monitors)
3. Processing of data and analysis of the time for the extraction of key components
4. Recommendations for potential thresholds of time for extraction

Each step will be described in the next sections.

4.1. Analysis of the scientific literature

As illustrated in Sections 1 and 2, several authors highlighted the relevance of the “ease of dismantling” of TV and the need of the preventive extraction of key components to maximize yields and quality of recycled materials. However few figures have been published concerning the time for the dismantling of TV and monitors. Additionally, published figures are generally aggregated (without the detail of the time for extraction of components).

In 2009, a research on dismantling trials in a European plant\(^8\) showed that it took from 10 to 35 minutes to dismantle one monitor, with an average time of 18 minutes. The time to dismantling a TV set ranged from 14 to 40 minutes, being 24 minutes the average time\(^9\) [Salhofer et al., 2011]. The study also observed that at the moment the material revenues obtained from recycling electronic displays do not cover the costs of their full dismantling. However, considering that more than 84% of the revenues are from separating PCB, a selective dismantling of these components could decrease the costs for dismantling and making the process economically feasible. Unfortunately, authors did not provide disaggregated figures about the dismantling time of PCB or other parts.

A study of Kim et al. (2009) analysed the disassembly of some 17” LCD monitors (Figure 1). According to the authors, the disassembly times range from 3.6 to 8.7 minutes and the quantity of screws used from 33 to 108 units. Authors also suggest that “particularly important for cost efficient disassembly is the provision of a suitable disassembly plan under consideration of the acquired test results for each product. A certain order of disassembly steps is usually predefined

\(^8\) The study’s sample included 47 datasets for LCD monitors and 41 of LCD TV.

\(^9\) For monitors, size ranged from 15” to 42” with a most frequent size of 17”. TV sets in the sample reached from 15” to 42” dominated by the size of 32” [Salhofer et al., 2011].
by the products design” [Kim et al., 2009]. Kim et al. (2009) also provide a breakdown of the disassembly times of components. Based on these figures it is estimated that the extraction of PCBs (controller, sound card and inverter) and of the LCD module requires about 6.2 minutes.

Figure 1 . Breakdown of a dismantled monitor [Kim et al., 2009]

A study by Kopacek (2008) compared the time to dismantle one LCD with different techniques: manually, with water jet cutting, laser cutting and circular saw. The results showed that manual dismantling was the best choice as it has the lower costs per item and ensures a higher quality and a quantity of the substances contained in the recovered fraction. Furthermore, the author observed that already 40% of the dismantled panels were designed to be easy to dismantle (i.e. with a time for manual dismantling lower than 1.4 minutes). This percentage is expected to rise up to 60% in the coming years [Kopacek, 2008].

The next sections describe two other studies about measuring the dismantling times of LCD TVs and monitors.

4.1.1 Project HÅPLA: Sustainable recycling of Flat Panel Displays

The research project HÅPLA (Sustainable recycling of Flat Panel Displays) analysed and compared the existing treatment of recycling LCD waste [Jönbrink, 2012]. Research shows that flat panel displays present one of the greatest environmental challenges associated with their recycling; furthermore, from a recycling perspective, printed circuit boards (PCB) are one of the most important components in electronic display as they contain the greatest number and amount of scarce metals. At present, the dismantling of LCD TV and monitors usually require high time (from 18 to 24 minutes) and thus it is costly On the other hand pre-processing electronic displays by large scale shredding requires less time and are more economic. However valuable or scarce materials are dissipated and lost in other fractions from which they are hard, if not impossible to recover (ferrous or organic fraction) [Jönbrink, 2012].

Jönbrink (2012) estimated that in general about 10% of the scarce materials are lost in the fines fraction and an additional 10-15% is lost in other fractions due to insufficient materials
separation. Manual dismantling of PCBs allows also the recovery of certain components with critical materials, e.g. capacitors with tantalum, from PCBs, which can be reused in other electronics. The project concludes that the manual dismantling of an electronic display recovers almost 99% of the total mass contained whereas by mechanical separation as shredding only recovers about 70-75% [Jönbrink, 2012].

The HÅPLA project analysed and compiled data of forty-one computer monitors (with sizes up to 22 inches diagonal, and between 2 to 6 kg in weight [Letcher, 2011a]), and nineteen LCD TVs (from 2006) and seven newly designed LCD TVs (from 2010) over 24” diagonal [Letcher, 2011b]. The database also includes commercial information as: brand, module manufacturer, dimensions, weight and certain components and features.

The dismantling process reviewed in the HÅPLA project consists of 3 basic steps (Table 3):

1. Separation of the outer housings (including plastic shell, back covers and supports, if present),
2. Extraction of electronic parts, wires and other fixtures,
3. Separation of the diffuser, optical filters, TFT panel and back-lighting system.

Some of the results of the HÅPLA project are presented in Table 3(values refer to the full dismantling of the waste).

Reports from the HÅPLA research shows that monitors have increased in thickness, screen size and weight [Letcher, 2011a]. On the other hand, the number of screws in newer models was reduced to approximately half the number of old models. Such decrease reduced the disassembly time by one minute. In broad terms new LCD monitors can be dismantled quicker than others, although some dismantling steps of old LCD’s take less time than those of new units. Letcher (2011a) also showed that the total dismantling time for full disassembly has been reduced from 502 seconds (in old devices) to 402 (in the new ones) [Letcher, 2011a]. Additional improvements could be obtained by improving the design of the module metal front frame and plastic snap fit frame.

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Dismantling time (whole product) [minute]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Monitor</strong></td>
<td></td>
</tr>
<tr>
<td><strong>2001</strong></td>
<td>6.4</td>
</tr>
<tr>
<td><strong>2003</strong></td>
<td>8.4</td>
</tr>
<tr>
<td><strong>2007</strong></td>
<td>6.7</td>
</tr>
</tbody>
</table>

**Table 3 Dismantling times for some LCD monitors and TV [Letcher, 2011a; Letcher, 2011b]**

<table>
<thead>
<tr>
<th>Monitor</th>
<th>Dismantling time (whole product) [minute]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2007</strong></td>
<td>21.6</td>
</tr>
<tr>
<td><strong>2010</strong></td>
<td>10.4</td>
</tr>
<tr>
<td><strong>2010</strong></td>
<td>16.5</td>
</tr>
</tbody>
</table>
Concerning LCD TV, from 2006 to 2010, old and new LCD TV show differences in average thickness, weight, screen size and dismantling time [Letcher, 2011b]: new TV had an increase of approximately 4 Inches in typical screen size, whilst being lighter (around 4 kg less) and thinner (approximately 3 cm less).

The dismantling time of new electronic display units is 25% less the time for old displays. Such reduction in time is in part attributed to a more rational layout and the use of less metal parts, PCBs, fasteners, fixings etc. However, the reduction of times for dismantling may be gradually eroded as the size of screens increases [Letcher, 2011b]. Furthermore, smaller TVs are manually dismantled faster than larger TVs because easier to be handled. An average size TVs - with approximately 36” screen and 20kg of weight - can be manually dismantled by one operator whereas one TVs of larger size (above 60”) require two operators and mechanical assistance. The study concludes that the time for dismantling can be potentially improved by redesigning the LCD module front frame and the inner plastic frames.

4.1.2 Project PRIME: Perfecting Research on Intelligent Material Exploitation

A recent study by Vanegas and Peeters (2013) analysed the dismantling time of LCD TVs with an average age of 6 years, from different brands and sizes. Each dismantler was provided with a set of common dismantling tools\textsuperscript{10}. After the collection of general information\textsuperscript{11} about each LCD TVs, they were torn out in the following components: PCBs (separated according to the higher or lower content of precious metals), cables, optical foils, LCD Panels, back covers (separated according to the type of plastic), small fraction and rest. Back covers made by one big plastic part of a single material were completely disassembled, extracting all attached components and metal inserts.

The average time for the full manual dismantling of one TV was 508 seconds (ranging from 222 to 1461) [Vanegas and Peeters, 2013]. Such average time can rise up to 634 seconds when the effectiveness of workers is considered (e.g. to take into account the effect of fatigue). The time necessary to extract both PCBs and the LCD matrix amounts to about 390 seconds\textsuperscript{12}.

Vanegas and Peeters (2013) suggest that the dismantling time can be affected by the following factors:

- ergonomics of the dismantling site;
- LCDs characteristics as size, weight, age, brand;
- usage period;

\textsuperscript{10} The set included: a pneumatic screw driver with a set of bits; a drill, two pliers, two wire cutters, a chisel, a hammer.

\textsuperscript{11} This includes: Type, Brand, Weight, Screen Size, Color, and Production Year.

\textsuperscript{12} This value includes the following dismantling steps: dismantling of the back cover and stand; dismantling of the metal cover of PCBs and extraction of signal board, power supply and other PCBs inside (when included); dismantling of the chassis and front cover and extraction of timing controller and other side PCBs (when included); dismantling of LCD and separation of the screen.
- destructive removal of components.

4.2. Measurement of the dismantling time of electronic displays

In order to analyse the time for dismantling of electronic displays a campaign for the measurement of was organized in an Italian recycling plant\textsuperscript{13}. The number and type of devices studied were:

- 25 units of LCD Monitors:
- 42 units of LCD TV;
- 4 units of Plasma Display Panel (PDP) TV.

\textsuperscript{13} According to communication from an association of recyclers and an international take back scheme, the plant is considered as representative of current treatments of electronic displays in Europe.
Table 4  Details of analysed electronic displays

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass [kg]</th>
<th>Size [inches]</th>
<th>Type</th>
<th>Mass [kg]</th>
<th>Size [inches]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monitor</td>
<td>4</td>
<td>14.1</td>
<td>Monitor</td>
<td>2</td>
<td>17.2</td>
</tr>
<tr>
<td>Monitor</td>
<td>6</td>
<td>14.9</td>
<td>Monitor</td>
<td>3</td>
<td>18.5</td>
</tr>
<tr>
<td>Monitor</td>
<td>6</td>
<td>14.9</td>
<td>Monitor</td>
<td>4</td>
<td>18.6</td>
</tr>
<tr>
<td>TV</td>
<td>8</td>
<td>14.9</td>
<td>Monitor</td>
<td>6</td>
<td>18.9</td>
</tr>
<tr>
<td>Monitor</td>
<td>3</td>
<td>14.9</td>
<td>TV</td>
<td>5</td>
<td>19.1</td>
</tr>
<tr>
<td>Monitor</td>
<td>5</td>
<td>14.9</td>
<td>Monitor</td>
<td>4</td>
<td>19.2</td>
</tr>
<tr>
<td>Monitor</td>
<td>2</td>
<td>14.9</td>
<td>Monitor</td>
<td>4</td>
<td>19.9</td>
</tr>
<tr>
<td>Monitor</td>
<td>3.9</td>
<td>14.9</td>
<td>TV</td>
<td>12</td>
<td>20.0</td>
</tr>
<tr>
<td>Monitor</td>
<td>3.5</td>
<td>14.9</td>
<td>TV</td>
<td>4</td>
<td>20.0</td>
</tr>
<tr>
<td>Monitor</td>
<td>4</td>
<td>14.9</td>
<td>TV</td>
<td>9</td>
<td>20.1</td>
</tr>
<tr>
<td>TV</td>
<td>7</td>
<td>15.0</td>
<td>TV</td>
<td>4</td>
<td>20.3</td>
</tr>
<tr>
<td>TV</td>
<td>2</td>
<td>15.0</td>
<td>TV</td>
<td>5.9</td>
<td>22.0</td>
</tr>
<tr>
<td>Monitor</td>
<td>3</td>
<td>15.0</td>
<td>PLASMA</td>
<td>20</td>
<td>24.0</td>
</tr>
<tr>
<td>Monitor</td>
<td>5</td>
<td>15.0</td>
<td>TV</td>
<td>8</td>
<td>26.0</td>
</tr>
<tr>
<td>Monitor</td>
<td>4</td>
<td>15.0</td>
<td>TV</td>
<td>10.5</td>
<td>26.0</td>
</tr>
<tr>
<td>TV</td>
<td>4</td>
<td>15.0</td>
<td>TV</td>
<td>13</td>
<td>26.0</td>
</tr>
<tr>
<td>Monitor</td>
<td>4.7</td>
<td>15.0</td>
<td>TV</td>
<td>10</td>
<td>26.2</td>
</tr>
<tr>
<td>Monitor</td>
<td>3.2</td>
<td>15.0</td>
<td>TV</td>
<td>13</td>
<td>27.2</td>
</tr>
<tr>
<td>TV</td>
<td>3.9</td>
<td>15.0</td>
<td>TV</td>
<td>15</td>
<td>31.5</td>
</tr>
<tr>
<td>Monitor</td>
<td>4</td>
<td>15.0</td>
<td>TV</td>
<td>5</td>
<td>31.5</td>
</tr>
<tr>
<td>TV</td>
<td>4</td>
<td>15.2</td>
<td>TV</td>
<td>10</td>
<td>31.6</td>
</tr>
<tr>
<td>TV</td>
<td>2.5</td>
<td>15.6</td>
<td>TV</td>
<td>16</td>
<td>32.0</td>
</tr>
<tr>
<td>TV</td>
<td>2.5</td>
<td>15.6</td>
<td>TV</td>
<td>10</td>
<td>32.6</td>
</tr>
<tr>
<td>TV</td>
<td>2</td>
<td>15.7</td>
<td>TV</td>
<td>10</td>
<td>32.6</td>
</tr>
<tr>
<td>TV</td>
<td>2.5</td>
<td>16.0</td>
<td>TV</td>
<td>11</td>
<td>32.6</td>
</tr>
<tr>
<td>TV</td>
<td>6</td>
<td>16.2</td>
<td>TV</td>
<td>20</td>
<td>37.0</td>
</tr>
<tr>
<td>TV</td>
<td>6</td>
<td>16.9</td>
<td>TV</td>
<td>21</td>
<td>37.2</td>
</tr>
<tr>
<td>TV</td>
<td>6</td>
<td>16.9</td>
<td>TV</td>
<td>29</td>
<td>37.6</td>
</tr>
<tr>
<td>Monitor</td>
<td>4</td>
<td>16.9</td>
<td>TV</td>
<td>11</td>
<td>37.6</td>
</tr>
<tr>
<td>TV</td>
<td>3.9</td>
<td>17.0</td>
<td>PLASMA</td>
<td>35</td>
<td>41.3</td>
</tr>
<tr>
<td>Monitor</td>
<td>6</td>
<td>17.1</td>
<td>PLASMA</td>
<td>28</td>
<td>41.6</td>
</tr>
<tr>
<td>Monitor</td>
<td>6</td>
<td>17.1</td>
<td>TV</td>
<td>27</td>
<td>42.1</td>
</tr>
<tr>
<td>Monitor</td>
<td>5</td>
<td>17.1</td>
<td>PLASMA</td>
<td>29</td>
<td>42.1</td>
</tr>
<tr>
<td>Monitor</td>
<td>3.5</td>
<td>17.1</td>
<td>TV</td>
<td>24</td>
<td>53.0</td>
</tr>
<tr>
<td>TV</td>
<td>3.5</td>
<td>17.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The dismantling of displays was performed by two experienced workers with the following tools: a pneumatic screw driver with a set of bits, pliers, wire cutters, hammers. The workers did
not know in advance the dismantling sequence, but they were proceeding based on the observations and their experience\textsuperscript{14}.

The dismantling times were measured by a team of trained analysts and included:

- The time to register the information about the electronic display (brand, model, dimensions, mass; some information are illustrated in Table 4);
- The time to register the dismantling steps of the display;
- The time to record each step of the dismantling sequence and complete a datasheet specifically arranged for the task.

5. Processing of data and analysis of the time for the extraction of key components

According to the analysis in [Ardente and Mathieux, 2012], PCB and TFT panel\textsuperscript{15} are two hot-spots of flat-screen TV and monitors. A design for easy extraction of these key components can help to divert them from other waste flows and identify treatments that improve the recovery yield and quality of some of the material fractions they contain. In overall, separating PCB and TFT panels from electronic displays help hence to improve recovery yields and thus the material efficiency of the product.

The time to extract PCB and TFT panels is estimated based on the dismantling sequences described above. Data were processed to exclude the time required to dismantle components whose extraction is not related to PCBs and TFT panels\textsuperscript{16}.

The time for extraction of PCB generally comprises the following sequences:

- Dismantling of support and back covers
- Dismantling of internal chassis and framework (supporting the inner PCB)
- Dismantling and extraction of PCB and power supply
- Dismantling of front cover and extraction of side PCB and film conductors

The time for extraction of TFT panel comprises the following sequences (when included):

- Dismantling of support and back covers

\textsuperscript{14} The lack of knowledge of the dismantling sequence represents an element of uncertainty in the measurement process. As confirmed by the scientific literature, dismantling time largely depends on the adopted dismantling sequence [Li et al., 2013]. In order to reduce the uncertainty of the measurements during e.g. the verification process of potential requirements and to allow repeatable measurements, the dismantling sequence should be set in advance.

\textsuperscript{15} According to Ardente and Mathieux (2012), the LCD screen was identified as a hot-spot of TV. However the current analysis was restricted to TFT panel, which is the most relevant part of the screen because rich in critical raw materials (indium), potentially containing hazardous substances and strictly connected with precious components (film conductors).

\textsuperscript{16} The data processing was supported by the datasheet compiled during the dismantling processes and the registered videos.
• Dismantling of internal chassis and framework
• Dismantling of front cover
• Dismantling and extraction of the TFT panel.

The breakdown of the time for the extraction of PCB and TFT panel of the dismantled electronic displays (LCD TV and monitors) is included in Annex 1 (Annex 1 – Table A1.1 and Figure 2, Figure 3 and Figure 417). Plasma TVs were excluded from the analysis18.

Generally, displays with higher size require larger time for dismantling. However, there is a large variability for displays with the same size. For example, the time to dismantle the PCB contained in an electronic display with a size 32”- 33” vary from 150 seconds to over 700 seconds. According to recyclers, such difference is due to:

• the complexity of the design of some televisions enclosing several different fastening systems (e.g. several screws of different sizes);
• displays not designed for easy disassembly (e.g. PCB sometimes is glued or welded to the supports19).

The analysis also plot the time for extraction versus the displays’ masses. Results are similar to those presented in the previous figures. Also in this case it is observed that displays with similar masses can have very different dismantling times, with some extreme cases of monitors whose dismantling times are similar to television ten times heavier.

In addition, the analysis derived the overall time for the extraction of both the components (PCB and TFT panel). It is highlighted that this overall time doesn’t correspond to the sum of the time for the extraction of the components separately, due to common steps in the sequence of dismantling (e.g. the dismantling of the back cover).

17 Plasma TVs have been not included in the Figure 3 and Figure 4 because these displays are not provided with TFT panels.
18 The reasons for the exclusion were: Plasma TV have not TFT panel; the very large time for the extraction of PCB from Plasma TV is much higher compared to other displays; small number of dismantled Plasma TV at the recycling plant (low representativeness of the measured sample).
19 It is highlighted that PCB glued and welded to their support are difficult to be manually dismantled and, in addition, they cannot be separated after mechanical treatments (like “pre-shredding”).
Figure 2  . Time for extraction PCB in electronic displays of different sizes

Figure 3  . Time for extraction TFT panel in electronic displays of different sizes
5.1. Recommendations for potential thresholds of time for extraction

Some considerations can be derived from the analysis of previous results, as:

- Plasma Display Panels (PDP) have generally larger time for dismantling compared to other displays of similar dimensions. Furthermore, there is a limited number of data concerning this type of displays. For these reasons it has been decided to exclude Plasma TVs from the analysis. However, PDP are assumed not relevant. In fact, according to some recent documents this type of displays currently represents only 5% share in value of electronic displays sold in the EU and they are expected to disappear from the European market within the next 3-4 years [EC, 2013].

- It is noticed that the extractions of the PCB and the extraction of TFT panel have some common steps. Therefore, it is highlighted that the setting of an objective (threshold of time for extraction) for both the components together would imply less uncertainty. Moreover, such option would leave more flexibility to the designer. It is therefore selected to refer to results of Figure 5 as the most relevant for the analysis.

- Although it is observed a better correlation between time for extraction and display’s mass more than the correlation with the display’s size, the former is preferred for the analysis. The size of displays (visible screen area) has been, in fact, already used in European product policies for televisions [EC, 2009, EC 2009b]. The size of displays is also assumed as a proxy for the complexity of the device and of the time for its dismantling;
- It is observed a general dependency of time for extraction of key components from the size (and therefore complexity) of the display. However, the range of displays sizes can be generally divided in two groups: smaller devices (<25”) and larger devices (≥25”).

Based on these considerations, Figure 5 plots the overall time for the extraction of key components and some possible threshold lines (for the two groups of devices smaller or larger than 25”). Table 5 shows the number of displays compliant with different thresholds.

![Image](image_url)

**Figure 5**  Potential thresholds for the time for extraction of key components

**Table 5**  Analysis of possible thresholds for time for extraction key components

<table>
<thead>
<tr>
<th>Size of the display [inches or cm]</th>
<th>Threshold time for extraction (PCB and TFT) [seconds]</th>
<th>Number of displays below the threshold [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;25” or 63.5 cm</td>
<td>240</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>260</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>62%</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>76%</td>
</tr>
<tr>
<td></td>
<td>360</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td>440</td>
<td>29%</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>52%</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>62%</td>
</tr>
<tr>
<td>≥ 25” or 63.5 cm</td>
<td>360</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td>440</td>
<td>29%</td>
</tr>
<tr>
<td></td>
<td>480</td>
<td>52%</td>
</tr>
<tr>
<td></td>
<td>520</td>
<td>62%</td>
</tr>
</tbody>
</table>
It is observed that the previous figures refer to displays currently at the EoL but designed in the past 5-8 years. According to association of manufacturers, modern displays have a sensible lower mass and also their design for dismantling has been improved. In fact “the time of recycling of a large TV has already dropped to currently 6 minutes (by a professional); this is due to the fact that for instance the number of screws used in a TV set has dropped from 170 to about 70 today” [DE, 2013]. This value, if assumed as representative average for modern designed devices, is sensibly lower, on average, than values of the dismantling times measured during the current study.

Furthermore, as underlined in section 4.2, the dismantlers did not know in advance the dismantling sequence of the TV. The knowledge of the sequence would have the effect of decreasing the times for the dismantling times.

According to this analysis a potential ecodesign measure about the time for the extraction of key components in electronic displays is following proposed. Time thresholds have been set in order that at least 50% of dismantled devices are compliant.

**Potential requirement on the time for extraction of key components in electronic displays**

*For electronic displays smaller than 25 inches or 63.5 cm (diagonal screen size), the time for the extraction of Printed Circuit Boards (PCB) assembly larger than 10 cm², film conductors and TFT panel embedded in electronic displays shall not exceed 260 seconds.*

*For electronic displays equal to or larger than 25 inches or 63.5 cm (diagonal screen size), the time for the extraction of Printed Circuit Boards (PCB) assembly larger than 10 cm², film conductors and TFT panel embedded in electronic displays shall not exceed 480 seconds.*

The verification of this requirement needs the development of a standardized procedure for repeatable measurements of the time for the extraction20.

The aim of the previous potential Ecodesign requirement is not to promote the excellence (more related to e.g. Ecolabel criteria) but to cut from the market those devices with characteristics far away from the requirement. Considering that recent TV are easier to be disassembled (compared to the investigated sample of dismantled TV) and considering that the procedure for the measurement would assume the prior knowledge of the dismantling sequence21, it is derived that large part (estimated around 70 – 80%) of newly designed displays would comply with the previous requirements22. Nevertheless, in order to meet the suggested potential requirement, manufacturers are supposed to implement Ecodesign measures that will facilitate key components extraction.

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20 A potential method for the measurement of the time for extraction of key components is discussed in a separate report titled “Feasibility study on a standardised method for repeatable measurements of the time for extraction of certain target parts from an Electrical and Electronic Equipment” (draft under development – September 2013).

21 The knowledge of the dismantling sequence reduced the dismantling times. This means that it will be easier for the manufacturers to reach the thresholds as suggested in the requirement.

22 Assuming that the time for extraction of new designed LCD-TV is 30% lower, around 75% of currently LCD-TV (>25”) will comply with the potential threshold.
5.2. Potential Benefits and Impacts related to the thresholds of time for extraction of key components

Potential benefits and impacts related to the previously discussed potential requirement for electronic displays have been here following identified and discussed. The results are based on figures from a JRC study on resource efficiency [Ardente and Mathieux, 2012] and contributed to the development of the draft “Report on Impact Assessment for Electronic Displays” [EC, 2013]. In particular, it has been estimated that the improved extractability of key components will contribute to optimize the EoL treatments of displays, increasing the recovery of rare, precious and critical raw materials and reducing the risk of contamination of other waste fractions by potentially hazardous substances (contained in PCB and TFT matrix).

As underlined in the scientific literature, “the major economic driver for recycling of electronic waste is from the recovery of precious metals. Behind the precious metals come copper and zinc [Cui and Zhang, 2008]. It is therefore noticed that thresholds of extraction time of key components would support the recycling of LCD TV by allowing higher recovery yields of relevant materials contained in (including rare, precious and critical materials), compared to a base-case scenario when no requirement is set [Ardente et Mathieux, 2012]. The following subsections examines in detail the recovery of precious metals from PCBs, indium from LCDs and discusses the potential benefits of their recycling.

5.2.1 Recycling of precious metals from Printed Circuit Boards (PCBs)

Table 2 illustrates how different pre-treatments of PCB affect the overall recovery yields of some metals (copper, silver, gold and palladium). Assuming an average composition of PCB23, recovery yields of some metals from PCB are estimated (Table 6), based on different pre-treatments (i.e. PCB manually extracted in line with the potential Ecodesign requirement compared to PCB mechanically sorted after shredding). The recovery yields are significantly higher, in the range of 95-99% if the PCB is manually extracted in line with the potential Ecodesign requirement compared to yields when the PCB is mechanically sorted after shredding (12-60%).

In the analysis of possible thresholds for the time to extract key components, LCDs were grouped in two types: smaller than 25”, and equal and larger than 25”. The estimation of the potential recoverable metals from PCBs is done for a 20”24 and a 37”25,26 LCD TV in order to be in line with the two groups of LCDs size.

Table 6 presents information about the content of copper and some precious metals in PCBs and their recovery yields after different EoL pre-treatments.

---

23 Content (in grams) of some metals in PCBs of LCD TV: copper (132 g), silver (0.54 g), gold (0.2 g), Palladium(0.043 g) [Ardente et Mathieux, 2012]. It is also noticed that this composition of PCB did not change sensibly compared to more up-to-date figures as in [Peeters et al., 2013].

24 [Ardente and Mathieux 2012]

25 Information about the content of copper, silver, gold and palladium in the 37”LCDs has extrapolated on the basis of TV mass.

26 We selected a 37”LCDs as representative for LCDs greater than 25” because the TV market is progressively shifting towards devices with larger size (mainly in the range from 30” to 40”) [Jones 2007].
Table 6  Recovery yields of some metals in PCB based on different EoL pre-treatments of 20” and 37” LCD TV

<table>
<thead>
<tr>
<th>Metal</th>
<th>Average content of metals in PCB</th>
<th>A. Recovery yields after mechanical shredding and sorting</th>
<th>B. Recovery yields after manual extraction</th>
<th>Difference of recovery yields (B - A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[g/TV]</td>
<td>[%]</td>
<td>[g/TV]</td>
<td>[%]</td>
</tr>
<tr>
<td>20” LCD TV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>0.0040-0.003</td>
<td>46.20</td>
<td>0.15-0.18</td>
<td>80.74</td>
</tr>
<tr>
<td>Silver</td>
<td>0.408-0.326</td>
<td>0.445</td>
<td>0.14-0.18</td>
<td>0.776</td>
</tr>
<tr>
<td>Gold</td>
<td>24.78-19.83</td>
<td>0.145</td>
<td>2.87-3.59</td>
<td>0.253</td>
</tr>
<tr>
<td>Palladium</td>
<td>13.26-10.61</td>
<td>0.031</td>
<td>0.33-0.42</td>
<td>0.055</td>
</tr>
</tbody>
</table>

The recovery yields in Table 6 are used to calculate the related potential economic gains. Additional gains for each metal are estimated in Table 7, assuming that the cost for recycling is from 20% to 30% of the current price for primary metals.

Table 7  Potential economic gain related to additional yields of metals in PCB for 20” and 37” LCD TV

<table>
<thead>
<tr>
<th>Metal</th>
<th>Price of metal28</th>
<th>Difference of recovery yields (B - A)</th>
<th>Additional gain29</th>
<th>Difference of recovery yields (B - A)</th>
<th>Additional gain29</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[€/g]</td>
<td>[g/TV]</td>
<td>[€/TV]</td>
<td>[g/TV]</td>
<td>[€/TV]</td>
</tr>
<tr>
<td>Copper</td>
<td>0.004-0.003</td>
<td>46.20</td>
<td>0.15-0.18</td>
<td>80.74</td>
<td>0.26-0.32</td>
</tr>
<tr>
<td>Silver</td>
<td>0.408-0.326</td>
<td>0.445</td>
<td>0.14-0.18</td>
<td>0.776</td>
<td>0.25-0.32</td>
</tr>
<tr>
<td>Gold</td>
<td>24.78-19.83</td>
<td>0.145</td>
<td>2.87-3.59</td>
<td>0.253</td>
<td>5.03-6.28</td>
</tr>
<tr>
<td>Palladium</td>
<td>13.26-10.61</td>
<td>0.031</td>
<td>0.33-0.42</td>
<td>0.055</td>
<td>0.58-0.72</td>
</tr>
</tbody>
</table>

Considering an overall labor cost for a dismantlers of about 150 €/day [Salhofer et al. 2011], it is estimated that the extraction of PCB is economically viable when:

- For LCD TV of 20” or 50.8 cm the time for extraction is below 650 seconds (i.e almost 11 minutes).
- For LCD TV of 37” or 93.98 cm the time for extraction is below 1280 seconds (i.e. about 21 minutes).

27 The mass of a 32” LCD TV is assumed to be 12.6 kg [Samsung 2013] (http://www.samsung.com/us/video/tvs/LN37D550K1FXZA-specs).
28 Values of the prices of copper, silver, gold and palladium are taken from Infomine 2013 (http://www.infomine.com) and metalprices 2013 (www.metalprices.com). The prices given in table 7 results from subtracting the cost for recycling, estimated to be from 20% to 30% the price for primary metals.
29 The additional economic gains to recover the precious metals in PCBs are calculated assuming that the cost for recycling each metal represents 20-30% of its price.
In 2012, 51.44 million TVs were sold within the EU27 [GfK 2013]. The market share of the size of displays has been rapidly changed in the last years. In 2007, the market share of LCD TVs was 22% for 14”-26” LCD size, 53% for 27”-39” LCD size and 25% for LCDs greater than 40” [IZM 2007]. As the market share for LCDs between 30”-40” sizes has continued to increase [GfK 2013], we estimated that currently 20% of the market share of LCD TV is for those smaller than 25”and 80% for LCDs equal or larger than 25”.

The potential additional recovery yields of precious metal in the EU related to the requirements have been estimated according to assumed future recycling scenarios30.

The implementation of the previous proposed requirement would allow the additional31 recovery of about 86-261 tonnes of copper, 7-15 tonnes of silver, 2-5 tonnes of gold and 0.5-1 tonnes of palladium. The potential economic benefit of recovering such amount of metals is from 56 to almost 140 million € (based on price figure of Table 7). Such amount of precious metals corresponds to about of 7-14% of copper, 17-33% of silver, 14-28% of gold and 15-29% of palladium contained in PCB of TV sold in the EU in 2012. This additional recovery of metals implies also the reduction up to 30% of various life cycle impact categories (e.g. related to human toxicity, ecotoxicity and resource depletions) [Ardente et Mathieux, 2012].

5.2.2 Recycling of indium from thin film transistors (TFT)

Indium is used in electronic displays in the form of indium tin oxide (ITO) which contains 78% of indium, 17.5% of oxygen and 4.5% of tin [Buchert et al. 2009]. For 2012, 662 tonnes were obtained from primary production and 1,138 tonnes from pre-consumer scrap to total 1,800 tonnes. About 1,502 tonnes of indium were used for ITO in 2012 [Licht et al. 2013]. From this amount, only 10% is successfully deposited on the ITO substrate, 70% is contained on the surface of residual materials and later recycled in-process, and 20% is lost on the surface tools and chamber walls during manufacturing [Licht et al. 2013]. The content of indium in LCD varies from 56 to 780 mg per m² depending on whether the values have been theoretically or experimentally obtained [Socolof et al. 2005, Becker et al. 2007, Bogdanski 2009, IUTA EV 2011, Götte et al. 2012]. The average indium content is 234 mg per m², which corresponds to 58.5 mg per kg of display [Boeni et al. 2012]. Thus for instance, a 20”LCD TV with a mass of 7.19 kg contains 0.421 g indium whereas a 37”LCD TVs with a mass of about 12.6 kg contains about 0.735 g of indium32. In any case, the average concentration of indium in waste LCD is about 10 times that than in zinc concentrates, the main primary source for indium [Elsner et al. 2010; Tolcin 2011; Götte et al.2012].

30 The recycling scenarios consider that, in the next future, the rate of LCD TV recycled after full shredding will rise sensibly (although characterized by lower resource efficiency). However the setting of a potential requirement on the extractability of key components would make their extraction more economically competitive and preferable, influencing the evolution of future recycling scenarios [Ardente et Mathieux, 2012]. The scenario analysis estimated that, thanks to the improved extractability, from 20% to 40% of waste TV would be pre-dismantled before shredding instead of being shredded directly.

31 Additional recovery compared to the EoL scenario when the TV is directly shredded without manual pre-treatments.

32 These figures are in line with other analyses, as by [Nakajima et al. 2007] which estimated that a 32”LCD TV contained theoretically about 0.8 g of indium.
Indium is a scarce metal considered critical by various studies [US National Council 2008, Buchert et al. 2009, EC 2010]. In 2020, the demand for indium for ITO for different applications in various product groups is expected to double therefore finding alternative strategies (i.e., via recycling) is a way to ensure its future supply [EC 2010].

Although laboratory scale experiments proved the efficacy of such processes, indium is not yet recovered at industrial scale [Kawaguchi 2007, Virolainen et al. 2011]. Indium can be theoretically recovered by using different methods: a) direct smelting, b) comminution and mechanical separation; c) disassembly followed by the separation and purification of indium from ITO [Götze et al. 2012]. The direct smelting of LCDs is not feasible due to the high demand of energy to melt the glass contained in LCDs, which accounts for more than 85% of the total weight of the screen [Götze et al. 2012]. In addition, during the smelting process, indium may be mixed with other materials with similar chemical and physical properties from which it is difficult if not impossible to recover [Reuter et al. 2013]. Comminution and mechanical separation lead to high risk of indium losses during processing, and therefore is not a convenient process to recuperate metals contained in small amounts. Furthermore, studies in the literature evidenced the limitations and low recovery of indium after shredding treatments [Peeters, 2013].

The disassembly of LCDs can be done manually and automatically. Manual disassembly has very low breakage rates compared to pilot automated disassembly as it allows recover almost 95% of indium contained in LCDs [Boeni et al. 2012]. However, automated disassembly of LCDs is still in the exploratory phase and has current low recovery yields. Thus, the manual dismantling is still the treatment granting the highest recovery yields of indium.

Once LCDs are disassembled, the indium contained is separated by acid leaching or vaporization, which has a recovery yield of about 85% [Götze et al. 2012]. Indium can be then purified by solvent extraction, electrowinning or smelting. Purification processes have almost 99% indium recovery [Götze et al. 2012]. In overall, we can conclude that about 80% of the indium contained in LCDs can be recycled. This means that almost 0.337 g of indium from 20” LCDs and 0.588 g of indium from 37” LCDs can be recycled from end of life LCDs. Given the previous number of LCD TVs sold in 2012, the implementation of the proposed requirement on extraction time would allow the recovery from 5.5 to 11 tonnes of indium.

The recovery of indium from TFT can produce economic benefits. Historical data about the price of primary indium are shown in figure 6 [Ayers et al. 2013]. As illustrated, the price for indium is largely fluctuating. Current price of indium is about 700 $/kg. The previous amount of indium contained in a 20” and 37” LCD has an approximate economic value of 0.12-0.14€ and 0.21-0.24€ respectively. Such economic value is almost the cost to manually dismantle a 20” LCDs and 32” LCDs in about 25 seconds and 43 seconds respectively. Thus the cost to recover indium by manual disassembly is economically viable when this happens together with the extraction of other key parts (i.e., PCBs).

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Figure 6. Prices (solid line) and production (dotted line) of indium [Ayres et al. 2013].

Based on the same scenarios of section 5.2.2, the recovery the indium contained in LCDs TV can generate an additional yearly economic benefit of 2 to 4.6 million €. However, as indium is a critical metal and may suffer supply restrictions in the near future, its price can rise even higher than current price. For this reason, although indium is not systematically recycled at present, there are already companies in Europe starting to stockpile indium containing wastes.

5.2.3 Potential impact of recycling precious metals and indium from LCD

No significant negative impacts are expected from the discussed requirement on the extractability. According to the draft ‘Report on Impact Assessment’ “there is no EU-based manufacturing of the core component, i.e. the display panel, and the core electronic components (drivers, chipsets). The multinationals manufacturing of the core components (display panel, etc.) are mainly located in Asia [...] will be affected by the preferred option, but the required effort is not outside the boundaries of the global trends in the research and development and the timing of the design cycles” [EC, 2013]. Costs to re-design new devices complying with the discussed potential requirements are furthermore estimated to be negligible compared to other product’s costs\(^{34}\), also considering that the requirement will affect the new devices designed in some years\(^{35}\). Manufacturers will have therefore the sufficient time to adapt the new models to the thresholds for extraction.

Moreover, the introduction of a requirement about the combined extraction of PCB and TFT panel would leave more flexibility to the design teams, with fewer difficulties on how to design the products in order to be compliant with the expected thresholds. The time for disassembling

\(^{34}\) It is commonly acknowledged that the costs associated to the design phase of the product represent a limited share (less than 5%) of the life-cycle costs of an industrial product [Salomone, 1995].

\(^{35}\) Design for disassembly has low costs when it is accounted in the early design stages of the products and designers have a large flexibility in the selection of possible alternatives. If the potential requirement was enforced in a sufficient long term (e.g. in 5 years), it would not represent a burden for the design of new devices.
PCBs and TFT would allow additional recovery of copper, indium and some precious metals. This treatment is economically viable when the time for extraction of key components is up to 675 seconds for LCD smaller than 25” and up to 1323 seconds for LCDs equal or larger than 25”. Both of these thresholds are by far higher than the proposed thresholds for the potential requirement on extraction of key components (which are 260 and 480 seconds respectively).

It is also noticed that the potential requirement would also reduce the costs for the recycling of displays (due to the improved extractability of key valuable parts and reduced cost for labour) and would also increase revenues (due to the improved recyclability of some display parts) and improve the security of supply in Europe of some rare, precious or critical materials, which would be additionally recovered rather than being sent to landfill.

The recovery of precious metals and indium contained in such LCDs could produce and additional recovery of about 86-261 tonnes of copper, 7-15 tonnes of silver, 2-5 tonnes of gold, 0.5-1 tonnes of palladium and 5.5-11 tonnes of indium which at current prices are overall worth from 58 to 144 million €.

By 2020, the number of LCD TVs sold will reach 90 million units\(^{36}\), the implementation of the proposed requirement would allow the additional\(^{37}\) recovery of about 1,330-2,660 tonnes of copper, 13-26 tonnes of silver, 4-8 tonnes of gold, 0.9-2 tonnes of palladium and 10-19 tonnes of indium, which has an economic benefit from 104 to almost 260 million €.

Finally, it is assessed that the potential requirement on extractability would not affect users. However, the design for extraction of key parts can be related to an improved design for durability of the displays (i.e. simplifying the access to key parts for their disassembly and repairing/substitution), with potential benefit on the extension of the lifetime of the products.

\(^{36}\) Draft final report on impact assessment of displays. VhK for European Commission. 5.06.2013

\(^{37}\) Additional recovery compared to the EoL scenario when the TV is directly shredded without manual pre-treatments.
Conclusions

The present study analysed possible measures for resource efficiency of electronic displays (LCD-TV and monitors). The study focused on possible thresholds for the time of extraction of some key components (PCB and TFT panels) in the displays.

Different representative thresholds for displays of different sizes have been identified. It has been concluded that thresholds more suitable for potential requirements are those for which at least 50% of the investigated devices were compliant\textsuperscript{38}. However, it is highlighted that the present analysis refers to displays currently at the EoL but designed in the past 5-8 years. According to association of manufacturers, modern displays have a sensible lower mass and also their design for dismantling has been improved. Therefore it can be concluded that more than 50% of currently designed displays would comply with the previous requirements\textsuperscript{39}.

The potential benefits and impacts related to the requirement on extractability have been also assessed. It is estimated that the improved extractability of key components will contribute to optimize the End of Life treatments of displays, with relevant benefits in terms of increased recovery yields of some rare, precious and critical raw materials and reducing the risk of contamination of other waste fractions by potentially hazardous substances. The potential requirement would also reduce the costs for the recycling of displays (due to the improved extractability of key valuable parts and reduced cost for labour) and also increase additional revenues (due to the improved recyclability of some display parts). Recovering precious metals and indium from LCDs would bring more supply security in Europe and report a potential economic benefit of from almost 58 to 144 million € when they will reach their end-of-life.

No significant negative impacts are expected. Costs to re-design new devices complying with the discussed potential requirements are furthermore estimated to be negligible compared to other product’s costs, also considering that the requirement will affect the new devices designed in some years.

Finally, it is noticed that the enforcement and verification of a potential requirement on extractability of key components needs a standardized method for the measurement of the time for extraction\textsuperscript{40}.

\footnotesize{\textsuperscript{38} These correspond to 260 seconds for display smaller than 25” and 480 seconds for displays larger than 25”.
\textsuperscript{39} Percentage of compliant devices larger than 25” is expected to be around 75%.
\textsuperscript{40} A potential method for the measurement of the time for extraction of key components is discussed in a separate report titled “Feasibility study on a standardised method for repeatable measurements of the time for extraction of certain target parts from an Electrical and Electronic Equipment” (draft under development – September 2013).}
References


Acknowledgments

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Annex 1 – Analysis of times for the extraction of key components

Table A1.1 Times for the extraction of PCB and TFT panel in electronic displays

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Abstract
The main objective of this report is to provide scientific support for the development of measures to improve the extraction of key components from electronic displays, and discusses about their benefits and environmental impact. The analysis focus on two types of components: printed circuit boards (PCBs) and thin film transistors (TFT). The report analyses several possible thresholds for a combined time for their extraction. The report proposes that the time to extract PCBs larger than 10 cm$^2$, TFT panels and film conductors in electronic displays smaller than 25 inches (63.5 cm) shall not exceed 260 seconds, whereas for electronic displays equal or larger than 25 inches (63.5 cm) shall not exceed 480 seconds. The implementation of the proposed requirement would allow the recovery of about 7-14% of copper, 17-33% of silver, 14-28%, of gold, 15-29% of palladium and 16-32% of indium contained in LCD TVs sold in the EU in 2012. The potential economic benefit of recovering such amount of metals is estimated to be 58 to 144 million Euros.
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Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new standards, methods and tools, and sharing and transferring its know-how to the Member States and international community.

Key policy areas include: environment and climate change; energy and transport; agriculture and food security; health and consumer protection; information society and digital agenda; safety and security including nuclear; all supported through a cross-cutting and multi-disciplinary approach.