Impact of innovations in electronic equipment and components on their reuse and recycling

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Abstract

The electronics industry is marked by continuous evolution and tremendous development. Through the rapid technological change new products are being constantly introduced, inducing shorter use phases and leaving growing amounts of obsolete equipment behind.

This master thesis aims at investigating the innovations that have occurred in selected information and communication technology equipment, including display technologies, external power supplies, printed circuit boards and packaging technologies. Special focus is put on the change in the equipment's material composition and how it impacts recycling and reuse practices.

The principal sources of information for the research have been the databases of the Institute of Electrical and Electronics Engineers and life cycle inventories as well as scientific journals. In addition, guideline-based interviews with experts from recycling and reuse facilities in Austria have been carried out.

The findings indicate a tendency towards system integration and miniaturization of the electronics components and substitution and reduction of valuable resources, in particular, gold and indium.

Referring to the change in display technologies, twofold trends are being observed. Until now, the conventional display technologies have been predominantly recycled in a “closed-loop” system; however, their demise from the market due to the entering of innovative technologies requires alternative recycling and application strategies.

Furthermore, the innovative technologies are characterized by their different material composition, including mass-relevant and valuable materials in low concentrations. Currently, mainly the mass-relevant materials are recycled; while most of the valuable materials in low concentrations are not being recovered. Considering the resource scarcity and the importance of resource autarky, a shift towards integrated waste management should be made.

Key words: *innovations, flat panel display, power supply, printed circuit boards, electronic packaging, reuse, recycling, waste electronic and electrical equipment (WEEE)*

Titel: Einfluss von Innovationen bei Elektrogeräten auf die Wiederverwendung und Verwertung

Abstrakt

Die Elektronikindustrie erfährt eine rasche technologische Entwicklung. Auf dem Markt werden neue Produkte in kürzer werdenden Innovationszyklen eingeführt, deren Lebensdauer allerdings nachlässt und dadurch die Menge an Altgeräten kontinuirlich zunimmt.

Die vorliegende Arbeit setzt sich zum Ziel, die Innovationen in ausgewählten Informaions- und Telekommunikationstechnik-Geräten zu untersuchen. Dafür werden Bildschirmtechnologien, externe Netzgeräte, Leiterplatten und Verbindungstechnologien analysiert. Der Schwerpunkt fällt auf die Veränderung ihrer Materialzusammensetzung sowie auf deren Einfluss auf die Verwertung und Wiederverwendung.

Als Informationsquellen für die Literaturrecherche wurden Datenbanken des Institutes of Electrical and Electronics Engineers, Ökoinventare sowie wissenschaftliche Zeitschriften - herangezogen.
Zusätzlich wurden Experteninterviews mit Verwertungs- und Wiederverwendungsfachleuten durchgeführt.

Die Ergebnisse weisen darauf hin, dass die zunehmende Miniaturisierung, Integration der elektronischen Bauteile und die Substitution von Wertstoffen zur relativen Reduktion von Wertstoffen beitragen.

In Anbetracht der Bildschirminnovationen lassen sich folgende Tendenzen feststellen: Die konventionellen Technologien wurden bisher im „Closed-loop“ System verwertet. Allerdings wurden diese durch innovative Technologien vom Markt abgelöst. Dadurch entstand der Bedarf an alternativen Verwertungs- und Einsatzmöglichkeiten.

Weiterhin sind innovative Bildschirmtechnologien durch eine unterschiedliche Materialzusammensetzung gekennzeichnet, die sowohl massenrelevante Stoffe, als auch Stoffe in niedrigen Konzentrationen enthält.
Gegenwärtig werden massenrelevante Stoffe verwertet, Wertstoffe in niedrigen Konzentrationen dagegen nicht. In Hinsicht auf die Ressourcenknappheit sowie auf die in Europa angestrebte Ressourcenautarkie, ist ein Richtungswechsel zur integrierten Abfallwirtschaft erforderlich.

Schlüsselbegriffe: *Innovation, Flachbildschirme, Netzgeräte, Leiterplatten, Verbindungstechnik, Wiederverwendung, Verwertung, Elektroaltgeräte (EAG)*

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List of abbreviations

AC	Alternating Current
Ag	Silver (chemical element)
AMOLED	Active Matrix Organic Light Emitting Diode
ASIC	Application Specific Integrated Circuit
ATO	Antimony Tin Oxide
Au	Gold (chemical element)
BAT	Best available Technique
BC	Battery Charger
BGA	Ball Grid Array
BOM	Bill of Materials
CCFL	Cold Cathode Fluorescent Lamp
CRT	Cathode-ray Tube
DC	Direct Current
EC	European Commission
EEE	Electrical and Electronic Equipment
EOL	End-of-Life
EU	European Union
IC	Integrated Circuit IT Information Technology
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry
ICT	Information and communications technology
ITO	Indium Tin Oxide
FPD	Flat Panel Display
FR	Flame-retardant
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LMPS	Linear-mode Power Supply
MCV	Maximum Concentration Values
MOSFET	Metal-oxide-semiconductor Field-effect Transistor
MoU	Memorandum of Understanding
MP	Mobile Phone
OLED	Organic Light Emitting Diode
PBB	Polybrominated Biphenyls
PC	Personal Computer
PCB	Printed Circuit Board
Pd	Palladium (chemical element)
PEDOT	poly(3,4-ethylene dioxythiophene)
PFC	Power Factor Correction
PLED	Polymer Light Emitting Diode
PM	Precious Metal
POLED	Passive Organic Light Emitting Diode
ppm	parts per million
SFA	Substance Flow Analysis
SMOLED	Small Molecule Organic Light Emitting Diode
SMPS	Switched-mode Power Supply
SMT	Surface Mount Technology
TFT	Thin Film Transistor
THT	Through-hole Technology
WEEE	Waste Electrical and Electronic Equipment

1. INTRODUCTION

The market of IT and communication as well as of consumer electronics is in a rapid evolution stage. The electronics manufacturers are under constant competitive pressure to be the first-to-market with products that are unique.

New types of products are constantly introduced through the massive technological change, making the use phase of products shorter and thus leaving ever growing amounts of obsolete equipment behind. Indeed, the electronic waste is one of the fastest growing waste streams in Europe.

The European Union has recognized the various environmental impacts associated with the electronics waste and has passed several legislations that aim at regulating all stages of the equipment's lifecycle, especially at the End-of-Life phase, by encouraging the End-of-Life management of the product, eco-design and life cycle thinking.

One of the key factors that influence recycling and the reuse of electronics equipment is its material composition. However, significant differences in the material composition occur through the technological innovations, not only between the different types of electronic equipment, but also within individual types of product.

Currently, recycling practices in Europe concern the main and mass-relevant fractions of End-of-Life electronics equipment; however there is no established scheme for the recovery of materials in low concentration yet.

1.1. Problem statement

Nowadays, the IT- and communication as well as the consumer electronics market is marked by the introduction of new products and constant technological improvements and innovations. The demise of old technologies and the constant changeover to new ones are key factors that characterize technological development.

However, as the technologies develop, so is their material composition. In order to achieve better technological performance, new materials are introduced and the utilization of many others is being explored. As a consequence, WEEE is not only the fastest growing waste stream in Europe, but is also characterized by great material composition complexity.

As there was a dominant technology in the past and thus it had a well established recycling scheme, currently each technology utilizes different type of materials that brings its own challenges to the End-of-Life management of the equipment.

1.2. Objective of the master thesis

In order to study the impacts of innovations in electronics on their recycling and reuse, particular devices have been selected for the purposes of this master thesis. Particularly, the innovations in screen technologies, external power supplies as well as printed circuit boards and packaging technologies have been investigated.

The goal of this master thesis is to reveal the innovations, occurring in the above mentioned technologies. In order to gain more knowledge about the technologies, their structure and operating principles have been studied. A special focus has been put on the material content of the respective equipment, including the valuable materials as well as hazardous substances. Recycling and reuse (where reasonable) of each technology have been considered being a key aspect of the thesis.

Further, this thesis aims at identifying the reuse potential of electronics components after the disassembly from the printed circuit boards. Therefore the innovations and perspectives of the new packaging and assembly technologies have been analyzed.

1.3. Structure of the master thesis

In **chapter 2**, the monitor and display technologies is presented. The analysis for each technology reflects its structure and operating principles, material composition (valuable as well as hazardous substances), the market perspectives and the recycling practices of the respective technology. CRT, LVD and OLED monitors represent this category. Additionally, an insight about the future display technologies is also provided.

Chapter 3 tackles the external power supplies (EPS) and battery chargers (BC) for notebooks and mobile telephones. The two power converting principles – linear-mode and switched-mode technologies, are presented. In order to observe the impact of the two technologies, a dismantling trial was undertaken. The results are presented further in this chapter. Market perspectives of this technology are also outlined there. The recycling of EPS and BC is given at the end of the chapter.

In **chapter 4**, a characterization of the Printed circuit boards (PCB) is given at the beginning. The analysis here includes the different substrate and layer types for PCB. Further in this chapter, the innovations in the packaging technology are illustrated. Particularly, the evolution on the first level as well as of the second level packaging techniques are described. In addition, the material content with focus on the metal fraction of the PCBs is presented. The impact of innovations on the total metal content is also treated. At the end of the chapter, the recycling of PCBs is analysed.

Chapter 5 studies the reuse of electronics equipment. In this section, the reuse of electronics components is specifically outlined.

In **chapter 6,** a summary of the findings from the literature review are given.

In order to investigate the impact of innovations in the electronic equipment on recycling and reuse, interviews with experts from major recycling and reuse companies have been undertaken. The process of the interviews and the findings are laid out in **chapter 7.**

Chapter 8 presents the conclusion of the study. Topics for future research are proposed.

1.4. Legislation

Concern about the environment has provoked the European Union to pass several legislations that are specific to the waste electric and electronic equipment (WEEE).

Directive 2002/95/EC on the Restriction of the use of certain Hazardous Substances in Electrical and Electronic Equipment (RoHS) and Directive 2002/96/EC on Waste

Electrical and Electronic Equipment (WEEE) entered into force on 13 February 2003.

By 13 August, 2004 the Member States had to comply with the Directives' provisions and to implement them into the national law.

The broad aims of the **WEEE Directive** are to reduce the volume of WEEE and to prevent pollution from improper treatment of WEEE. Further, the WEEE Directive demands the implementation of the principle of producer's responsibility that links the production and the waste phase of a product and concerns actors involved in the life cycle of EEE, i.e. producers, distributors and operators of treatment plants (CHANCEREL, 2010; SANDER et al., 2007).

The WEEE Directive specifies ten categories of types of EEE and each category has defined recovery, reuse and recycling targets. The electronic equipment discussed in this master thesis belongs to category 3 (IT- and communication technology) and category 4 (consumer electronics) defined in the Directive.

For both categories the recovery targets are 75% and for recycling and reuse – up to 65% of the weight of the input WEEE. Here, the reuse and recycling targets have been combined; hence the target can be achieved by recycling alone. As a consequence, only an insignificant part of the WEEE with potential for reuse is actually being reused (e.g. in Austria 1,8% of the WEEE from category 3 and 1,6% of the WEEE from category 4 have been reused in 2010) (EAK, 2010).

The key objectives of the **RoHS Directive** are the protection of human health and the environment through the restriction on the use of certain hazardous substances in EEE. In particular, the RoHS restricts lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and certain polybrominated diphenyl ethers. With an exception of the medical, monitoring and control categories, the Directive concerns all of the 10 categories under the WEEE Directive. According to the Directive, as of 1 July, 2006 none of the electronics equipment put on the market should contain the restricted materials above the defined maximum concentration values (MCV) – 0.1% by weight for each of the proscribed materials, except cadmium, for which the MCV has been set at 0.01% (RoHS DIRECTIVE, 2003; GOOSEY, 2009).

The reuse of electronics equipment is addressed in Article 4 of the WEEE Directive, concerning the design of electronic products. Accordingly, the design should favor the reuse and recycling of the WEEE, their components and materials (WEEE, 2003).

Further, the reuse of electronic equipment is supplemented by the **Waste Framework Directive 2008/98/EC** of the European Parliament and of the Council. The Directive defines a waste hierarchy, according to which, the prevention of waste should be the measure with highest priority to the Member States. Other waste management measures, hierarchically classified, include the reuse, recycling, recovery (including energy recovery) and disposal (WFD, 2008).

2. MONITOR AND DISPLAY TECHNOLOGIES

The beginning of television era is marked with the development of the cathode ray tube (CRT). For many decades, the CRT was the dominant TV and computer monitor technology. However, in the last ten years CRTs have been extensively replaced due to the penetration of the flat panel display (FPD) technologies.

A FPD is a thin, lightweight video display, which used already in many applications, including laptop and desktop computers, television sets and microdisplays. The market share of FPDs started to gain importance in 1990, because the demand of portable devices increased which resulted in a raise of the demand for FPDs. It is presumed that FPDs will soon replace all CRT appliances, especially desktop monitors and TV sets (GOOSEY, 2009).

FPDs are classified as emissive and non-emissive types. Emissive displays emit light, while non-emissive displays must have an external light source to make the images on the screen visible. Examples of emissive FPDs are plasma displays, and light-emitting diode displays. Liquid crystal displays (LCD) are non-emissive displays, because they need an external source of light (LEE et al., 2008). Currently, LCDs represent the dominant FDP technology, followed remotely by plasma displays and OLED (organic light-emitting diode) displays (LEE et al., 2008).

Here the CRT, LCD and OLED display technologies are presented. In addition, a perspective of the technologies being currently under extensive research is also included. The large-scale penetration of FPDs and thereby the drop out of CRTs is already affecting the recycling of End-of-Life CRTs. This aspect is discussed in the section 2.1.4.

Plasma display panels (PDP) is a technology not being included. Due to specification in their fabrication, PDPs are mainly suitable for large-screen applications (KCSWD, 2007). In addition they use a lot of energy (up to 700 Watts) and displays are inclined to screen burn, if the device is left on for a long time. This is a precondition that will limit plasma technology’s penetration into the potentially high-volume market (KCSWD, 2007). Thus, PDP are not expected to impact substantially the recycling.

2.1. Cathode ray tube (CRT)

The CRT technology has been invented by the German physicist Karl Ferdinand Braun in 1897. For many decades, this technology has been used in all television sets, computer monitors, video monitors, oscilloscopes and other appliances.

2.1.1. Structure and operating principles

CRT consists of three basic parts - the glass envelope, the electron gun assembly and the phosphor viewing surface (ENOTES, 2012). The CRT functions as it employs a focused beam of electrons (HISCHIER et al., 2007). Cathode rays work in the form of streams of high speed electrons emitted from the heating of a cathode inside a vacuum tube. The emitted electrons form a beam within the tube due to the voltage difference between the two electrodes. The screen is covered with a phosphorescent coating of transition metals as well as of rare earth elements, which emits visible light when excited by the electrons (HISCHIER et al., 2007).

2.1.2. Material composition

On a quantity basis, the CRTs are predominantly composed of glass. Basically, in a CRT there are four different types of glass composition, each one is responsible for a different task. In the next section the chemical composition of the CRT glass is discussed as well as of the CRT housings.

2.1.2.1. CRT Glass

The weight of a typical CRT monitor (17 inches) amounts to 21.16 kg, whereas a CRT TV set (29 inches) weights 30 kg (Socolof et al., 2001; BIPRO, 2006).

CRT appliances consist of 85% glass and accounts for 65 mass-% of the overall weight of a CRT TV or PC monitor.

The CRT glass is constituted of three main glass parts that are varying in their chemical and physical forms (PRICE, 1999). Fig. 1 illustrates a CRT and its glass parts on the right side.

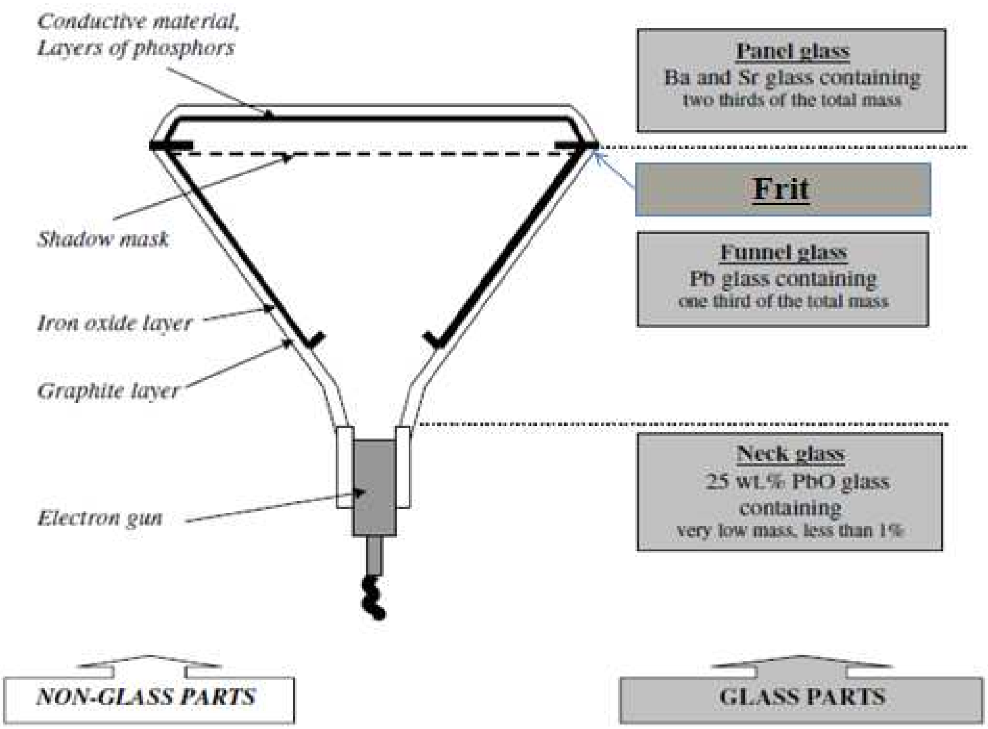


Figure 1: Schematic view of the CRT components, showing the non-glass and glass parts (left and right side of the figure, respectively) (source: MEAR et al., 2006)

The four main CRT glass parts are the panel, the funnel, the neck glass and the frit.

The **panel glass** (66 mass-%) (known also as screen or face plate) is used in the front screen showing an image (GREGORY et al., 2009). The glass contains barium oxide (up to 14%) and strontium oxide (up to 12 %) (ICER, 2004). The panel glass is lead-free since 1995 (MEAR et al., 2006).

The **funnel glass** (33 mass-%) contains up to 25 mass-% lead oxide and is used to prevent emissions of X-rays (GREGORY et al., 2009; ICER, 2003; MEAR et al., 2006).

The **neck glass** (1 mass-%) houses the electron gun. It has up to 40 mass-% of lead oxide in order to absorb the UV and X-ray radiation produced by the electron gun (MEAR et al., 2006).

The three glass components are joined together using a solder glass – the **frit** which contains between 70 – 90 mass-% lead oxide (MONCHAMP, 2000; PRICE, 1999).

According to ICER (2003) the amount of lead (in the form of lead oxide) varies from 0,5kg in 12” CRT to approximately 3kg in a 32” CRT. Glasses made by different manufacturers will be of a different composition, especially the face plate glass (ICER, 2003). Tab. 1 illustrates the range of chemical composition of mixed waste CRT glass, as well as face, funnel and neck glass.

Oxide	Mixed waste CRT glass	Face glass	Funnel glass	Neck glass
SiO_2	60.92	63.87	58.00	53.59
BaO	10.80	7.99	3.47	4.05
Na_2O	8.96	8.06	7.03	3.02
K_2O	7.44	9.35	8.57	13.01
PbO	5.02	-	12.99	21.34
SrO	2.39	3.89	-	-
Al_2O_3	2.07	3.26	4.12	2.04
CaO	0.67	2.18	3.64	1.32
ZrO_2	0.43	-	-	-
B_2O_3	-	-	-	1.11
Sb_2O_3	0.33	-	-	-
F	0.30	-	-	-
CeO_2	0.16	0.16	-	-
Fe_2O_3	0.15	-	-	-
MgO	0.14	1.04	2.18	0.52
TiO_2		0.20	-	-

Table 1: Range of chemical composition of CRT glass (in mass-%) (source: ICER, 2003)

The inside of the panel and funnel glass are coated with a luminescent substance (also known as phosphor[1]) which accounts for 0,04 mass-% of the total CRT-appliance. To obtain an image performance, pixels are formed which in return constitute of red, green and blue luminescent substances. The color is determined by doping the luminescent substance with a very small amount of material called an activator (ENOTES, 2012). The most common luminescent substance is zinc sulfide (ZnS). For blue and green color, the zinc sulfide is doped with silver (Ag) and copper (Cu) or gold (Au), respectively. For the red color the luminescent substance used is europium-doped yttrium oxysulfide (Y_2O_2S:Eu) (RONDA et al., 1998).

The luminescent substances are usually ground into a fine powder before they are applied to the inside of the face plate.

[1] Not to be confused with the chemical element phosphorus (P)

2.1.2.2. Plastics and other materials in a CRT equipment

Other materials found in the CRT, include the iron oxide layer which coats the inside and a graphite monolayer which coats the outside of the funnel and the components electron gun, metal mask, deflector coil, metal pins and cables.

The CRT itself is housed in a plastic housing, but also metal or wood housings are possible by older models (ICER, 2003). The plastic housing accounts for 17,5 mass-% of the CRT monitor and 16,5 mass-% of the CRT TV set.

In CRT equipment different plastic types are found, including acrylonitrile-butadiene styrene (ABS), high-impact polystyrene (HIPS), polypropylene (PP), polystyrene (PS), polyamide (PA), blends of polycarbonate (PC/ABS) and blends of HIPS/poly(p-phenylene oxide) (PPO) (MARTINHO et al., 2012).

MARTINHO et al. (2012) investigated the plastic composition of CRT appliances. They find out that the CRT housing is made of up to 10 different polymers. Fig. 2 and fig. 3 illustrate the plastic composition of CRT TV set and CRT monitor, respectively.

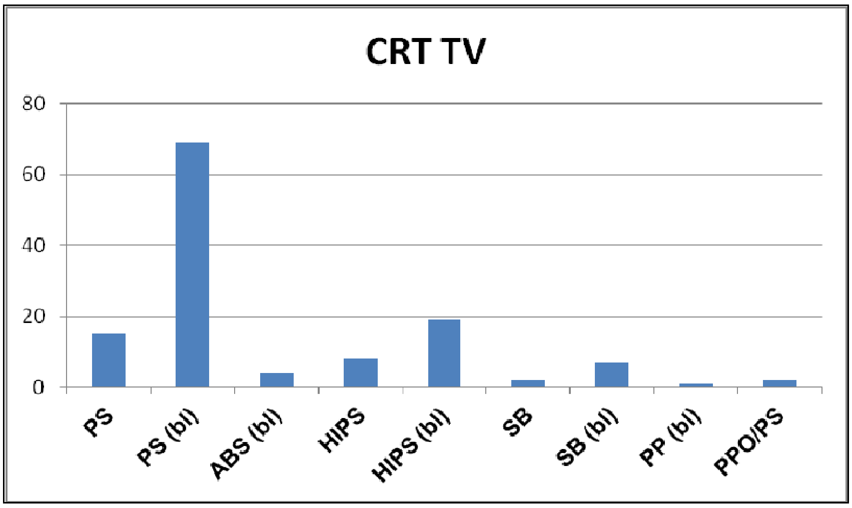


Figure 2: Plastic composition of CRT TV set (in mass-%) (source: MARTINHO et al., 2012)

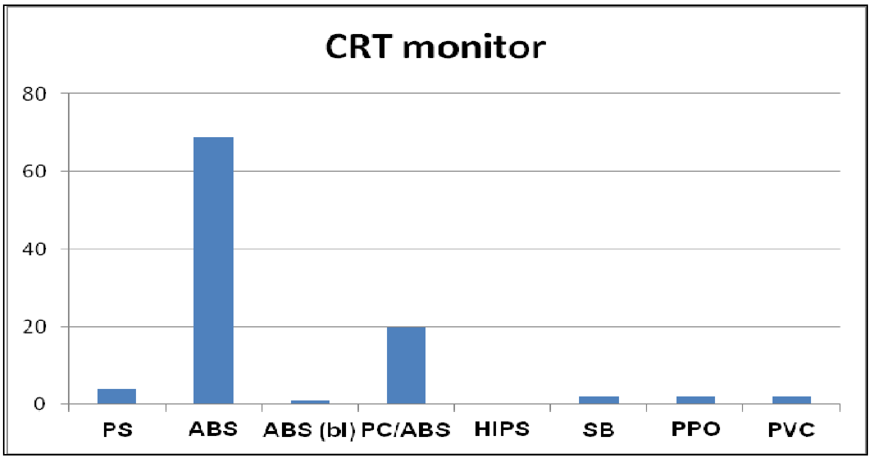


Figure 3: Plastic composition of CRT monitor (in mass-%) (source: MARTINHO et al., 2012)

In CRT TV set housings, the main polymers are blend of polystyrene (PS) (43%) and high-impact polystyrene (HIPS (bl)) (19%). Additionally, polystyrene (PS), high-impact polystyrene (HIPS) and blend of styrene-butadiene (SB (bl)) are included.

CRT monitors have predominantly acrylonitrile butadiene styrene (ABS) (69%) and 20% polycarbonate/acrylonitrile butadiene styrene (PC/ABS) in their housings (MARTINHO et al., 2012).

Additionally, many organic and inorganic materials are added to the plastics – color pigments [e.g. titanium oxide (TiO_2), zinc oxide (ZnO), cadmium (Cd)], flame retardants, as well as various stabilizers or plasticizers (e.g. compounds of Ba, Cd, Sn, Pb and Zn, or polychlorinated biphenyls) (MARTINHO et al., 2012).

Flame retardants are chemicals that are added to the plastics in order to increase resistance to ignition, reduce flame spread and to prevent the burning of the elements. In general, flame retardants are classified as halogenated (bromine or chlorine) phosphorus containing, nitrogen-containing and inorganic flame retardants (STEVENS and GOOSEY, 2009).

The bromine-containing flame retardants, known as brominated flame retardants (BFR), have occupied the largest market segment for the last 30 years (STEVENS and GOOSEY, 2009). There are five main BFRs that are mostly used in thermoplastics – tetrabromobisphenol A (TBBPA), hexabromocyclododecane (HBCD) and three mixtures of polybrominated diphenyl ethers (PBDEs) or byphenyl oxides – decabromdiphenyl ether (DBDE), octabromdiphenyl ether (OBDE) and pentabromodiphenyl ether (pentaBDE). Both penta- and octabromdiphenyl ethers have been phased out in Europe because of their potential toxicity and the formations of dibenzodioxins and dibenzofurans during combustion at high temperatures (STEVENS and GOOSEY, 2009).

However, with the introduction of the RoHS Directive the above mentioned hazardous materials have been restricted (WÄGER et al., 2010). As mentioned in section 1.4, the RoHS restricts the concentration of lead, mercury, hexavalent chromium, polybrominated biphenyls and polybrominated diphenyl ethers above the defined MCVs (RoHS Directive).

WÄGER et al. (2010) investigated End-of-Life electronics equipment in order to determine the concentrations of substances regulated from the RoHS Directive. In regard to the flame retardant content, it was found out that the CRT plastic fraction is a main source of BFR. OctaBDE in the ABS of the CRT monitors exceeded the MCV defined in the RoHS. The average concentration of DecaBDE in the HIPS in CRT TV sets was above the MCV of the RoHS Directive as well (WÄGER et al., 2010).

2.1.3. Perspectives of the technology

CRTs have been widely used in TV sets and computer monitors until the development of the new flat screen display technologies. Due to the rapid development of technology, flat screen panels have replaced the CRT TV sets and monitors. MICHELS et al. (2010) have forecasted that the European market for CRT-PC-monitors will be closed in 2009 and CRT-appliances will be closed in 2012. This trend is illustrated in figure 4.

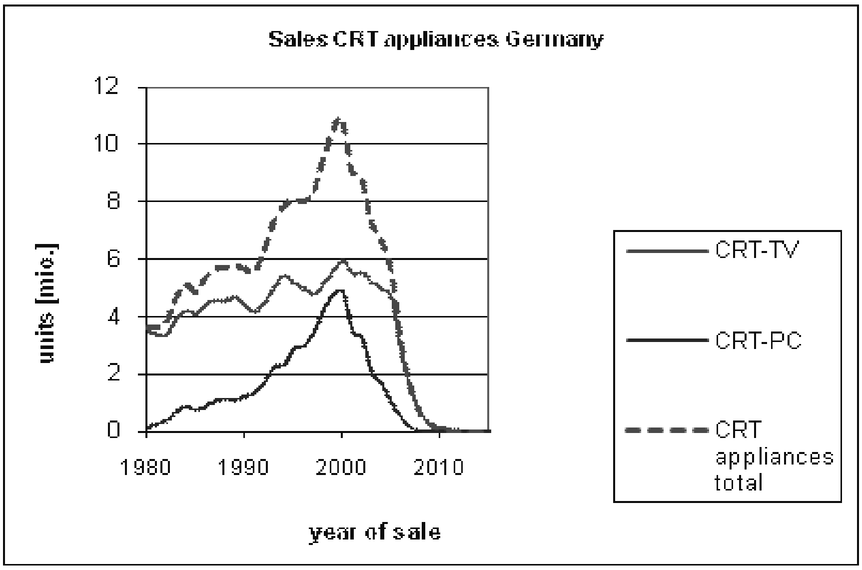


Figure 4: Historic and current sales data for CRT-appliances as obtained by back- and forecast estimations (source: MICHELS et al., 2010)

MICHELS et al. (2010) applied two different methods to forecast the future arisings of EOL-CRT glass. Both methods are based on sales figures. The first one takes into consideration the static average lifetime of CRT-appliances which is then applied to the historic CRT sales data. Three scenarios were then drawn, considering short-term, mid-term and long-term average lifetime. In tab. 2 the lifetime assumptions are illustrated.

Scenario	Short-term	Mid-term	Long-term
CRT-TV	12a	15a	20a
CRT-PC	5a	9a	12a

Table 2: Lifetime assumptions of CRT-appliances (source: MICHELS et al., 2010)

The results are presented in fig. 5.

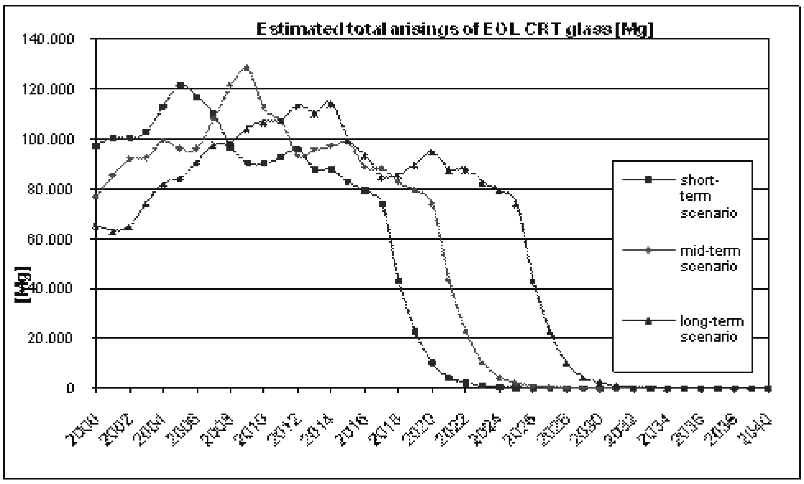


Figure 5: Static estimation of future arisings of total CRT-EOL-appliances based on average lifetime (source: MICHELS et al., 2010)

Taking into account the assumptions above, the peak of CRT-TV-devices will reach their End-of-Life and will come to recycling between 2012 (short-term scenario), 2015 (mid-term scenario) or 2018 (long-term scenario). The last TV-appliances will occur for recycling between 2027 and 2033. The estimation for PC-monitors shows that the peak of arisings will occur between 2005 and 2012. Between 2011 and 2012 EOL-monitors will drop considerably and last devices will come to recycling between 2021 and 2029 (MICHELS et al., 2010).

As mentioned above, the second estimation method is also based on sales data, but instead of considering the average lifetime, an age distribution of EOL-CRT-devices was used to forecast the EOL. The second method regards the CRT appliances of different age that are coming to recycling in one year – varying from 1 to 30 years (PC monitors) and from 1 to 34 years (TV) and their average lifetime (9 years for PC monitors and 15 for TV) (MICHELS et al., 2010).

To obtain a forecast of current and future CRT arrisings, the age distribution is applied on historic and current sales data. Considering consumer behavior and device's lifetime, the overall EOL-CRT-TVs and EOL-CRT glass monitors should have come to recycling in 2009 and 2008 respectively. In addition, the last TV set will come to recycling in 2046. For PC-monitors, due to their much shorter lifetime and faster replacement, it is predicted that their recycling will end significantly earlier. In conclusion, CRT-recycling will become obsolete between years 2025-2033 (MICHELS et al., 2010).

The gradual closure of the CRT market and thus of the demand for CRT-glass represents a challenge for the appropriate and adequate End-of-Life CRT treatment, which is discussed in the following.

2.1.4. Recycling of CRT

2.1.4.1. Recycling of CRT glass

The recycling of CRT appliances is affected by the WEEE Directive. CRT equipment is covered by the scope of the Directive in two categories – computer monitors (Category 3: IT and telecommunications equipment) and TV sets (Category 4: Consumer Equipment) (ICER, 2004). The recovery targets for equipment from category 3 and 4 amounts to 75% and for reuse and recycling – 65% (CHANCEREL, 2010).

Due to their different chemical compositions, CRT glass cullet must generally be separated into the panel and the funnel glass and to be used extensively in the production of new CRTs (PRICE, 1999).

Currently, 81% of the EOL-CRT-glass is being closed-loop recycled and is used in the manufacturing of new CRTs. Considering the drop out of the technology and thus the decline of the CRT glass market, future recycling will have to concentrate on other appliances (MICHELS, 2010; HUISMAN et al., 2007). Fig. 6 illustrates the current mass flow of CRTs.

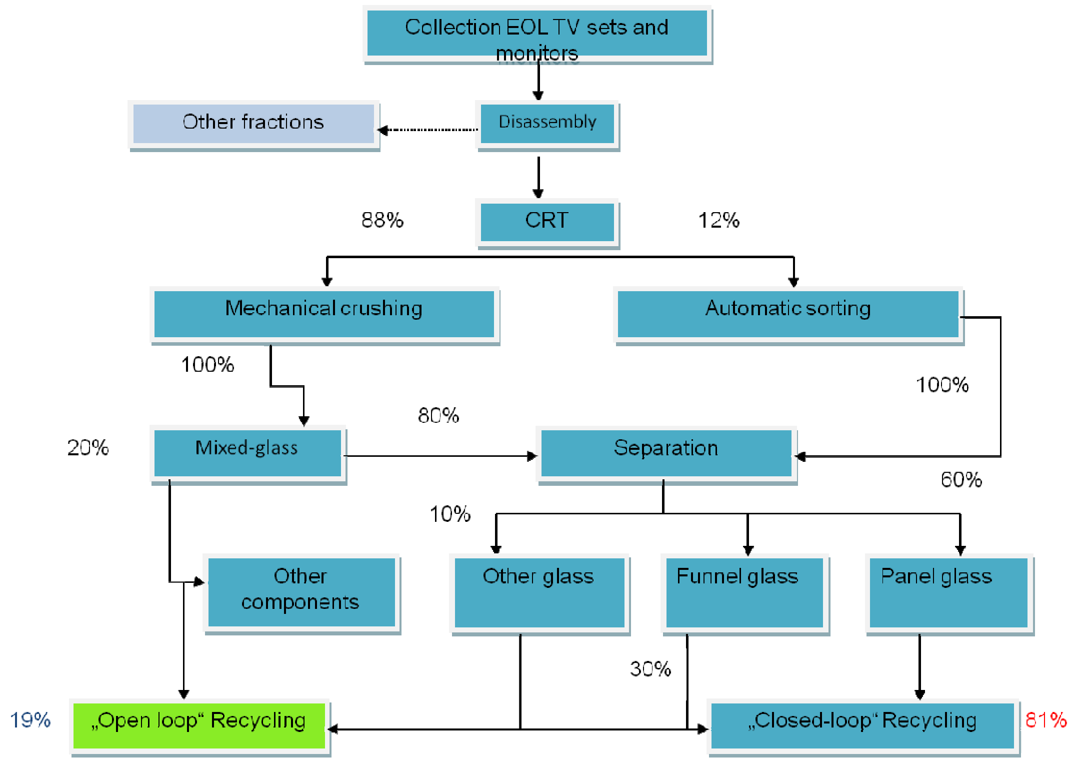


Figure 6: Mass flow of EOL-CRT-glass (source: adapted from MICHELS, 2010)

Although the market for CTR-glass experiences some increase in Eastern countries (China, India, Korea and ASEAN) it cannot counterbalance the worldwide decreasing demand. Considering the fact that nowadays 81% of EOL-CRT-glass is mainly directed to the closed-loop recycling, there is a need and potential for new recycling paths as well as for new appliances (MICHELS et al., 2010). Current open-loop recycling alternatives include mine filling (for funnel and mixed glass), secondary copper smelters (funnel glass), secondary lead smelters (funnel and mixed glass). In addition, CRT glass can be employed for the manufacturing of mineral- and fiber glass; cement and concrete as well as for radiation shielding (encapsulation of radioactive waste) (MICHELS et al., 2010). However, reasonable in quantity terms alternatives for open-loop applications are still in research and development phase.

2.1.4.2. Recycling of plastics from CRT appliances

In order to achieve the quotas set from the WEEE Directive for recovery and recycling of CRT equipment, the plastics should also be considered and comprised in the recycling process. According to Annex 7.4.2 of the WEEE Directive, plastic treatment technologies include mechanical recycling and feedstock recovery (UNU, 2007).

Mechanical recycling includes the (automated) identification of polymers and additives by sensors as well as separation of the shredded streams with the help of mechanical methods (dry, wet or the combination of two).

The automated identification of the polymers is realized through spectroscopic methods – infrared, laser induced and X-ray fluorescence spectroscopy (UNU, 2007; TAURINO et al., 2010).

Mechanical methods for the recycling of plastics include size and gravity separation, thermal heating separation, sink/float separation and floatation (UNU, 2007).

Feedstock recovery or thermochemical recovery implies mainly the use of plastics as a secondary raw material. The plastics are used in coke ovens and in iron steel works and non-ferrous metal foundries (UNU, 2007).

Energy recovery implies the co-combustion of plastics in municipal solid waste incinerators (MSWI) with energy recovery and the use of plastics as secondary fuel in cement kilns (UNU, 2007). Both alternatives imply high operating burning temperatures, thus the brominated flame retardants are destructed.

Although it is technically possible to recycle most polymers, they first have to be separated into single or compatible polymer types in order to use them in high value applications (HUISMAN et al., 2007). There are several drawbacks that affect the plastics recovery and recycling.

The identification is a prerequisite for the correct separation of the different polymeric parts. In dismantling facilities that involve predominantly manual sorting, the identification of the different type polymers in the plastics relies on recognition of the resign identification code (RIC) (MARTINHO et al., 2009). However, MARTINHO et al. (2012) analyzed 187 CRT monitors and 103 CRT TV set housings by means of spectroscopic methods. The results indicate that only 25% of the monitors and 58% of the TV sets had a RIC.

Furthermore, a main drawback of the recycling of plastics from CRT appliances is the presence of brominated flame retardants in the plastic fraction. Brominated flame retardants, when thermally treated or introduced to pyrolysis or gasification, can act as precursors of the highly toxic polybrominated dibenzodioxins/ dibenzofurans (PBDD/PBDF). Thus, when the End-of-Life treatment involves plastics recovery, it is important to consider the formation potential of PBDD/PBDF in different thermal treatment categories (KOUGOULIS et al., 2011). Tab. 3 illustrates the possible thermal treatment categories for plastics as well as the formation potential for PBDD and PBDF.

Category	Process	Condition	PBDD/PBDF formation potential
Thermal stress	Production/ recycling (include shredding, molding and extrusion)	100 - 300°C	Low-> moderate
Pyrolysis/ gasification	Pyrolysis/ gasification facilities, accidental fires, uncontrolled burning	350 - 800°C, low oxygen content	High
Insufficient combustion conditions	Accidental fires uncontrolled burning, non-BAT incinerators. Secondary metal Plants	Uncontrolled parameters: temperature, residence time, oxygen content, turbulence	High
Controlled combustion conditions	BAT incinerators, cement plants	Optimized combustion control	Low

Table 3: Categories of plastics thermal treatment and potential of formation PBDD/PBDF (source: KOUGOULIS et al., 2011)

In order to destroy BFRs and the formation potential of PBDD/PBDF, plastics, when thermally treated, should be recovered in incinerator plants that are constructed in accordance to the best available technology (BAT), i.e. an air pollution control system should be present. In this way, BFRs can be destroyed with high efficiency and the formation potential of PBDD/PBDF is low compared to the other thermal treatment options (KOUGOULIS et al., 2011).

However, it should be noted that thermal recovery of plastics in BAT incinerators is expensive (the cost of a ton of incinerated material amounts to 100 $/t) and is available predominantly in the developed countries (KOUGOULIS et al., 2011).

Currently, extensive research is being conducted in order to develop recycling practices for plastics containing BFR. The extraction of the BFR will allow the recycling and the reuse of the plastics cullet in the manufacturing of new electronics equipment. The Fraunhofer Application Center for Processing Machinery and Packaging Technology (Germany) developed a process (referred as CreaSolv process) for material recycling of the plastics as extracting the BFR and PBDD/PBDF with elimination rates of 70 up to 93%. The process involves special solvents for the BFR extraction, precipitation of the polymers from the solution and an extrusion of the finished pellets (FREEGARD et al., 2006). However, the process is currently available only at a small technical scale.

At the moment, plastics containing BFR are mostly thermally treated as alternative oil in cement kilns (MARTINHO et al., 2012; HUISMAN et al., 2007).

2.2. Liquid crystal display

LCDs hold the mainstream position in the flat panel displays industry and are being extensively used in notebook computers, desktop computer monitors, TV sets and many other electronic appliances (MATHARU and WU, 2009).

As LCDs continue to penetrate the flat-panel display market and largely substitute the CRT-appliances, there is an increasing concern about their End-of-Life stage. LCD-containing WEEE has been recognized as one of the fastest growing waste streams in the European Union, increasing by 16-28% every five years (MATHARU and WU, 2009). Nowadays, the active matrix displays using thin film transistors (TFT), known as AMTFT-LCD are dominant on the market and are applied in television sets, computer monitors and mobile phones. A TFT is a combined small transistor and a capacitor unit located at every pixel, acting as a variable on and off switch. In color LCDs, each individual pixel is divided into three cells colored red, green and blue. Each of these pixels can be regulated independently to project millions of possible colors (KCSWD, 2007).

2.2.1. Structure and operating principles

In this section the basic structure of a TFT-LCD device are presented.

Typical weight of a LCD monitor (15 inches) accounts for 5,73 kg and of LCD TV set (32 inches) – for 8 kg (SOCOLOF et al., 2001; LG ELECTRONICS, 2012).

Basic components of a TFT-LCD unit are the top cover, LCD panel (or light box), PCB mounting frame, LCD control layer (including PCBs and sound box) and the back cover (RYAN et al., 2011).

The light box itself is constituted of a metal frame, liquid crystal glass panel, a number of plastic polarizer and diffuser sheets, perspex sheet, the backlight unit, reflective foils and the support frame. The light box accounts for approx. 50 mass-% of the overall weight of the appliance (RYAN et al., 2011; MATHARU and WU, 2009). Fig. 7 illustrates the structural elements of an LCD device.

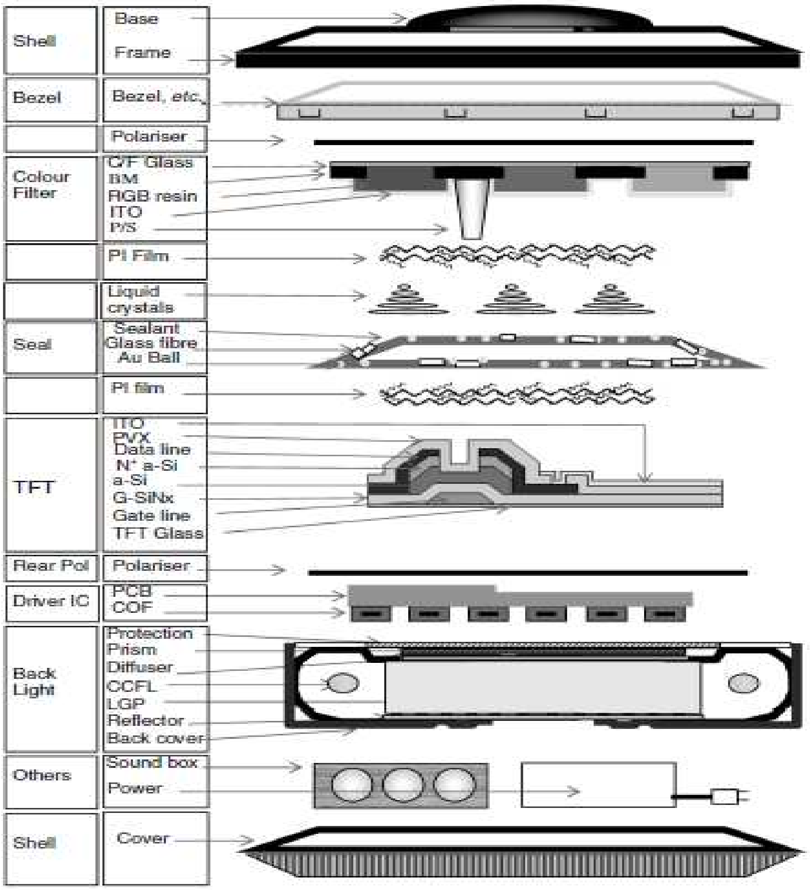


Figure 7: complete assembly of an LCD device (source: MATHARU and WU, 2009)

The LCD glass panel is formed by liquid crystal molecule mixtures that are suspended and form a uniform layer between two glass substrates with two polarizing filters on the outer side (LEE and COOPER, 2008). On the glass substrates TFT and color filters are applied. There are additionally conductive electrodes and orientation films on both sides of the LC mixture (LEE and COOPER, 2008).

2.2.2. Material composition

As mentioned before, an LCD-device is a complex mix of liquid crystals, glass, plastic, metal and electronic circuitry. Concerning the hazardous potential of LCDs, MATHARU and WU (2009) pointed out that: “Perhaps the two most contentious materials are mercury, used in the CCFL lamps as part of the backlight assembly, and the liquid-crystal mixture itself, which is a chemical cocktail of up to 20 different organic compounds, comprising mainly the elements C, H, N, O and F” (MATHARU and WU, 2009). Tab. 4 illustrates the bill of materials in a 15” LCD (SOCOLOF et al., 2001).

Component/element	Subcomponent	Material	Weight-% of total input
Steel			44,12%
Polarizer foil		PVA; PET; TAC; COP	0,15%
Glass panel	Glass	Silicon dioxide; Boron oxide ; Aluminium oxide; Barium oxide	10,31%
	Indium tin oxide (ITO)	Indium; Tin	0,01%
	Liquid crystals	LC polymers including cyano groups, fluorine, chlorine, and bromine;	0,04%
	Orientation film	Polyimide	0,01%
Black light	Diffusion foil	PET PC	1,03% 9%
	CCFL	Mercury	0,03%
	Reflector foil	PET	1,03%
Printed circuit board and components			6,52%

PVA - Polyvinyl alcohol; PET - Polyethylene terephthalate; TAC - Triacetyl cellulose; COP - Cyclic Olefin Polymer , PC - Polycarbonate

Table 4: Bill of materials of a 15" LCD (in mass-%) (source: adapted from SOCOLOF et al., 2001)

In tab. 5 the material composition of LCD monitor is given. Additionally, the mass-% of the materials is also presented.

Material/component	Mass: g/unit	Mass-%
Steel low alloyed	1771	**33,5%**
Aluminium	130	**2,5%**
Printed circuit boards	410	**7,8%**
Cables	340	6,4%
Backlight	2	0,04%
LC display	644,75	12,2%
Indium	0,07	0,001%
ABS	360	6,8%
PC	520	9,9%
PMMA	450	8,5%
Other plastics	651	12,3%
Total	5279	

Table 5: Material composition of LCD monitors (source: adapted from SALHOFER et al., 2012)

In the following section the materials of potential concern in an LCD are described.

2.2.2.1. Liquid crystals

Liquid crystals are organic compounds with optical and structural properties of crystals but with mechanical features of fluids. In general, they consist of polycyclic aromatic hydrocarbons such as phenylcyclohexanes and biphenyls (SOCOLOF et al., 2001). There are approx. 300 of liquid crystal compounds that are used in LCDs, each of them having different physical and optical characteristics. A typical LCD contains as many as 25 different compounds that are mixed together to form a white, opaque liquid that flows easily. The liquid crystal layer is typically about 3 to 5 µm thick (KCSWD, 2007).

According to the Decision 2000/532/EC[2], liquid crystals (after disassembling of the backlight unit) are considered as non-hazardous (MATHARU and WU, 2009).

Liquid crystal manufacturers have conducted extensive toxicological and ecotoxicological testing of the liquid crystals (including acute toxicity, mutagenic properties, skin/eye irritation, aquatic toxicity, and bioaccumulation potential) (KCSWD, 2007; HECKMEIER et al., 2002). On the basis of these tests, the overall conclusions claim that liquid crystals are not toxic or mutagenic and in general they are not endangering human health or the environment (KCSWD, 2007). However, the conclusions are made on the premise that long-term exposure to large quantities of liquid crystals is not likely and thus no chronic studies have been conducted. In addition, there are no toxicological and ecotoxicological tests found from independent sources. Further, there are no data on the potential for liquid crystal release and exposure during End-of-Life management of LCDs. Thus, the definitive conclusion about the hazardous potential of liquid crystals has to be drawn carefully (KCSWD, 2007).

2.2.2.2. LCD Glass

For the glass substrates, a glass with high melting point is used. LIN et al. (2009) analyzed the chemical composition of TFT LCD glass. Tab. 6 shows the typical chemical composition of TFT LCD glass.

Composition	Concentration
Silicon dioxide (%)	72.84
Calcium oxide (%)	20.06
Natrium oxide (%)	0.3
Copper (mg/kg)	11
Zinc (mg/kg)	77
Lead (mg/kg)	5
Chromium (mg/kg)	11

Table 6: Chemical composition of TFT LCD glass (source: adapted from LIN et al., 2009)

The analysis indicated that the major components in the glass are Silicon dioxide (72.84%), Calcium oxide (20.06%) and Natrium oxide (0.3%) (LIN et al., 2009).

2.2.2.3. Indium

The liquid crystals are sandwiched between two glass substrates whose inner surface has been coated with a transparent electrical conducting layer. This inner layer applies an electric field across the liquid crystal materials. Mostly a thin layer of indium tin oxide (ITO) is used (MATHARU and WU, 2009).

The main application of indium is in the form of ITO and is being predominantly used in flat panel displays and photovoltaic. The compound is made out of 90% indium

[2] The Decision 2000/532/EC is adopted by the European Commission with the aim of establishing one Community list which integrates the list of wastes and list of hazardous waste (source: ECOLEX, 2012)

oxide (In_2O_3) and 10% tin oxide (SnO_2), which results in 78% indium contained in ITO (BÖNI and WIDMER, 2011). BUCHERT et al. (2012) estimated the average indium content in different LCD devices. The results are presented in tab. 7.

	Mean screen area (cm)	Mean Indium content per device (mg)
Notebooks	552	39
Computer monitors	1.126	79
TV set	3.626	254

Table 7: Mean indium content of different LCD devices (source: BUCHERT et al., 2012)

Indium is a valuable as well as a scarce resource. Moreover, it is estimated that flat panel displays use about 80% of the global indium production and supplies are predicted to be exhausted by 2025 (SALHOFER et al., 2011). However, optimized recycling technologies are still in R&D stage and plants are located mostly in China, Japan and the Republic of Korea (USGS, 2010).

2.2.2.4. Backlight unit

The backlight unit of the LCD includes the following subassemblies: a lamp; diffusion foils that produce uniform light out the light coming from the lamp and a plastic reflector sheet that reflects the light into the liquid crystal panel direction. Until now cold cathode fluorescent lamps (CCFL) were mostly used (MATHARU and WU, 2009).

A CCFL is a sealed glass tube, filled with argon (or neon) and mercury (2-7 mg), with electrodes on both ends. The inner surface of a CCFL glass tube is coated with luminescent substance and the emission color depends on the type of the gas and appropriate mix of red, green and blue luminescent substances (MATHARU and WU, 2009).

Mercury is found in the fluorescent layer of CCFLs and its amount varies dependently on the device type as well as the size. In a large-area LCD TV containing CCFLs mercury may exceed 300mg (MATHARU and WU, 2009). Usually, the average amount of mercury in a lamp amounts to 5 mg/lamp (MCDONNELL and WILLIAMS, 2010). Fig. 8 illustrates the number of lamps according to the size and type of the LCD device.

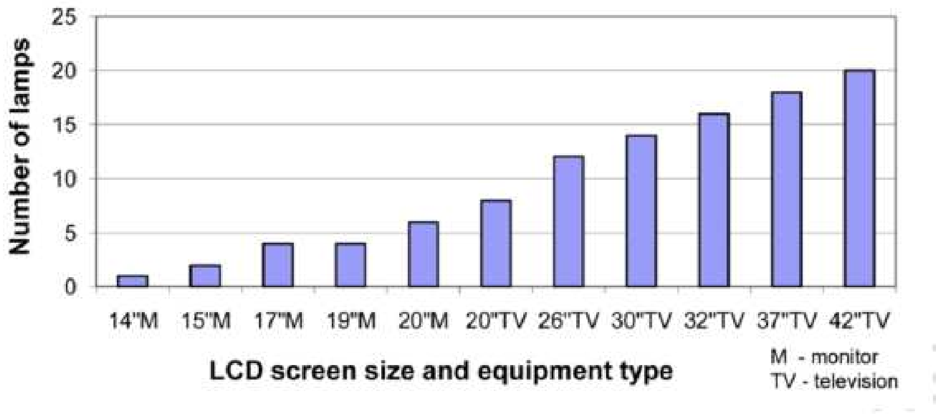


Figure 8: Number CCFLs in LCD equipment (source: MCDONNELL and WILLIAMS, 2010)

Recently LCD manufacturers introduced a new U-shape lamp that reduces the number of CCFLs by 50%. A general alternative of the mercury CCFLs is represented by the LED backlighting. The advantages of LED over CCFL backlight will be discussed in the next section.

2.2.2.5. Plastics in LCD equipment

In a LCD appliance, the average plastics content accounts for approximately 30% of the overall weight of the device. In tab. 8 the main sources for plastics in a LCD device are summarized. Fig. 9 and fig. 10 illustrate the share of each identified plastic type in a LCD monitor, respectively in a TV set.

Component	Mass-%	Chemical composition
Front frame	7	ABS; HIPS; ABS/PVC; ABS/PC; PPO/PS
Back frame	15	
Difuser foils	1	PET; PVC
Polarizer	0,01	PET
Light guide	9	PMMA

Table 8: Plastics in LCD equipment (source: adapted from Socolof et al., 2001; LEE and COOPER, 2008)

According to TESAR and ÖHLINGER (2012), the dominant plastic types identified in LCD equipment are ABS, PMMA, PC and blend of ABS/PC. The main plastic types in LCD monitors are PMMA and ABS (each with approx. 40%), whereas in LCD TV sets the ABS (59,5%) has the dominant plastic share, followed by PS (14,3%) and PMMA (5,60%).

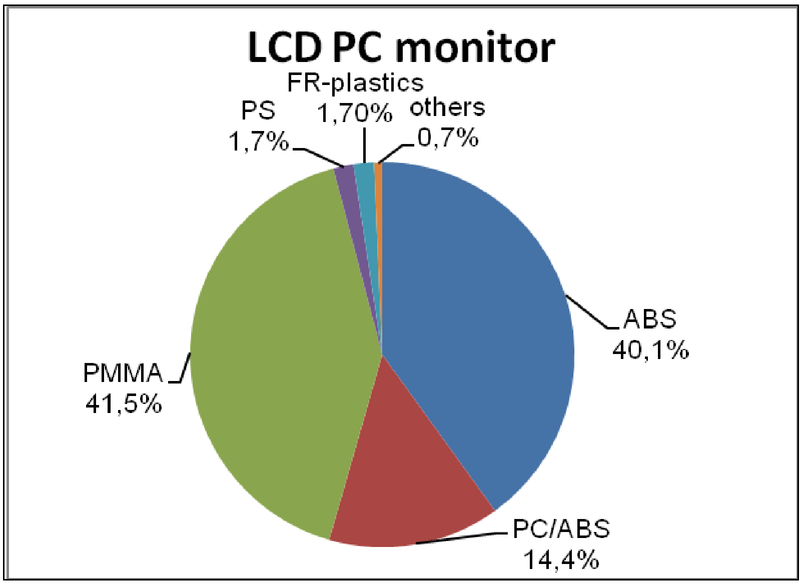


Figure 9: Plastic types in LCD PC monitor (source: TESAR and ÖHLINGER, 2012)

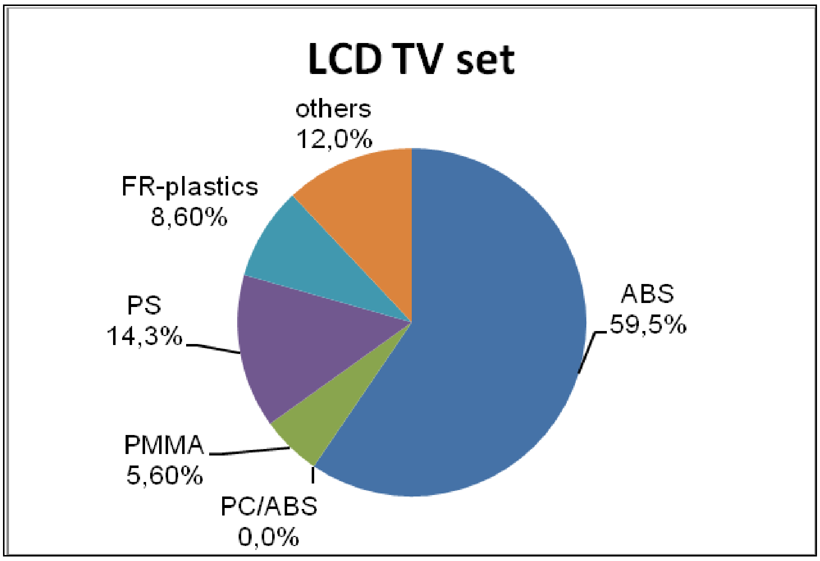


Figure 10: Plastic types in LCD TV set (source: TESAR and ÖHLINGER, 2012)

In a study aiming at investigating the concentrations of substances regulated by the RoHS Directive, WÄGER et al. (2010) found out that the content of Deca-BDE, Penta-BDE and Octa-BDE as well as of PBB in LCD appliances is compliant with the maximum concentration values defined by the RoHS Directive. The concentrations of lead, mercury, cadmium and chromium have also been found to be below the MCV.

Salhofer et al. (2012) have denoted the market potential for several types of plastics that are found in LCD appliances. PMMA (from light guides) as well as ABS and ABS/PC (used in the housings) were characterized as most valuable plastics with the potential revenues as follows – for PMMA[3] an average value of 2500 €/t has been defined, for ABS- 1700 €/t and for the blend ABS/PC the average revenue amounts to 2325 €/t.

Polymer type	Composition Monitor: kg/t	Composition TV: kg/t	Revenue price 2012 (EUR/t)	Revenues monitors	Revenues TV
ABS	120	179	1700	204	304
ABS/PC	43		2325	99,9	
PMMA	124	17	2500	310	42,5
Total				613,9	346,5

Table 9: Material revenues from LCD monitor and LCD TV (source: adapted from SALHOFER et al., 2012)

Further, SALHOFER et al. (2012) assessed the plastics content in LCD TV sets and monitors (per ton). The estimation is given in tab. 9.

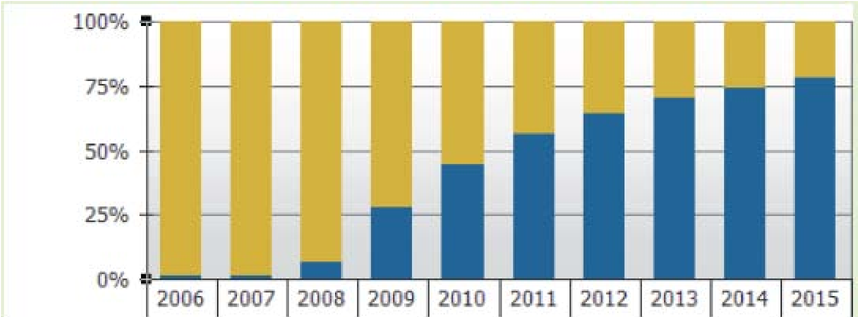
Considering the content of plastics in LCD appliances (monitors and TV sets) and the average revenue obtained from the plastics, as presented in the tables above, the following can be stated: the total revenue from the processing of the three types of

[3] The PMMA secondary price is approximate and was assumed on the basis of the prices on the commodity exchange (source: PLASTICKER, 2012). The secondary prices for ABS and ABS/PC have been revealed from the site of Kunststoff Information.

plastics in a LCD monitor amounts to 613,9 €/ton and 346,5 €/ton of recycled plastics of LCD TV set.

2.2.3. Perspectives of the technology

Because of the toxic characteristics of mercury, producers strive to develop backlight technologies to substitute the CCFLs. In the last years, LEDs have been used as a successful alternative to CCFLs, either in form of full LED, or in edge LED technology. LEDs emit less heat, use less space and more important - are mercury-free (KCSWD, 2007). The estimation of the development of the different types LCD-backlight is presented in fig 11.



	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
CCFL/EEFL	99.0%	99.0%	93.3%	72.2%	55.7%	43.6%	35.8%	29.8%	26.1%	21.7%
LED	1.0%	1.0%	6.7%	27.8%	44.3%	56.4%	64.2%	70.2%	73.9%	78.3%

Figure 11: Technology changeover of LCD backlight in pc monitors, TV sets and laptops (source: BÖNI and WIDMER, 2011)

As can be seen from the figure above, it is expected that LCDs with LED backlight will definitely dominate over the CCFL and EEFL backlights in near future. This inevitably poses the question of the environmentally sound processing of CCFL backlight units as well as of the LCDs panels.

Recent price fluctuation and supply concerns about indium motivated the development of ITO substitutes. Instead of ITO coatings in LCD, an antimony tin oxide (ATO) has been developed (USGS, 2010). The utilization of graphene quantum dots is still in a development stage but is expected to replace ITO in LCD. Researchers investigate the use of a more adhesive zinc oxide nanopowder that has to replace ITO in LCDs (USGS, 2010). It is predicted that the technology will be available on the market in 2013. For flexible displays and touch screens, carbon nanotube coatings are applied. As a substitute for ITO in flexible displays and OLED, a poly(3,4-ethylene dioxythiophene) (PEDOT) has also been developed and tested (USGS, 2010).

2.2.4. Recycling of LCD

The glass in the LCD accounts for approx. 90% of the overall weight of the LCD panel, thus it is feasible to ponder over its reuse or deviation from landfill (MATHARU and WU, 2009). Just as the case of indium recovery, there are no state-of-the-art recycling technologies for End-of-Life TFT-LCD glass yet. Several studies explored the recycling and reutilization of TFT-LCD waste glass. For example, LIN (2007) proposed the reutilization of TFT-LCD waste glass as a clay substitute to produce eco bricks. The results of the study indicate that bricks containing mixtures with 30% TFT-LCD glass fulfill the quality standards for bricks.

Nevertheless, according to HAGELÜKEN and MESKERS (2009) more research in the field of LCD-panels recycling is essential, in order to achieve processing technologies that are cost efficient and feasible at industrial scale. TFT LCDs are characterized by the low mass and concentration of valuable metals per device, thus the economic drive for their recycling is still low. Recovering indium from TFT-LCD glass through smelting requires a lot of energy due to the glass high melting temperature (1150°C) and thus is not feasible yet. That is why the separation of the relevant layers from the glass substrate by leaching or by mechanical or thermal treatment needs to be optimized (HAGELÜKEN and MESKERS, 2009).

LI et al. (2009) proposed a combined technological process for recovering indium and other valuable materials from the End-of-Life LCD panels. The procedure includes separation of the polarizing film through thermal shock; ultrasonic-assisted cleaning for removal of the liquid crystals; and dissolution of indium from ITO glass by mixed acid solution. By this process the recovery rate is about 90 mass-% (LI et al., 2009).

Considering the CCFLs, they are still a bottleneck for the recycling. Firstly, as mentioned above, it has high mercury content and secondly during the disassembly process, it is found out to be difficult to remove from the LCD device (GRIEGER, 2010). Sales of LCD are predicted to increase, thus the quantity of mercury is also rising. RYAN et al. (2011) estimated that in 2010 between 209kg and 480kg of mercury from EOL LCDs will have to be disposed of all 80 million devices in use. Hence, it is essential to develop disassembly system that can process this volume of EOL CCFLs (RYAN et al., 2011).

Current CCFL recycling processes are not or not enough capable to remove the fluorescent layer from the CCFL because of the small radius and diameter of the lamp- approx. 2.4mm to 4.0mm. Contemporary, CCFLs are chemically treated or end in underground depot (GRIEGER, 2010).

2.3. Organic Light Emitting Diodes

One of the next generation display technologies is represented by Organic Light Emitting Diodes (OLED).
Variations of OLED include Polymer LEDs (PLEDs) and SMOLEDs (Small Molecule OLEDs). PLEDs and SMOLEDs use molecules as an organic material which generates light when tweaked with an electric current (PCTECHGUIDE, 2012). Further, OLEDs can be differentiated according to the matrix they use – active (AMOLED) or passive (POLED). Recently, a transparent OLED display has been developed (BOUZAIDI and DUFLONT, 2008).

2.3.1. Structure and operating principles

OLEDs use two different types of organic material – relative small molecules or polymers. The basic structure of OLED is illustrated in the next figure (fig. 12).

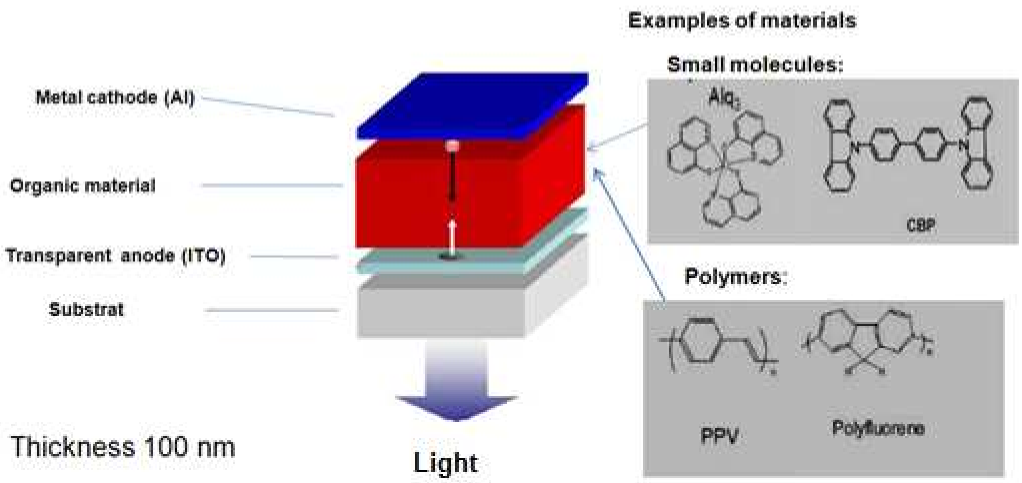


Figure 12: Structure of OLED (source: BOUZAIDI and DUFLONT, 2008)

SMOLED structure contains multiple layers of organic material. The organic material is sandwiched between two electrodes. ITO with high transparency is used as a transparent anode, followed by a metal cathode, usually made out from aluminum or calcium (KCSWD, 2007). Additionally, a layer of tris-8-hydroxyquinoline aluminium [$Al(C_9H_6NO)_3$] is used to support the transport of electrons. A layer of mixture of $Al(C_9H_6NO)_3$ and C540 (a carbon derivative) is also added for more fluorescence (GURSKI and QUACH, 2005).

PLEDs use polymers made from chains of organic molecules, such as polyphenylene vinylene (PPV). The advantage of PLED molecule over the SMOLED is that the PLED organic material is water soluble and can be processed with ink-jet printing; a technique allowing a low-cost production. A disadvantage of PLEDs is their relative short life time compared to SMOLEDs (GURSKI and QUACH, 2005).

Further OLEDs can be differentiated in passive or active OLEDs. Passive OLEDs are best utilized in small display applications such as in mobile phones and video games. On the contrary, AMOLEDs are suitable for large screen visualizations, TV sets as well as for notebook displays. In the design of AMOLED a top emitting structure is preferred. A top emitting structure uses a transparent or semi-transparent top electrode emitting light directly (LEE et al., 2008). A bottom emitting structure uses a transparent or semi-transparent bottom electrode to get the light through a transparent substrate. As illustrated in fig. 13 top- and bottom-emission devices use different anode material.

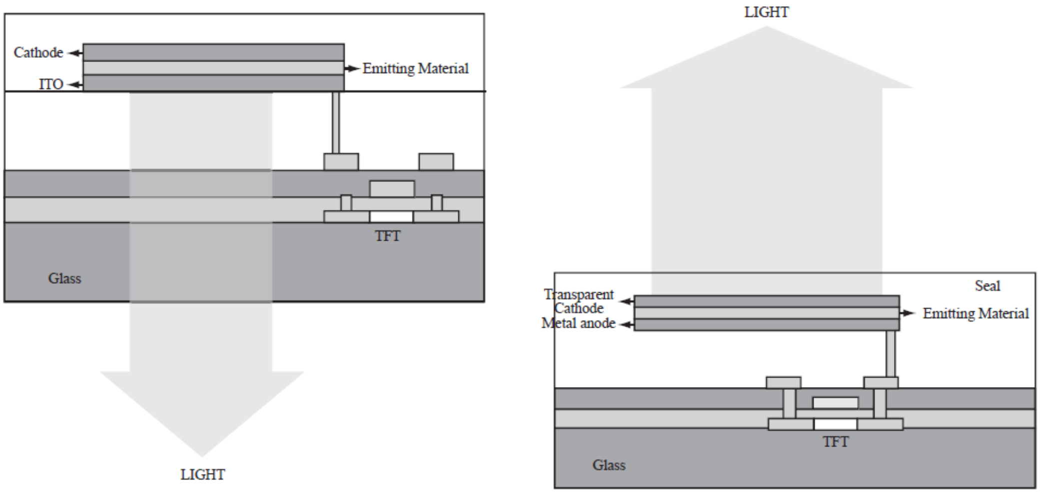


Figure 13: Bottom-emission (left) and top-emission (right) OLED configuration (source: LEE et al., 2008)

Usually a top-emission OLED configuration employs a metal anode (mostly silver), where as the bottom emission OLED uses an ITO as an anode (LEE et al., 2008).

2.3.2. Material composition

BÖNI AND WIDMER (2011) estimated the content of ITO and of indium in OLED displays. In tab. 10, the results of their estimation are presented. They are based on the studies of ANGERER et al. (2009) and STEINFELDT et al. (2004).

	OLED (ANGERER et al., 2009)	OLED (STEINFELDT et al., 2004)
mg ITO/m²	188	120
nm/ layer	157	100
mg In/m²	147	94

Table 10: Layer density, ITO and indium concentration in OLEDs (source: BÖNI and WIDMER, 2011)

Further, ANGERER et al. (2009) estimated the overall consumption of indium and silver in 2006 as well as the demand of these two resources for 2030. Tab. 11 illustrates the results given in tones.

Resource	Production 2006	Consumption 2006	Estimated demand 2030
Indium	580	230	355 - 1.581
Silver[4]	20.200	0.2	10-28

Table 11: Global indium and silver consumption in displays (in tones) (source: ANGERER et al., 2009)

Although the OLED demand for silver in 2006 accounts for only 0.2 tones, in 2030 a significant increase is expected. Regarding the indium, there is definitive grow in its

[4] The estimation for silver regards only the demand for OLED-Displays

demand towards 2030. This trend points out the significance of the development of acute technologies for the recovery of indium.

2.3.3. Perspectives of the technology

OLEDs, AMOLEDs and transparent OLEDs already find application in mobile phones and video displays. As the technology develops, it further continues to make progress toward applications in TV sets and notebooks. As shown in fig. 14 OLEDs may successfully substitute the AM-TFT-LCDs by 2015 (BÖNI and WIDMER, 2011).

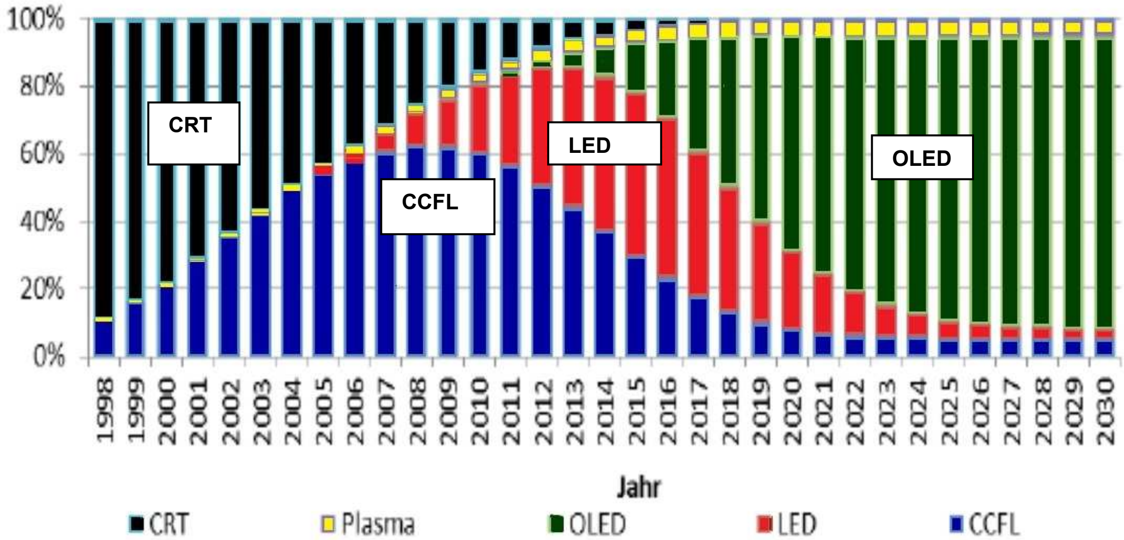


Figure 14: Market distribution of different display technologies in Switzerland 1998-2030 (source: BÖNI and WIDMER, 2011)

An advantage of the OLED TVs, computer and the laptop monitors, is the fact that they do not need a backlight, because of their emissive nature. This allows a thinner construction and lower weight. In addition, due to specification of the manufacturing technology, namely roll-to-roll processing, OLEDs can be produced at a lower cost compared to the LCDs (LEE et al., 2008).

In 2006 the overall sale of OLED-Displays amounts to 72 Mio units. It is estimated that the OLED display market will rapidly grow and will reach 297.3 million units in 2015. Fig. 15 illustrates the market trends for OLED shipments between 2010 and 2015 (OLED-INFO, 2012).

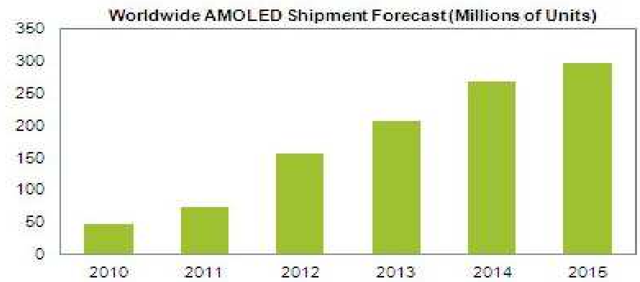


Figure 15: Forecast of AMOLED shipments 2010-2015 (source: OLED-INFO, 2012)

The forecast regards only the shipment of 4 and 7 inches small display AMOLEDs. It is important to take into consideration that Samsung and LG presented a 55 inches TV display in 2012. Later in 2012, the TVs should be available on the market. In accordance with further estimations, sales of OLED TVs will grow to 1 million units in 2013 to 10 million in 2015 and this trend will continue to 30 million in 2017 (SEMI, 2012).

2.3.4. Recycling of OLED

The recycling of OLEDs is discussed in the following (section 2.4.3).

2.4. Emerging display technologies – flexible displays

Currently, an area under extensive research is the field of flexible electronics for flexible displays. Flexible displays based on primarily LCD, OLED and electrophoretic displays are gaining considerable attention and are expected to show significant growth on the market in the next decade (MACDONALD et al., 2005). SLIKKERVEER (2003) defines a “flexible display” as: “a flat panel display constructed of thin (flexible) substrates that can be bent, flexed, conformed, or rolled to a radius of curvature of a few centimeters without losing functionality” (CRAWFORD, 2005). The evolution of technology makes the concept of new flexible displays possible. The development of fields such as flexible substrates, conducting layers, electro-optic materials and thin film transistors allows the realization of various displays for different applications and forms (CRAWFORD, 2005).

2.4.1. Structure and operating principles

In contrast to rigid glass-based FPDs, flexible displays are thin and lightweight. They can be fabricated by roll-to roll process; a technique which has a potential of low cost manufacturing. As a mechanical characteristic flexibility is classified by GLESKOVA et al. (2009) in three categories: bendable and rollable, permanently shaped and elastically stretchable (shown in fig. 16) (GLESKOVA et al., 2009).

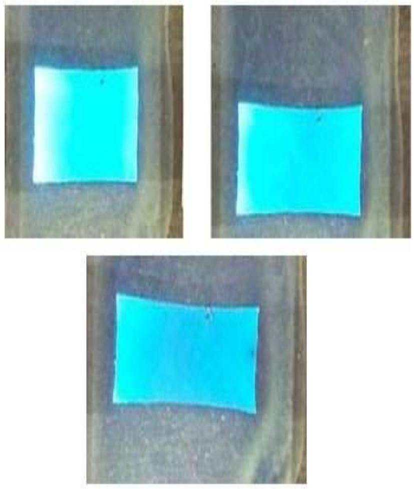


Figure 16: Bendable AMOLED (left) and stretchable AMOLED (right) (source: PHONEARENA, 2011, GIZMAG, 2012)

There is also a high interest in large-area flexible electronics and displays fabricated using flexible substrates. Flexible substrates allow significant thinness and weight less; they are highly stabile and have minimized likelihood to break. In addition, their fabrication cost is lower compared to conventional rigid glass substrates. They enable a variety of new applications because of their ability to perform unique forms and curves (SARMA, 2009).

An extensive research in LCD and OLED flexible displays is being conducted in the last few years. Fig. 17 illustrates a schema of a flexible LCD structure with molecularly aligned polymer crossing-lattice walls and polymer fiber networks (FUJIKAKE, 2008).

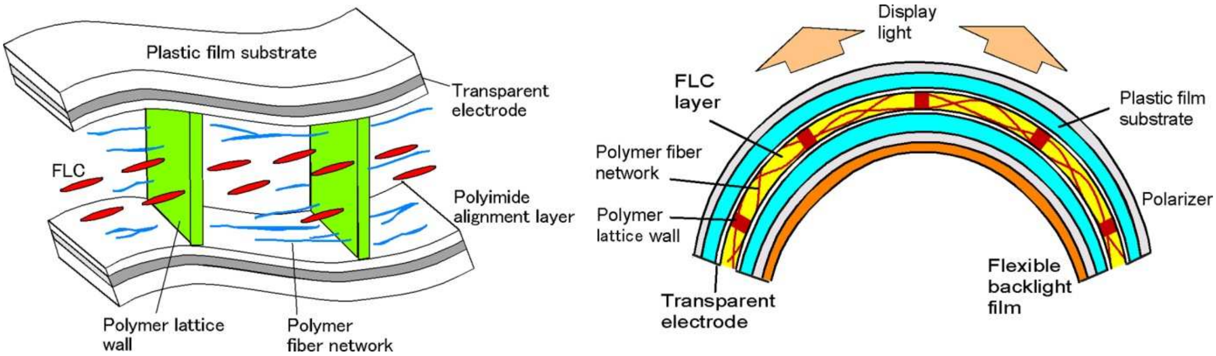


Figure 17: Cross sectional structures of ferroelectric liquid-crystal (FLC)/polymer composite device (left) and flexible display (right) using a flexible backlight film (source: FUJIKAKE, 2008)

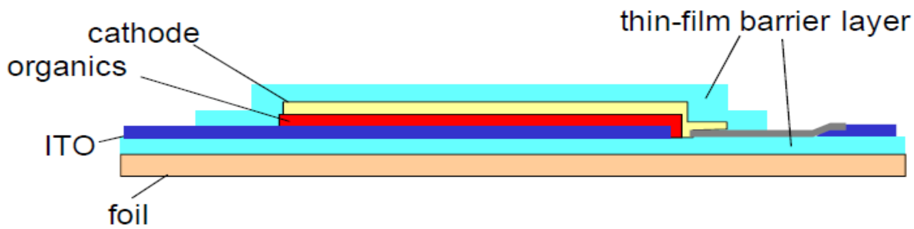


Figure 18: Schematic diagram of a flexible OLED device that is protected by a thin-film barrier layer on both sides of the OLED device (source: WEIJER and MOL, 2009)

In flexible electronics, the rigid plate glass substrate of current liquid crystal displays is replaced by substrates, which is made out of ultrathin glass, thin plastic or metallic foils. The substrates are still in a development and have some bottlenecks to deal with. It is possible to produce ultrathin glass (up to 100μm). However, the technique is very expensive as well as the glass foil is fragile and difficult to handle (CHENG and WAGNER, 2009). Another substrate alternative is represented by the plastic. Polymer foil substrates are inexpensive and are highly flexible. A disadvantage of the polymer substrates is their lower stability. In addition, they are easily permeated by oxygen and water and thus not suitable for OLED applications (because they require low permeability) (CHENG and WAGNER, 2009). Among the metal foil substrates, stainless steel, molybdenum, and aluminium foils have been used for thin-film applications and are suitable for emissive and reflective displays, which do not need transparent substrates (SARMA, 2009).

The backlight is carried out through two systems - the first is based on direct illumination of LED chips sensitive to the three primary colors (RGB), mounted on a flexible polyamide film (FUJIKAKE, 2008).The second type backlight is a flexible light-guide film of transparent silicon resin with edge-light sources consisting of thin RGB LEDs (FUJIKAKE, 2008).

2.4.2. Material composition

In tab. 12 the material composition of the flexible displays is summarized.

Material	Function	Technology	Toxicological aspects
Aluminium	metal cathode	OLED	non-hazardous
Calcium	metal cathode	OLED	non-hazardous
Magnesium	metal cathode	OLED	non-hazardous
Silver	metal cathode	OLED	non-hazardous
Glass (soda, borsilicate)	substrates	e-Ink, OLED	non-hazardous
Polymerfilm (Poly-Phenylen-Vinylen; Polyfluoren; Polythiophen; Polyvinylchlorid	polymer coating	OLED	not known

Table 12: Composition of flexible OLED display (source: BEHRENDT, 2004)

For the manufacturing of OLEDs, different synthetic materials are used. Usually the organic material is made out of polyphenylene vinylene (PPV), polyfluoren, polythiophen and polyvinylchloride (PVC) and ITO is used for the anode (BEHRENDT, 2004). Unlike the conventional LCDs, flexible displays do not need backlighting such as CCFLs, thus mercury is not included (BEHRENDT, 2004).

2.4.3. Recycling of flexible displays

The field of flexible displays is still in its early stage of development. According to the current level of knowledge, in contrast to conventional FPDs, flexible displays are characterized by lower material input as well as lack of toxic substances in active quantities like mercury and lead. Hence, it is expected that when they reach their End-of-Life stage, their disposal will be facilitated (BEHRENDT, 2004).

However, flexible displays are distinguished with a multilayer plastic structure composed by different kind jointly laminated plastics. Thus, a mono-material separation is hardly achievable and according to the current state of the art recycling is not realistic (BEHRENDT, 2004). That is why the development and utilization of recyclable materials is essential (BEHRENDT, 2004).

3. EXTERNAL POWER SUPPLY AND BATTERY CHARGER

The electrical grid delivers power to the end consumer in form of alternating current (AC). Power supplies convert the AC into direct current (DC). Sometimes the current is also converted back to alternating current but in a different frequency. The energy conversion for consumer equipment is accomplished through two main technologies: the linear mode and the switched-mode technology (EKTM, 2008). In fig. 19, the key parameters of the two converting technologies are presented.

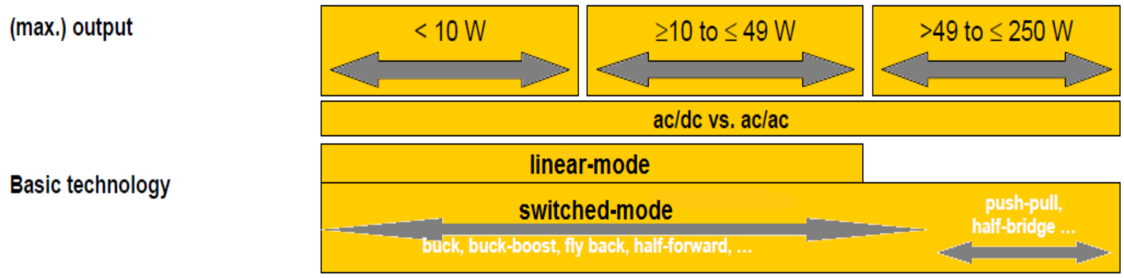


Figure 19: Key parameters of linear-mode and switched-mode EPS (source: MONIER et al., 2007)

In general, linear power supplies have been used for low-power applications (for max. 49W) whereas switched-mode power supplies find application in the higher power electronics segment (up till 250W)[5] (EKTM, 2008). However, nowadays switched-mode EPS (SMPS) is the dominant converting technology.

SMPS function as it switches loads on and off, which results in short, non-sinusoidal current pulses. This non-sinusoidal pulsating current causes unanticipated reflective currents, called harmonics, back into the power distribution system and they operate at other frequencies than the fundamental 60 Hz. Harmonics can have various harmful effects on the electronics components such as overheating of transformers, failing of capacitor banks and unreliable electronics equipment. In addition, the power distribution is characterized by low efficiency.

EPS and battery chargers[6] (BC) are mostly sold together with end-use appliances like notebooks and mobile phones. Usually, by manufacturing they are personalized so that they can be only used with the end-appliance they are sold with. Consequently, their lifetime is restricted. Moreovere, because of compatibility reasons EPS and BC cannot be reused for other appliances (MONIER et al., 2007).

[5] In general, the output power of a mobile phone EPS is less than 10 W. A typical notebook has output power of 65W or 95W (source: MONIER et al., 2007)

[6] There is no consensus about the concrete differentiation between EPS and BC. When regarding the technical aspects, EPS and BC stem from a uniform product family. MONIER et al. (2007) point out, that the most precise distinction between EPS and BC is their product design feature: “external power supply is connected to the end-use product via some form of wiring and does not have batteries that physically attach directly to it. Battery charger connects directly to the battery at the output”.

Recent legal orders are aiming to regulate the problems that affect the EPS and BC mentioned above. In the next part, a brief introduction of these regulations is presented, followed by an addition of the technical characteristics of the EPS and BC. A link to the required technical innovations is also given.

3.1. Legal regulations

In 2001, the European Union put the technical standard EN61000-3-2 into action. EN61000-3-2 addresses power supplies with input power of 75 Watts or greater. The aim of the standard is the insertion of power factor correction (PFC) in the switched-mode EPS. The PFC limits the harmonic currents and thus the degradation of the power quality (BERMAN, 2012). “It returns the power factor[7] of an electric AC power transmission system to very near unity by switching in or out banks of capacitors or inductors which act to cancel the inductive or capacitive effect of the load” (MONIER et al., 2007).

In 2008 the European Commission started the initiative “Communication on public procurement for a better environment”. In a close cooperation with relevant Commission services, industry, civil society and Member States criteria for the development of EPS were developed (EC, 2010). The following aspects, addressing the material use of external power supplies are included:

- Reducing the weight/size of coils and transformers
- Reducing the printed circuit board size
- Reducing the weight of copper and other materials in cables
- Reducing the weight/size/number of diodes
- Reducing the weight/size of big capacitors
- Use of recycled materials

In 2009 the European Commission launched the Directive 2009/125/EC which aims to improve the energy performance of EPS. It sets ecodesign requirements to all AC/DC and DC/DC units that have a separate enclosure and an output power of 250 Watts. The Directive covers power supplies for a large group of appliances, e.g. home electronics and IT equipment. It implements regulations that concern both the active efficiency of the EPS when power is supplied to the electronic equipment as well as the no-load power consumption, when the supply still uses power although not plugged in (ECODESIGN, 2009).
In the same year, the European Commission brought to a close a Memorandum of Understanding (MoU) with fourteen major mobile phone producer, inter alia Apple, LG, Motorola, Nokia, Samsung, Sony Ericsson, Texas Instruments as well as Atmel and Emblaze Mobile. In this MoU, all of the producers agreed to harmonize the EPS

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[7] The power factor of an AC electric current is defined as the ratio of the real power flowing to the load to apparent power in the circuit. Real power (watts) produces real work, where as apparent power is the product of the current and voltage of the circuit. In an electric power system, a load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred (source: FAIRCHILD, 2004)

for data enabled mobile phones. The aim of the MoU is to reduce the amount of WEEE and to augment the reuse of the EPS (EC, 2009).

3.2. Structure and operating principles

As mentioned above, external power supplies use two main technologies for the conversion of energy – linear mode and switched-mode technology.

3.2.1. Linear-mode power supply

Linear-mode power supply works as it steps down the AC voltage (127 V or 220 V) from the power grid to a lower value (e.g., 12 V) with the help of iron or steel laminated transformer. The AC voltage is rectified by using set of diodes or bridge diodes, transforming it into an unregulated one. The next steps include filtering of the AC voltage by an electrolytic capacitor, regulating the obtained DC voltage by Zener diode or voltage regulator IC (TORRES, 2008). A schema of the linear mode EPS is illustrated in fig. 20.

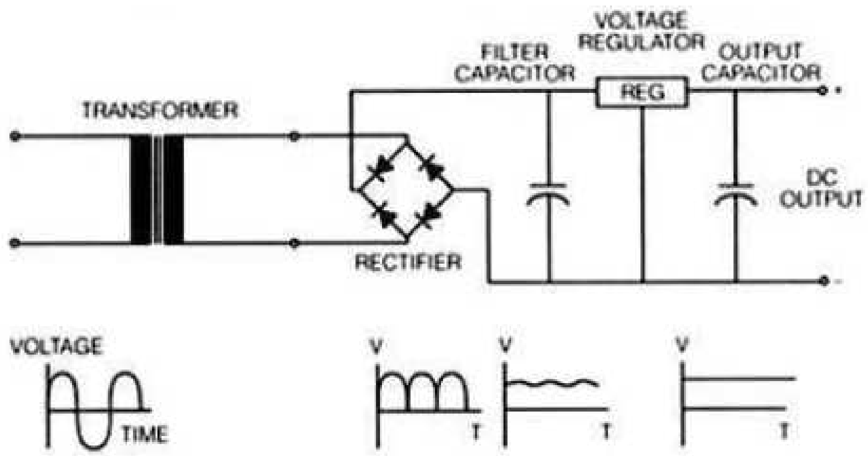

Figure 20: Power supply circuit for linear mode device (source: MONIER et al., 2007)

Linear-mode EPS are characterized with their lower noise, high reliability and low cost. However, a main obstacle of this technology is its size and low efficiency. This kind of supply operates on 50 or 60 Hz frequency. The size of the transformer and the capacitance (and thus the size) of the electrolytic capacitor are inversely proportional to the frequency of the input AC voltage; the lower the AC voltage frequency, the bigger the size of those components and vice-versa (TORRES, 2006). Also, the higher the output power of a linear-mode EPS, the more material for the transformer coils (ferrite core and copper for windings), but also for the housing (due to larger transformers) is needed (TORRES, 2006).

Since there is a trend towards portable and smaller applications, the linear mode power supplies have been largely substituted by switch mode power supplies. Moreover, in the last years the prices of raw materials have been dramatically rising which also makes linear technology economically unattractive (EKTN, 2008).

3.2.2. Switched-mode power supply

Power supplies with switched-mode technology operate at much higher frequency than linear mode EPS. This allows the utilization of a much smaller ferrite transformer and capacitor. It employs a switching regulator - an internal control circuit that switches the current rapidly on and off, in order to stabilize the output voltage. The higher frequency AC current is also easier to rectify and filter compared to the original 50-Hz AC line voltage, reducing the variances in voltage for sensitive electronic components. In fig. 21 the schema of switched-mode EPS is illustrated.

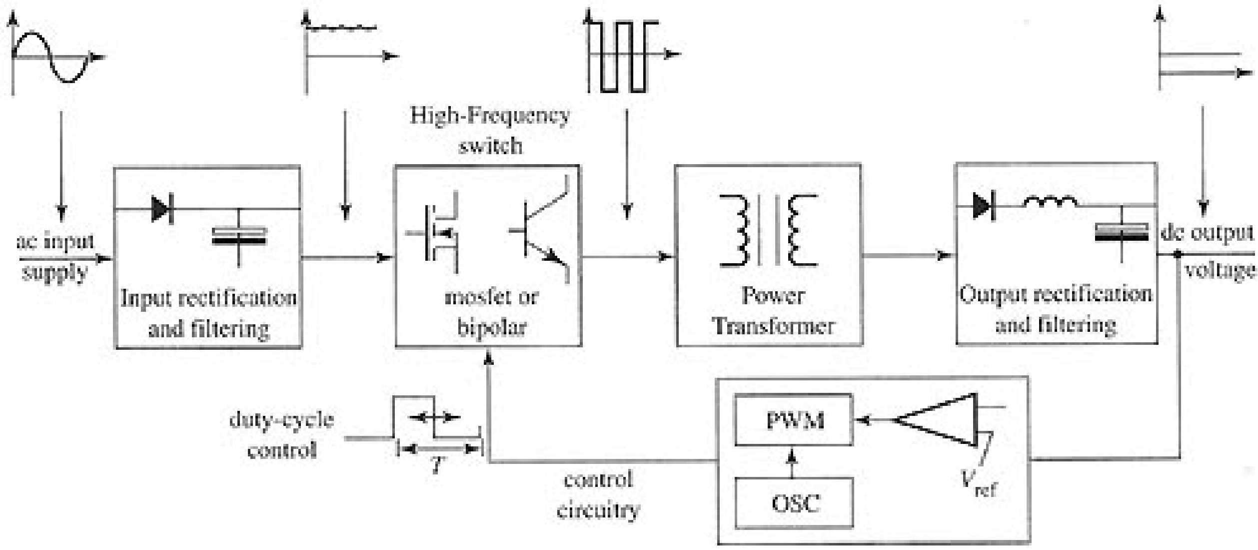

Figure 21: Power supply circuit for switch mode device (source: INDUSTRIAL ELECTRONICS, 2012)

As can be seen from the schema, the SMPS has more complex circuitry compared to the linear-mode EPS.

At first, the AC voltage is rectified to pulsing DC by a diode and capacitor and then filtered. Next, the DC voltage is converted back to an AC voltage, but at a higher frequency (MONIER et al., 2007). This step is accomplished through a metal–oxide–semiconductor field-effect transistor (MOSFET) or bipolar transistor. The transformer then regulates the voltage to the level required from the DC voltage. The output of the transformer is send to the second rectifier which operates at very high frequency (20-100 kHz). The second rectifier smoothens the pulsating to regulated DC. The last section of the SMPS includes the power supply control IC. It compares the output voltage to a reference voltage and continually makes adjustments to the output voltage.

3.3. Material composition

As discussed above (in section 3.1), since 2001 the implementation of power factor correction (PFC) is required for the EPS from 75W input upwards (MONIER et al., 2007).

Tab. 13 illustrates the bill of materials (BOM) for two notebook EPS. The comparison distinguishes the BOM of EPS for 65W notebook with the BOM of EPS for 90W notebook with a PFC.

		60W notebook EPS (without PFC)	90W notebook EPS (with PFC)
Materials	unit	mass-%	mass-%
Bulk Plastics	g	14,07	12,88
TecPlastics	g	18,25	18,43
Ferro	g	0,76	0,76
Non-ferro	g	30,42	23,48
Coating	g	0	0
Electronics	g	36,50	44,44
Miscellaneous	g	0	0
Total weight	g	**263**	**396**

Table 13: Mass-% of EPS for 60W (without PFC) and 90W notebook (with PFC) (source: adapted from MONIER et al., 2007)

In comparison with the 65W notebook EPS, the EPS with PFC contains significantly more electronics. However, the reason for the higher BOM of the EPS with PFC can be explained with the higher wattages of the 90W power supply (the higher the wattages, the bigger and heavier the electronics elements).

EKTN (2008) conducted a comparison study in order to investigate the BOM of the two main power supply technologies. Their results are summarized in the following table (tab. 14).

Characteristic	**Linear power supply**	**Switched-mode power supply with pulse width modulation (PWM)**	**Switched-mode power supply with resonant/quasi resonant switching**
Weight/size	High	Medium	Low
Efficiency	30 - 50%	65 - 85%	75 - 95%

Table 14: Comparison between linear and switch mode EPS (source: adapted from EKTN, 2008)

In accordance to the results, SMPS have higher number of electronic components. Nevertheless, the total weight of the switch mode EPS is about 50% less (EKTN, 2008).

Within the design of SMPS the BOM can vary considerably. It mostly depends on technical characteristics such as the circuit layout, level of integration and the assembly technology (EKTN, 2008). Meanwhile integrated ASIC (application specific IC) substitute the discrete components, thus a smaller size is feasible. Further, the surface mounted technology (SMT) rapidly replaces components that use through-hole technology which again contributes to the minimization of the EPS (EKTN, 2008).

However, this comparison has to be carefully observed since there are no numerical values and explanation how the “high”, “medium” and “low” values are defined.

In order to gain more information about the material composition of EPS, a dismantling trial was undertaken. Several notebook and mobile phone EPS were dismantled and weighted in order to trace the developments in size and mass of the components. In the following figures the dismantled EPS are presented. Fig. 22 and fig. 23 illustrate the dismantling process of a notebook SMPS. The weight of the disassembled components from the PCB was measured and the results are given in tab. 15. Figures 24-27 picture the dismantling of mobile phone BCs. In fig. 24-26 the switched-mode BCs are presented. Figure 27 illustrates a linear-mode BC. After the dismantling, the PCBs were weighted. The PCBs weight is presented in tab. 16.

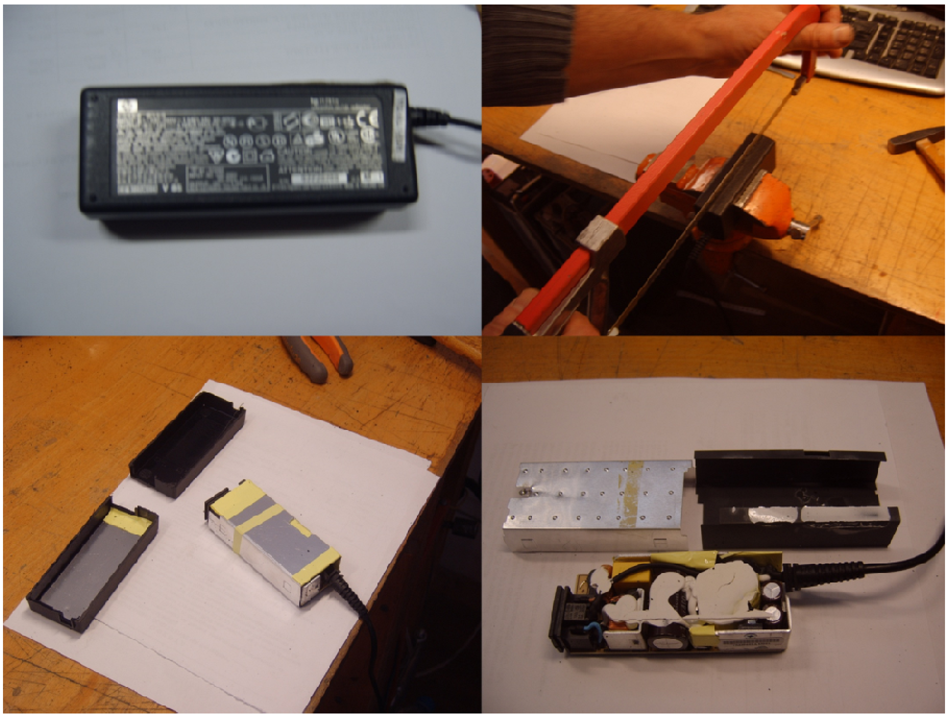

Figure 22: Sample of dismantling trials: Switched-mode notebook EPS, part 1

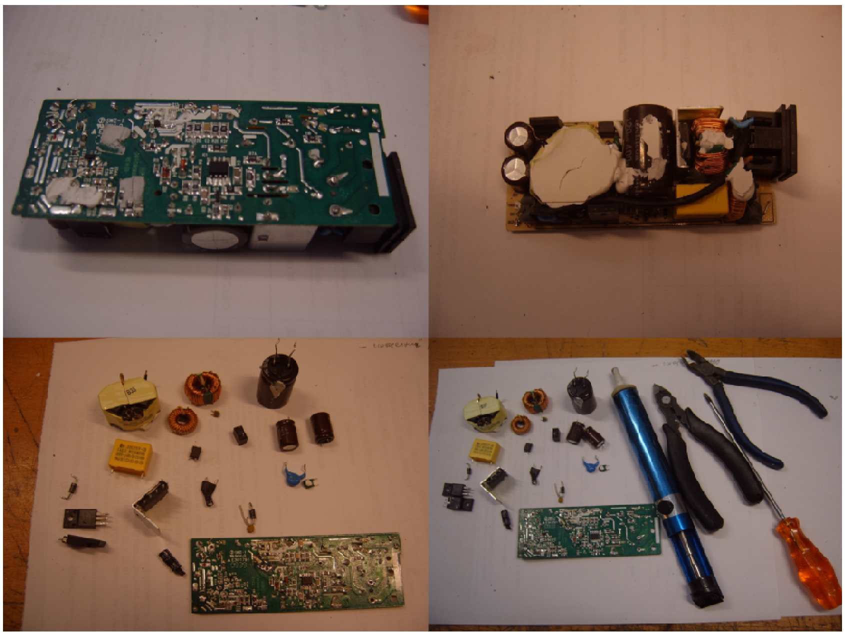

Figure 23: Sample of dismantling trials: Switched-mode notebook EPS, part 2

Type electronic element	Number of el. elements in the equipment	Mass of the element (gram)	Total weight of the elements
Ferrite transformer	1	32, 6	32, 6
Capacitor	4	a) 3,3 b) 1, 9 * 2 c) 0,4	3,3 3,8 0,4
Bridge rectifier	1	3,7	3,7
Inductor	2	a) 9,9 b) 4	13,9
Electrolytic capacitor	1	13,6	13,6
Schottky diode	1	2,3	2,3
Zener diode	1	0,2	0,2
Internal fuse	1	0,3	0,3
Transistor	1	2,2	2,2
Poly switch fuse	2	0,4	0,8
Printed circuit board	1	9,1	9,1
Aluminium chassis			32,6

Table 15: Weight of electronics components dismantled from notebook EPS

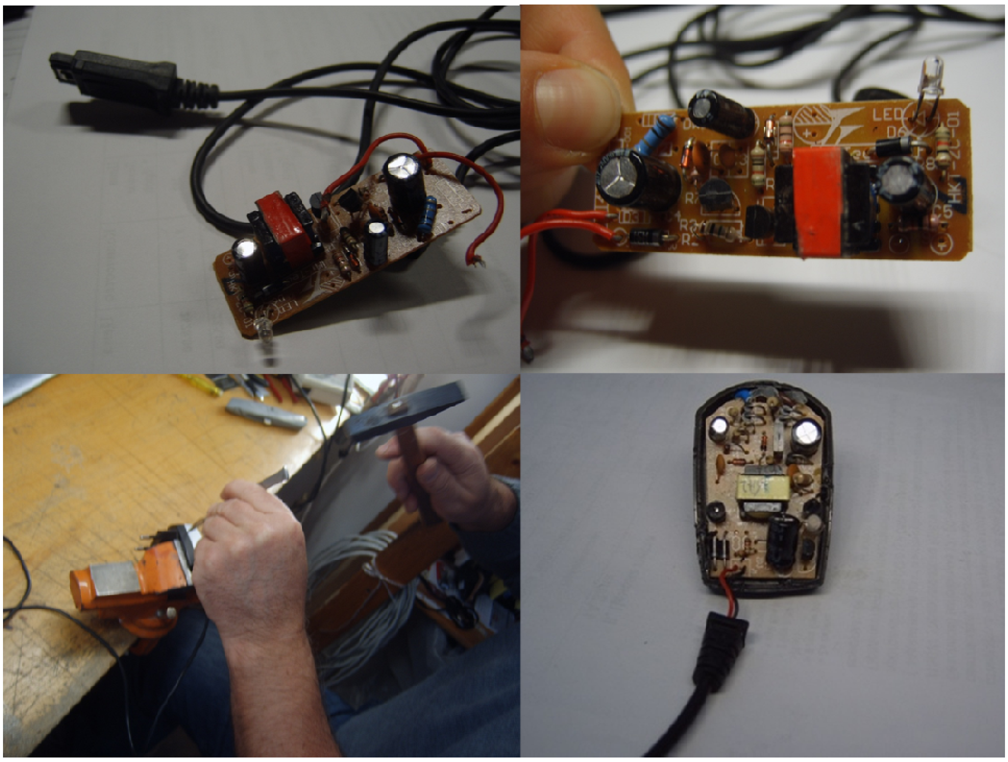

Figure 24: Sample of dismantling trials: Switched-mode mobile phone battery charger, part 1

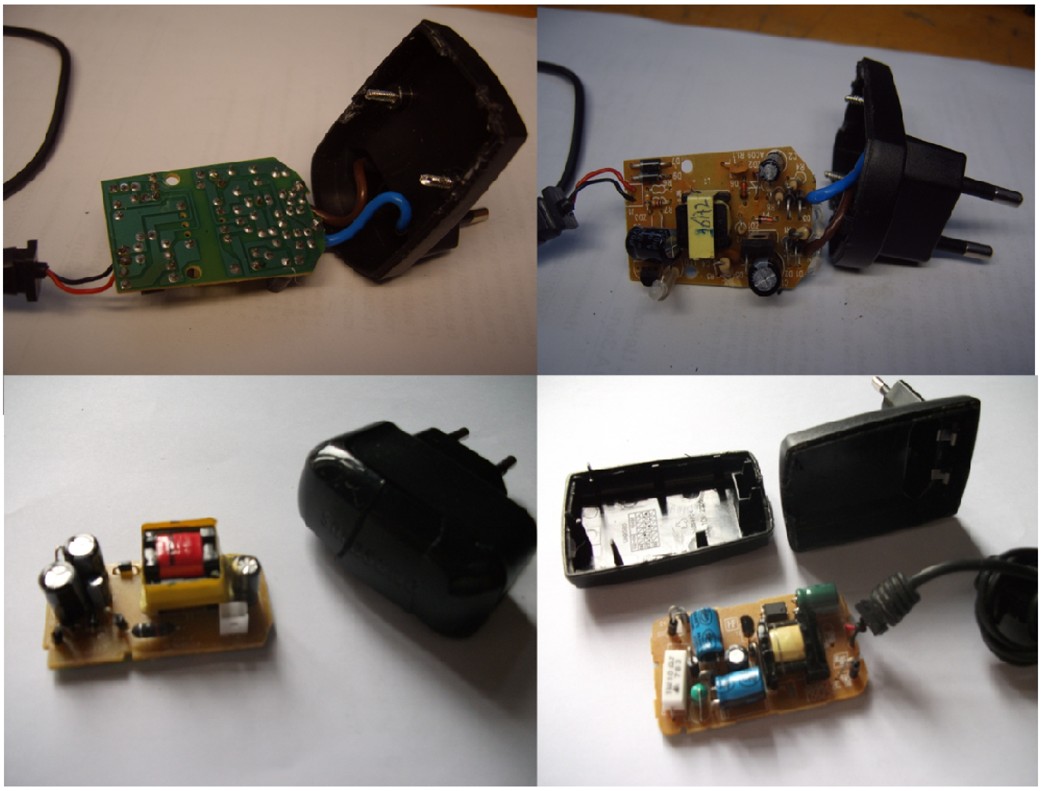

Figure 25: Sample of dismantling trials: Switched-mode mobile phone battery charger, part 2

Figure 26: Sample of dismantling trials: Switched mode mobile phone battery charger, part 3

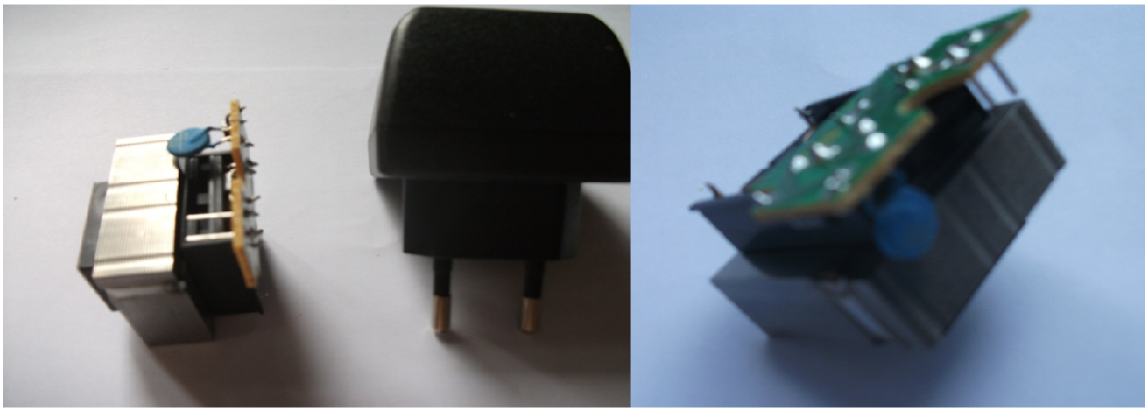

Figure 27: Linear-mode mobile phone battery charger, part 4

Manufacturer	Converting technology	Type of component	Weight (gram)
Nokia ACP-7 E	linear-mode	PCB with mounted components	133
Nokia	switched-mode	PCB with mounted components	21,1
Sony Ericsson	switched-mode	PCB with mounted components	38,2
Siemens	switched-mode	PCB with mounted components	21,5
Samsung Travel adapter	switched-mode	PCB with mounted components	14,6
Samsung SGH-250	switched-mode	PCB with mounted components	16
No name 1	switched-mode	PCB with mounted components	49,4
No name 2	switched-mode	PCB with mounted components	14,8
No name 3	switched-mode	PCB with mounted components	11

Table 16: Weight of PCBs with mounted electronics components

As can be seen from tab. 16, the linear-mode BC is significantly heavier compared to the switched-mode BCs. This noteworthy domination over the switched-mode BCs is due to the large size of the components used in the linear-mode BC (i.e. the transformer).

An important aspect that contributes to the BOM is presented by the cooling system of the EPS. As described above, EPS consist of many different electronic components such as resistors, capacitors, diodes, transistors, transformers and microprocessors mounted on a PCB and then enclosed within a support structure called chassis (DARNELL GROUP, 2011). The electronics components are the major source of heat in electronic systems. Since the level of integration in the electronic systems increases, more ICs are used to substitute the discrete components. ICs dissipate heat as they dissipate even more power at more and more voltages. In order to protect the components from damage and thermal runaway, the heat must be removed continuously. The generated heat is dissipated to the PCB and then conducted to the chassis, which is usually made out of aluminium. The chassis provides a low thermal resistance path to the heat sink which absorbs the heat from the component (EKTN, 2008). In addition, for the cooling of electronic components such as high-power semiconductor devices, heat sinks are applied. Usually, the heat sink is made out of a thermally conductive material such as copper or aluminium which is mounted on the IC.

3.4. Perspectives of the technology

Fig. 28 shows the amount of sold EPS (for 2005) characterized by their output power.

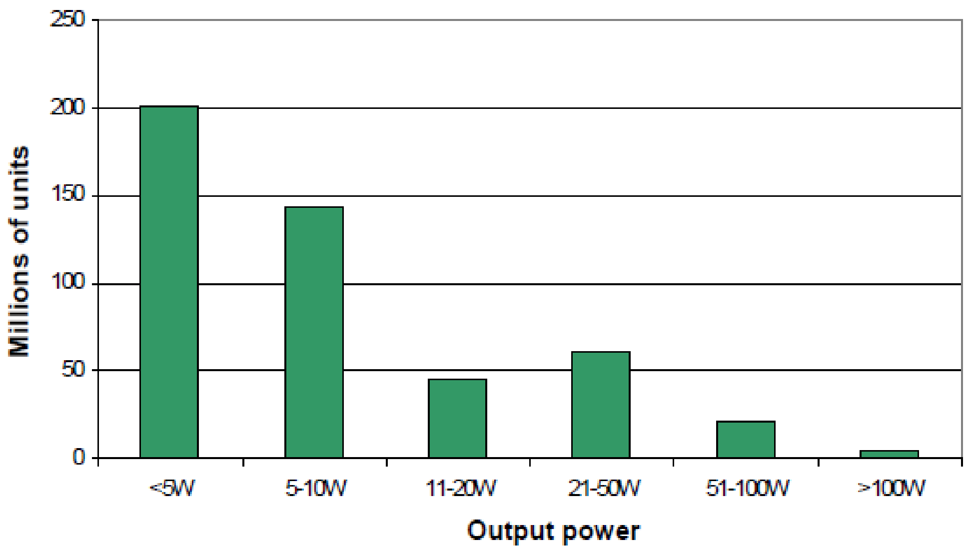

Figure 28: Distribution of European sales by output rating category, 2005 (source: MONIER et al., 2007)

As shown in fig. 28, the lower-wattage segment (from less than 5W to 10W) EPS hold the first place in the sales of EPS. However, MONIER et al. (2007) point out, that the higher-wattage EPS indicate growing tendency due to the increasing demand of high capacity notebooks.

Further, the share of linear and switched-mode technologies of the total sales is changing in aid of the switched-mode technology that accounts for about 24% of total EPS sales (in 2005). In addition, MONIER et al. (2007) estimated the EPS/BC stock on the base of sales data and average lifetime of the product. Tab. 17 and fig. 29 illustrate the results.

Application of the EPS	Sales (EU-25, 2005) [millions]	Lifetime [years]	Stock[8] (EU-25, 2005) [millions]
Mobile phone and portable audio/video	273	3	819
Notebook computers	20	5	99
Flat panel monitor	13	6	78

Table 17: EPS sold units in 2005 and the estimated stock of EPS (source: adapted from MONIER et al., 2007)

Reference year	1995		2005		2010		2020
CAGR %		9,4		9,4		5,0	
Stock (million units)	680		2080		2900		5000

Figure 29: Estimation of EPS/BC stock till 2020 (reference year 2005) (source: MONIER et al., 2007)

EPS and BC are sold together with end appliances. Due to changing consumer trends and technological innovations, the end appliances are being replaced at a faster rate. Because of compatibility reasons, the time in service (i.e. “active lifetime”) of the EPS and BC is restricted by the lifetime of the end product.

As illustrated in fig. 29, the EPS stock was estimated to rise with compound annual growth rate (CAGR)[9] of 9,4%. According to the above forecast, if the European EPS market continues to rise by 5%, the stock of EPS will reach 5000 million units in 2020.

In the last years, the power requirements for electronics equipment (notebooks and mobile phones) have increased drastically. Notebook computers and mobile phones are becoming constantly more functionally richer which has an impact on their growing power demand (FAIRCHAILD, 2004). In addition, battery capacities also increases as the charging requirements grow. As a consequence, EPS have to

[8] The stock is estimated on the basis of the sales in 2005 and the average economic lifetime (source: MONIER et al., 2007)

[9] The CAGR describes the rate at which an investment would have grown if it grew at a steady rate (source: INVESTOPEDIA, 2012)

operate with this twofold power increase; however, since there are demands concerning the overall minimization of the electronic products, bigger and heavier power supplies are not an option (FAIRCHAILD, 2004).

Further, as mentioned in 3.1 there are legal regulations, addressing the no-load and active efficiency of the EPS. Moreover, EPS for notebooks are not supposed to launch harmonics into the utility line (FAIRCHAILD, 2004).

Electronics manufacturing companies already introduced EPS that conform to the legal requirements and guidelines. These EPS minimize the power losses, have integrated PFC and achieve high efficiency (MONIER et al., 2007).

In general, there is a trend towards “ultra-minimization” of the EPS, for both high (more than 60W output power) and low power segment (<10W output power).

The Irish company “Commergy Ltd” introduced the “Breeze Lite Adaptor” (fig. 30) - a notebook EPS that utilizes a kind of topology that reduces power losses by 35%. Furthermore, the company achieved 35% size reduction, using 35% less plastics and cooper (MONIER et al., 2007).

Figure 30: Breeze Lite Adaptor (source: MONIER et al., 2007)

The manufacturing company FRIWO introduced in 2003 their EPS that uses flip-chip[10] technology for the packaging of the metal-oxide-semiconductor field-effect transistor (MOSFET), which is applied for the switching of the signals. The company uses MOSFET in a bare die version. Fig. 31 illustrates the comparison in the sizes of MOSFET in packaged and bare die version (MONIER et al., 2007).

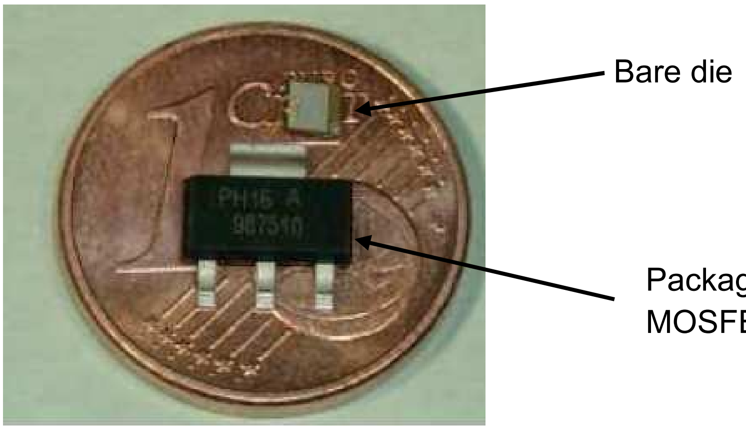

Figure 31: MOSFET for low power supplies in packaged and bare die version (source: MONIER et al., 2007)

[10] Flip-chip packaging technology is discussed further in section 4.2.1.

3.5. Recycling and reuse of EPS

As discussed above, EPS and BC are affected by the technological innovations. Due to the move away from the linear-mode EPS, the application of large transformers and capacitors is eliminated from the SMPS technology. It is argued that SMPS devices have smaller size and weight compared to the linear-mode EPS. In addition, as the technology develops, more integrated and miniaturized components are being applied.

Nevertheless, printed circuit boards (PCB) from external power supplies are characterized as low-grade (<200 ppm gold), consisting of low mass of valuable materials (GOOSEY and KELLNER, 2002). Theoretically, discarded PCBs from EPS can be processed, but this demands complicated dismantling processes, which is economically irrelevant, considering that concentrations of valuable materials are too low and too variable (LAMBERT, 2001).

With regard to the reuse of EPS, an opportunity is presented by the recently signed Memorandum of Understanding between the EC and fourteen electronics manufacturer. The agreement implies the harmonization for all EPSs for data enabled telephones and hence enables the reusability of the EPSs.

4. PRINTED CIRCUIT BOARDS

Printed circuit boards (PCB) are found in most electronics equipment. In general, a PCB accounts only for a limited percent of the overall mass of the equipment. Nevertheless its content of precious and special metals is responsible for the high intrinsic value of the boards (MESKERS et al., 2009; CHANCEREL, 2010). Precious metals (gold, silver and palladium) in PCBs are found as complex material mixtures contained in connectors, solders; in integrated circuits (ICs) and in the interconnecting layers (CHANCEREL et al., 2009).

Conventional PCBs are introduced at the beginning of this part. Recent developments in substrate, layers and interconnecting techniques are also highlighted. As next, the chapter handles the material content of PCBs identified in mobile phones, TV sets and laptops.

The technological progress inevitably affects also the field of microelectronics, posing higher standards for materials, cost and size of the electronics components. In the following, developments in the electronics packaging are discussed which are argued to have an impact on the material content, thus are expected to be interesting from a recycling point of view. Finally, the recycling of the PCBs is briefly outlined.

4.1. Characterization of PCB

A PCB is a platform which is used to mechanically support and electrically connect electronics components such as integrated circuits and other devices, using pathways (traces), etched from copper sheets and laminated onto an insulating substrate (LUDA, 2011). A PCB can be manufactured in through-hole technology (THT) or in surface mount technology (SMT).

From a recycling perspective End-of-Life PCBs are classified into three categories according to their inherent precious metal content – high-; medium-; and low-grade (GOOSEY and KELLNER, 2002). In general, End-of-Life PCBs are grouped according to the gold content (g/ton).

High-grade PCBs comprise more than 400 ppm gold. In general, high-grade PCBs are the PCBs consisting of the following elements: discrete components, gold-containing ICs, optoelectronic devices. Also gold pin and palladium pin boards and thermally coupled modules from mainframes belong to this category; medium-grade PCB contain 200-400 ppm gold and are found in personal computer, notebook computer and some mobile phones; low-grade PCBs contain less than 200 ppm gold. TV set and power supply unit PCBs having heavy ferrite transformers and large aluminium heat sinks, are classified as low-grade (GOOSEY and KELLNER, 2002; HAGELÜKEN, 2005).

Further, a common technical classification distinguishes the PCBs according to their substrate or the number of layers they have. In the following, a characterization of the different PCBs with the occurring innovations in the field will be introduced.

4.1.1. PCB substrates

The miniaturization and flexibility are becoming important part of the electronics today. PCB designers aim to implement substrates that can meet the requirements of modern electronics devices and meanwhile be in accordance with environmental regulations.

The PCB substrate determines the structure that physically holds the circuit components and printed wires and enables electrical insulation between the conductive parts.

Substrates can be rigid, flexible or combination of two. Mostly, printed circuit boards use rigid substrate (KOLLIPARA and TRIPATHI, 2005).

4.1.1.1. Rigid substrate

There are different rigid substrates available for the manufacturing of PCBs, including Teflon, ceramics and flame-retardant (FR) materials (MITZNER, 2009). The FR materials are mostly used. Tab. 18 illustrates the different dielectric materials used in FR substrates.

Flame-retardant	Type of dielectric material
FR 1 FR 2	Phenolic cotton paper
FR 3	Cellulose paper with epoxy
FR 4 FR 5	Resin epoxy reinforced with a woven fiberglass matrix

Table 18: Flame-retardant dielectric materials (source: Yamane et al., 2011, HISCHIER et al., 2007)

Commonly used types are FR1 and FR2 – both type use single layer of phenolic cotton paper coated with copper layer. FR2 is mostly used in television sets and household appliances such as personal computers (Yamane et al., 2011). FR3 uses cellulose paper with epoxy. FR4 and FR5 are flame-retardant composites of a resin epoxy reinforced with a woven fiberglass matrix (HISCHIER et al., 2007). FR4 is the most common rigid substrate and is used mainly in small devices e.g. mobile phones.

Metal-core boards are also boards using rigid substrate. They are used when a good thermal management of the circuit is required- for circuit boards integrated with power devices, such as power supplies and amplifiers, LED applications and TV regulators (YUNG, 2007). They consist of number of layers including a dielectric sandwiched between two metal layers. The metal layers are usually made of aluminium and copper, as of lately also iron and carbon are applied (YUNG, 2007).

4.1.1.2. Flexible and rigid-flexible substrate

As the technology develops and the miniaturization and higher integration are already custom, boards with mechanical flexibility, reduced size and weight and lower cost are explored. This can be achieved by using flexible and rigid-flexible boards.

Polyimide is the most common substrate for flexible and rigid-flexible boards. The structure is as follows - a flexible polyimide core is bonded with copper foil to both top and bottom sides. The outer rigid layer is made out of single-sided FR4 and is laminated to both sides of the flexible core (GALLANT, 2006). An alternative material for rigid-flex processing is a thin epoxy glass material. For the base core material, a glass prepreg is used, and then copper foil is laminated to form the inner layer (100 µm thick). Finally, this structure is encapsulated with polyimide film which allows the bending and flexibility of the board (KEATING and LARMOUTH, 1996). Other flex-materials include polyethylene naphthalate (PEN), polyethylene terephthalate (PET), polycarbonate (PC) and polyvinyl chloride (PVC) (KOSTELNIK, 2005).

The ever increasing requirements towards thinner and smaller PCB layout as well as growing performance expectations prompt the exploration of new substrate materials. In the last years a special research focus is put on the development of a flexible PCB substrate based on liquid crystalline polymers (LCP) (FRISK et al., 2010). Flexible LCP boards possess excellent thermal, mechanical, chemical and electrical characteristics and are believed to substitute which is substrate based on polyimide (KOSTELNIK, 2005).

4.1.2. PCB layers

Depending on the intended application, PCB can be single-sided, double-sided or multilayer. Single-sided boards have all of the components on one side. Single-sided boards usually use phenolic[11] or polyester resins with glass or paper reinforcement (KOLLIPARA and TRIPATHI, 2005). Double-sided boards have connections on both sides of the board. Multilayer boards consist of several thin etched boards or trace layers that are bonded together. Both double sided and multilayer boards are made out of glass-reinforced epoxy (KOLLIPARA and TRIPATHI, 2005). On fig. 32 and fig. 33 the cross-section of single-, double and multilayer PCBs is illustrated.

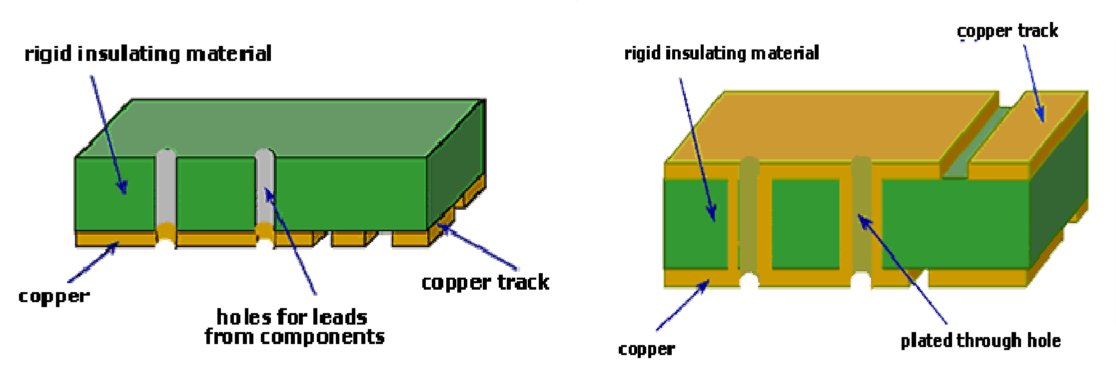

Figure 32: Cross-section of one- and double-sided PCB (source: UoB, 2012)

[11] **Phenolic resin** is a hard, dense material made by applying heat and pressure to layers of paper or glass cloth impregnated with synthetic resin (SDPLASTICS, 2012)

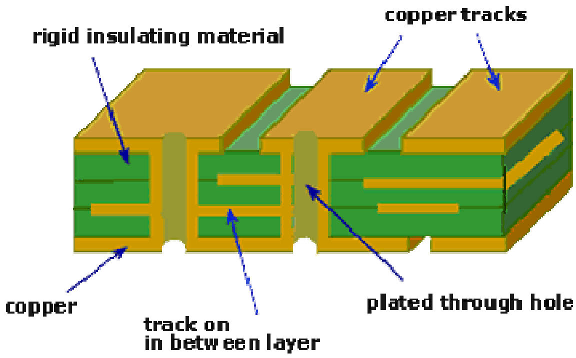

Figure 33: Cross-section of a multilayer PCB (source: UoB, 2012)

In general, the connection between the layers is accomplished through conductive holes filled with copper– the so called plated-holes (hole is the term when using through-hole technology) and plated-vias (vias is the term when using surface-mount technology) (AMBAT, 2006). To protect the copper from oxidation and to provide a good solderability, a finishing layer is plated on the copper base. For decades lead-finishing layers dominated the industry of electronics. However, since the introduction of RoHS Directive, the use of lead is restricted and now lead-free finishing layers are promoted. Lead-free finishing layers include plating of a few micron thick silver, nickel or tin coating on the copper base, followed by thin gold layer with thickness varying between 50 – 100 nm (AMBAT, 2006).

4.2. Electronic packaging

Until now, a PCB was regarded as a bare board, without the electronic components that that make the circuit fulfill its purpose.

Electronic packaging is an area in microelectronics that is experiencing tremendous development. Fundamental function of the packaging is to provide electric connections and to protect the chip against external stresses. In addition, it becomes a necessary technology for system integration (KESER et al., 2007).

Electronic packaging covers several levels, including chip interconnection technologies, package to board connections and multichip packages.
This chapter does not expatiate on all of the developments in microelectronics, but tries to outline these trends that could be of particular relevance for the reuse and recycling of the PCBs and the electronic components.

4.2.1. First level packaging

The first packaging level regards the interconnection between the die and its package. The main interconnection techniques commercially available are wire bonding and flip chip (RUIZ et al., 2007).

Wire bonding is the dominant technique. It is the primary method of making interconnections between the integrated circuit (IC) and the package lead frames or PCB substrate during semiconductor device assembly (IEP, 2011). It is used by 95% of the die mounted in multichip module or as single chip packages. As shown in fig. 34, the die is, firstly, attached to the substrate with an adhesive. As next its contact pads are connected to lead frames with wires with a diameter of 25-70μm and length between 1 and 5 mm (CLUFF and PECHT, 1999).

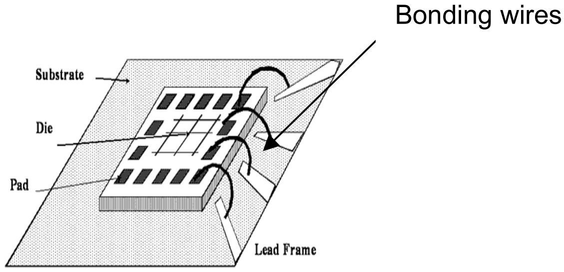

Figure 34: Wire bonding packaging technique (source: UoP, 2012)

Until now, gold has been mainly used for the wire bonds. Innovations in the ICs enable the substitution of gold with aluminum, copper, silver and nickel bonding wires (RUIZ et al., 2007). Copper wires show to have better material characteristics and electrical conductivity at room temperature than gold (RUIZ et. al, 2007). In addition, copper has a cost saving of more than 80% in comparison to gold wire. Nickel wires are also explored to replace gold wires, especially in power devices (CLUFF and PECHT, 1999).

Currently, polymer nanofibers with embedded oriented system of carbon nanotubes are tested with the aim to substitute the other wire materials. Carbon nanotubes have similar electrical conductivity as copper and have a potential to successfully create a new class of wiring materials (RUIZ, 2007).

With the development of smaller and cheaper electronics, there is a move away of the wire bonding. Considerable effort has been devoted to create direct chip attachment methods (IEP, 2011). **Flip chip** is a chip attachment technique that is most commonly used when there are requirements towards space and high number of chip connections. In general, components in flip chip are semiconductor devices.

However, there is a growing tendency for other components to be used in flip chip form, e.g. application-specific IC, chipsets, memory and microprocessors (IT, 2005).

The connection between the bond pads on the chip and those on the substrate is accomplished by bumps that have been deposited on chip's bond pads. The bumps are able to mechanically, electrically and thermally connect to the substrates. Bump sizes range from 90-125 microns in diameter. Fig. 35 illustrates the flip chip technique.

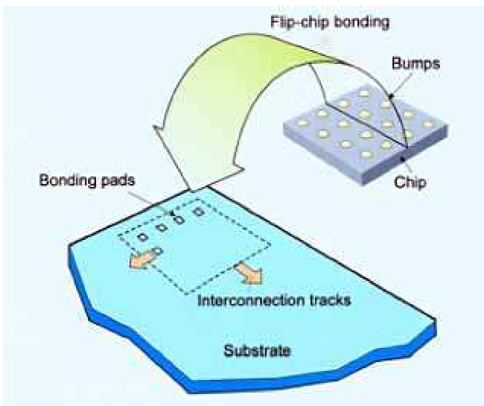

Figure 35: Flip chip technique (source: TWI, 2012)

Because of the absence of bond wires, the flip chip technique is the most space efficient and it features the smallest package size – it can reduce the board area by 95% and the weight of the package (weight can be less than 5% of packaged device) (RILEY, 2000). According to the exact flip chip technology, bumps are made out of aluminium, copper (underbump metallization), nickel or gold (LI et al., 2010).

According to CLUFF and PECHT (1999) flip chip packaging technique has less need for precious metals compared to the wire bonding technique due to the demise of the bonding wires. However, there was no data found about the material concentration of wire bonding and flip chip packaging techniques.

4.2.2. Second level packaging: package to board interconnection

The package to board interconnection represents the second level packaging.
There are two primary techniques used to connect the electronics component to a PCB. In the past, through-hole was the dominant assembly technology. Through-hole connections have straight pins on the package, which are inserted into holes in the PCB. A newer mounting technique is the surface mount technology (SMT). In SMT, the components are soldered directly to the surface of a PCB (KOLLIPARA and TRIPATHI, 2005). KOLLIPARA and TRIPATHI (2005) point out that using SMT instead of THT reduces the PCB size by 60%. In addition, SMT reduces the PCB weight as well as the number of PCB layers.

A recent advancement in the SMT is represented by the ball grid array (BGA) technique. BGA is used to connect the finished package to the PCB. Instead of pins, the BGA uses solder balls to connect to the PCB.

In fig. 36 a cross-sectional schema of a BGA assembly is presented.

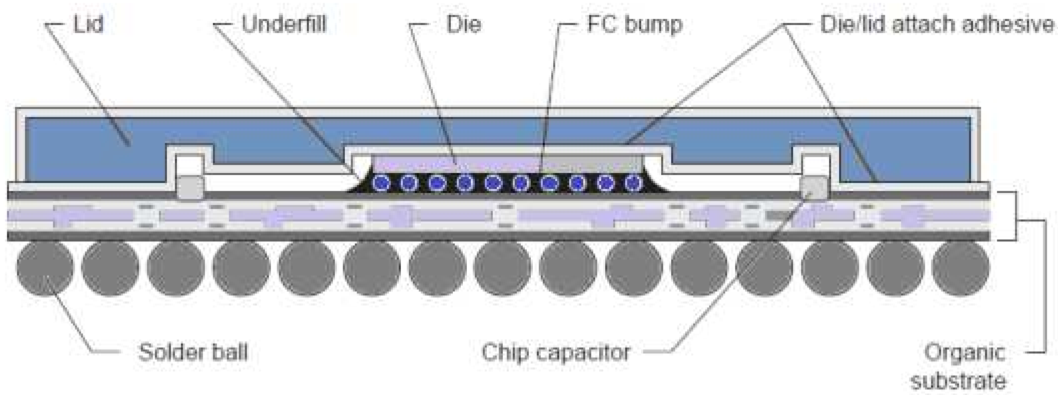

Figure 36: Typical Flip Chip BGA Package (source: TEXAS INSTRUMENTS, 2005)

The interconnection between the package and the PCB substrate is accomplished via solder balls. BGA is becoming the dominant attachment technology in modern electronics appliances, already being used in mobile phones and notebook computers. Since the RoHS Directive took an effect, the use of lead is restricted for the depositing of the solder balls. The compound, which is used now consists of 98,5% tin, 1% silver and 0,5% copper. The diameter of the balls varies between 0,1mm and 0,76 mm (KWAK and HUBING, 2007).

Major electronics companies are already implementing the BGA technology in their products. Fig. 37 illustrates the PCB with mounted electronics components of iPAD 3 (issue date March, 2012).

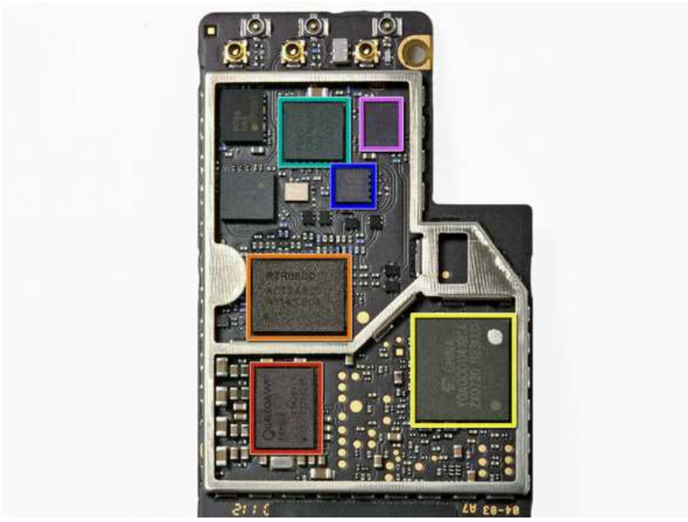

Figure 37: Disassembled PCB from iPAD (source: IFIXIT, 2012)

The elements on the iPAD 3 PCB are predominantly flip-chip BGA.

A major criticism towards BGA technology is that the IC's solder balls are inclined to the effects of aging and eventual failure of the connection (GOODMAN et al., 2007). In addition, to verify that the BGA IC is properly assembled, a visual inspection is demanded. Usually, such an inspection is very difficult to obtain and requires the use of X-ray transmission radiography or cross-section acoustic microscopy (C-SAM) (Ghaffarian, 2003).

4.2.3. Multichip packaging

Further miniaturization and higher integration of the electronics components is accomplished with the help of multichip packages (MCP). MCP contains two or more bare chips placed closely together on a multiconductor layer substrate to organize a multichip module (MCM). The MCM is then attached to the PCB either with wire bonding or flip chipped. Currently, the method of multichip integration, which is already introduced in the market, is the so called – three-dimensional (3-D) stacking or System in Package (SiP) technology (fig. 38).

Figure 38: 3-D stacking technology (source: PARK and MOLL, 2004)

The 3-D stacking of chips reduces the board area at the expense of vertical height. With the three-dimensional integration highly integrated systems can be formed by vertically stacking and connecting various materials, technologies and functional components together, including active as well as passive components (LANG, 2006). 3-D ICs has already found application in mobile phones such as in flash memories such and in NOR- and NAND[12] memories, as well as, in dynamic random-access memory (DRAM) (LU et al., 2012).

4.3. Material content

Circuit boards mirror the growing complexity of electronic devices. In 1980, PCBs consisted of 11 chemical elements; the content grew up to 15 elements in 1990. According to Nokia, nowadays in a single mobile phone, the amount of different components ranges between 500 and 1000 (OECD, 2010).

Special and precious metals are predominantly located in the PCBs. Usually the PCBs account for 10% of the overall mass of the equipment; nevertheless the precious (gold, silver and palladium) and special (indium, selenium, tellurium, tantalum, bismuth, antimony) metals are responsible for 80% of the intrinsic value of the boards (MESKERS et al., 2009; CHANCEREL, 2010).

A PCB can significantly vary in its material content according to the different appliances, manufacturers and age. A typical PCB from electronic equipment consists of components mounted on it, including integrated circuits (IC), connectors, capacitors, transistors etc. Different electronics components have a different material composition; hence it is complicated to analyze the PCB's general material composition with any great degree of accuracy. In general, PCBs with mounted electronics components are comprised of 40% metals, 30% plastics and 30% ceramics. For End-of-Life PCBs without mounted electronic parts, the material composition consists of approximately 28 mass-% metals (predominantly copper) and 72 mass-% non-metallic materials [i.e. 65 mass-% glass fiber, 32 mass-% epoxy resin and impurities (3 mass-% copper, <0,1 mass-% solder] (GUO et al., 2009; HONGZHOU et al., 2007).

Tab. 19 presents the estimation of precious metal content in the output of selected equipment (CHANCEREL et al., 2009).

[12] NOR- and NAND are types of memory technologies. The name NOR and NAND is derived from the Boolean algebra and refer to the type of logic gate used in each cell (source: TECHTARGET, 2012)

Equipment type	Amount in the input (kg/t)	PCBs in equipment type (mass-%)	Metal concentration in the PCBs (g/t of PCB)			Mass of metals in the input (g/t of input)		
			Ag	Au	Pd	Ag	Au	Pd
LCD monitor	10	4%	1,300	490	99	0.52	0.20	0.04
Laptop	5	15%	1,000	250	110	0.75	0.19	0.08
Mobile telephone	1	22%	5.540	980	285	1.22	0.22	0.06
Personal computer	210	13%	1,000	250	110	27.30	6,83	3.00

Table 19: Estimation of the content of silver (Ag), gold (Au), and palladium (Pd) in 1,000 kg of input (source: adopted from CHANCEREL et al., 2009)

Further, a comparison between the weight and value share of TV and PC boards and mobile phones was made. Tab. 20 shows the results.

mass-%	Fe	Al	Cu	plastics	Ag [ppm]	Au [ppm]	Pd [ppm]
TV-board	28%	10%	10%	28%	280	20	10
PC-board	7%	5%	20%	23%	1000	250	110
mobile phone	5%	1%	13%	56%	1380	350	210
Value share	**Fe**	**Al**	**Cu**	**sum PM**	**Ag**	**Au**	**Pd**
TV-board	4%	11%	42%	43%	8%	27%	8%
PC-board	0%	1%	14%	85%	5%	65%	15%
mobile phone	0%	0%	7%	93%	5%	0,67	21%

Table 20: Weight versus value distribution (source: HAGELÜKEN, 2006)

Although the weight of the precious metals in the appliances is less compared to the content of base metals (Cu, Al and Fe), for PC- and mobile phone PCBs the precious metals make up more than 80% and for TV-boards the precious metals contribute for 40% of the value (HAGELÜKEN, 2006).

Tab. 21 summarizes the results of different studies that compared the metals concentration in PCBs from WEEE.

Weight %	PARK and FRAY (2009)	YANG et al. (2009)	GUO et al. (2009)	GOOSEY and KELLNER (2002)	SUM (1991)
Silver	0.100	-	3300 g/t	0.05	0.2
Palladium	0.01	-	-	0.01	0.005
Aluminium	5.0	-	4.7	-	-
Gold	0.025	-	80g/t	0.03	0.1
Copper	16.0	25.06	26.8	16	20
Iron	5.0	0.66	5.3	3	8
Nickel	1.0	0.0024	0.47	2	2
Lead	2.0	0.80	-	-	2
Tin	3.0	-	1.0	-	4
Zinc	1.0	0.04	1.5	-	1

Table 21: Metal concentration (mass-%) of printed circuit boards reported in different works (source: YAMANE et al., 2011)

As tab. 22 illustrates, there is a variance in the material content from the different estimations. On the one hand, the comparison above is between PCBs from different equipment types. On the other hand, the samples of the analyzed equipment, therefore of the PCBs, have different manufacturing year, thus it can be expected that the trends of miniaturization already occurred in some of the equipments.

YU et al. (2009) estimated the metal content in a populated PCB. Tab. 22 illustrates the results.

Metal	**Concentration (Mass-%)**	**Metal price (2012) (€/kg)**	**Intrinsic value (€/1 kg PCB)**
Cu	**9.7**	**5,88**	**0.57**
Al	5.8	1,57	0,09
Ni	0.69	13,7	0.09
Pb	2.24	1,5	0.03
Sn	2.15	15	0.32
Ag	**0.06**	**743**	**0.44**
Au	**0.023**	**41.407**	**9.52**
Pd	**0.01**	**15.407**	**1.54**
Total	29.87		12.6

Table 22: Metal fraction in populated PCB (source: YU et al., 2009)

As it is demonstrated, 97% of the PCB intrinsic value lies in the content of copper, silver, gold and palladium. Moreover, gold has here the highest value with 76%.

However, through the implementation of the new packaging technologies a reduction in the precious metal content is achieved. Several studies focus on the trends towards the reduction in the size and material content in the electronics. In the following section, some of the findings with respect to these trends are presented.

4.4. Impact of innovations

Several authors emphasize the impact of technological innovations on the material content and concentration of precious metals in electronics equipment. In particular, the PCBs of mobile phones, personal computers, laptops and TV sets are of special interest. As shown above, these particular PCBs are mostly high-grade PCBs (more than 400g gold/ton) and thus have a special economical relevance.

TAKAHASHI et al. (2009) investigated the metals content of more than 100 mobile phones made between 1996 and 2008. After classifying the devices into eight groups in accordance to their level of functionality (from MP1 with basic functions to the category MP8 consisting of the phones with most functions), they dismantled each one of them. Through plasma optical emission spectrometry (ICP-OES and ICP-MS) the metal content was assessed. Via LCA the environmental and economic impact of the recycling was determined. In tab. 23, the metals found in the mobile phones are presented; in addition fig. 39 illustrates the metal content in each of the eight categories (TAKAHASHI et al., 2009).

Name of part	Detected element
Board	Au; Ag; As; Ba; Bi; Cr; Cu; Ga; Mn; Ni, Pb; Pd, Pt; Si; Sn; Ta; Ti; Zn; Zr;
Flexible substrate	Au; Ag; Cu; Pt
LCD	Au; Ag; As; Ba; Ca; Cu; In; Ni; Sb; Si; Sn
Motor	Au; Ag; Cu; Pt
Camera	Au; Cu; Ni
Speaker microphone	Cu; Mn; Zn

Table 23: Elemental analysis (source: TAKAHASHI et al., 2009)

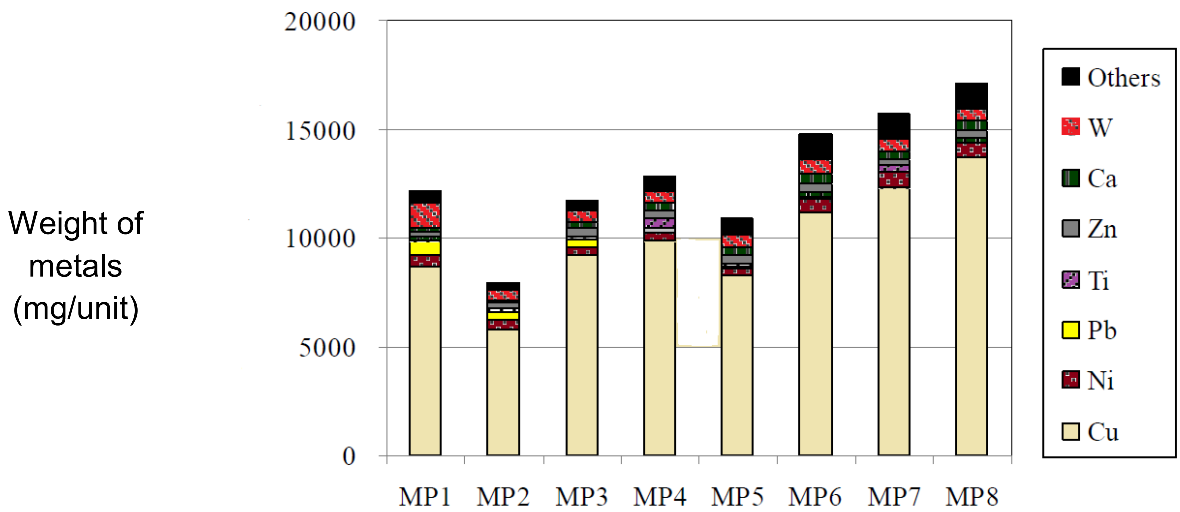

Figure 39: Metal content in mobile phones (source: TAKAHASHI et al., 2009)

The analysis shows that the amount of precious and rare metals increased as more functions were added to the device. In the latest models, copper is found to be the dominant metal followed by barium and nickel. Further, the average gold content was 44 mg, which is equivalent to 0,04 mass-% of mobile phone sets (TAKAHASHI et al., 2009). However, the gold content is found out to decrease gradually.

In the analysis, TAKAHASHI et al. (2009) identified the presence of wolfram (W) in the mobile phones. Wolfram is used as a substitution of gold in the surface material at the connection part of the phones. Connectors are used to connect one PCB with another PCB. Typical connectors consist of plastic housing with gold or wolfram coated contact part of an alloy metal (e.g. beryllium-copper, brass, phosphorus-bronze) (SINGHAL, 2005).

GEYER and BRASS (2010) analyzed the average mobile phone mass and gold content in models produced between 1992 and 2004. The trend of the decreasing gold content is illustrated in fig. 40.

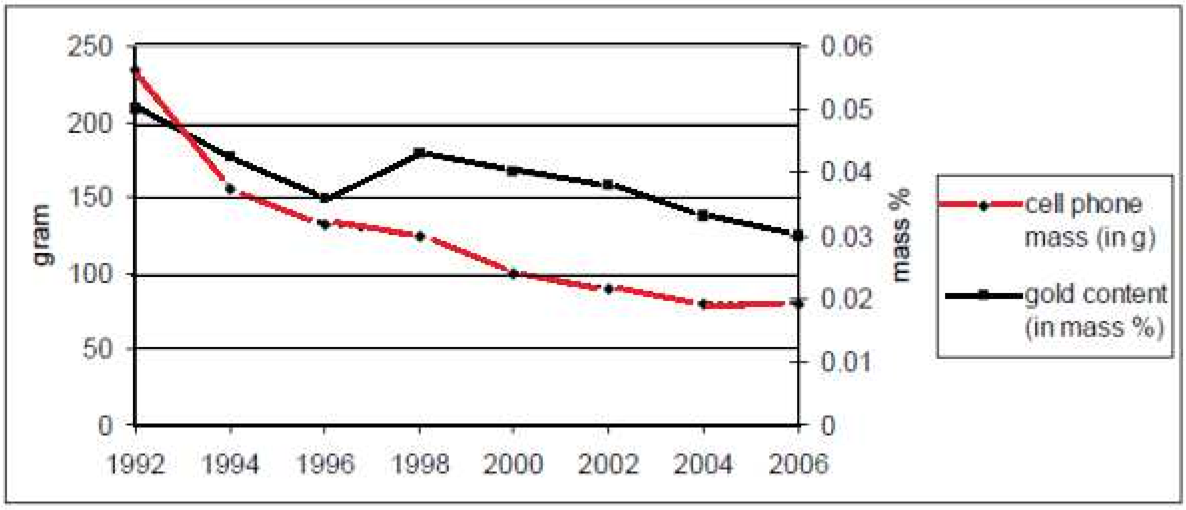

Figure 40: Mass and gold content in mobile phones between 1992 and 2006 (source: GEYER and BRASS, 2010)

The analysis indicates that the mobile phone mass leveled off threefold over the period of time - from 240 g in 1992 to 80 g in 2006. The gold content follows similar decreasing trend. If the average gold content amounted to 0,12 g in 1992, in 2006 it accounted for 0,02 g, which is a sixfold decrease.

YAMANE et al. (2011) compared the material content of two different kinds of PCBs – FR4 multilayer PCBs from mobile phones (MB) and FR2 single-sided PCBs from personal computers (PC). Firstly, the PCBs were introduced to mechanical processing, including comminution (the PCB PC were crushed to 2mm, the PCB MB to 4mm); particle size analysis; magnetic separation (the ferrous particles were collected via magnetic attraction, the non-ferrous were crashed in non-magnetic fraction by gravity); finally the non-ferrous metals were separated from the non-metallic fraction (e.g. polymers and ceramics) via electrostatic separation.

Aqua regia[13] leaching was used for the determination of the metallic fraction; in addition loss-on-ignition[14] was performed in order to determine the polymeric fraction of the PCBS. Finally, the metal concentration of gold, silver, iron, tin, copper, zinc, nickel, lead and aluminium were analyzed using inductively coupled plasma optical emission spectrometry (ICP-OES). For the analysis 10kg of samples of each type PCB were used.

The results of the metal concentration analysis are summarized in tab. 24.

Weight %	**PCB-MP**	**PCB-PC**
Silver	0.21	0.19
Palladium	-	-
Aluminium	0.26	5.7
Gold	0.00	0.13
Copper	34.49	20.19
Iron	10.57	7.33
Nickel	2.63	0.43
Lead	1.87	5.53
Tin	3.39	8.83
Zinc	5.92	4.48

Table 24: Metal concentration in mobile phone and personal computer PCBs after ICP-OES analysis (source: adapted from YAMANE et al., 2011)

The nickel concentration in the PCB-MB (2,6 mass-%) is found to be higher than in PCB-PC (1 mass-%). Nickel is used as a film under metallic contacts in phones, which can explain the higher concentration. Copper concentration was almost twofold higher in PCB-MP compared to PCB-PC. As mentioned above, PCB-MB are multi-layered, thus consist of more copper is deposited, in contrast to the single-sided PCB-PC where copper is deposited only on the surface. Zinc concentration are obtained in both types of PCBs. Zinc is used as a substitute of lead by soldering of the electronics components on the PCB.

Considering the precious metals, the total amount in the grounded material accounts for less than 0,2 mass-% - gold was found only in the PCB-PC and silver in both samples.

In addition, the results indicate that PCB-PC and PCB-MP are developing differently according to the concentration of the material composition. PCBs from mobile phones are composed of 63 mass-% metals, 24 mass-% ceramics and 13 mass-% polymers. On the contrary, PCBs from PC consist of 45 mass-% metals, 28 mass-% ceramics and 27 mass-% polymers. Further, the results show that copper concentration is increasing in MP-PCB and remaining constant in PC-PCB.

Because of the characteristics of each type PCB (higher copper concentration in PCB-MP and higher precious metal concentration in PCB-CP), the authors finally

[13] Aqua-regia (also called nitro-hydrochloric acid) is a highly-corrosive mixture of acids; it can dissolve some noble metals, gold and platinum (source: RSC, 2010)
[14] Loss-on-ignition is a test, commonly used test in the inorganic analytical chemistry for the determination (source: UCL, 2012)

recommend that the recovery goal should be different- for PC-PCB the main goal of the recycling process should be the recovery of precious metals, in contrast to the recycling of MP-PCB where the focus should be the recovery of copper. In addition, these PCBs should not be mixed before treatment (YAMANE et al., 2011).

HAGELÜKEN (2006) also emphasizes the impact of technological progress on the precious metals content in PCBs. According to him, the content is experiencing constant modification. Innovations and miniaturization of the equipment, respectively of the assemblies, lead to a growing tendency towards decrease in the absolute precious metals content (HAGELÜKEN, 2006). For example, the weight of a typical mobile phone (without battery and battery charger) in the 1990 was 298 grams; in 2000 it weighted 218 grams. In 2005, a typical mobile phone weight 113 grams (SULLIVAN, 2006). At present, the weight of a smart-phone varies between 107 and 130 grams.

Further, CUI and ZHANG (2008) pointed out that the concentration of non-ferrous metals and precious metals contents in the End-of-Life appliances is constantly declining. This is a result of the reducing power consumption of modern switching circuits and the rising clock frequency. In addition, 20 years ago the contact layer thickness varied between 1 – 2,5 µm. In modern appliances of today, it is between 300 and 600nm (gold wafer) (CUI and ZHANG, 2008).

4.5. Recycling of PCBs

Considering the twofold trend towards miniaturization and decrease of the precious metals content in the PCBs, an emphasis on the optimization of the recycling process chain, including preprocessing, recovery and disposal processes of the End-of-Life PCBs should be put (CHANCEREL et al., 2009).

By conducting a substance flow analysis (SFA), CHANCEREL et al. (2009) demonstrate that only 11,5 mass-% of the silver, 25,6 mass-% of the gold and palladium as well 60 mass-% of the copper attain output fraction for a potential recovery. It is argued that the size reduction of the PCBs during shredding has a direct impact on the concentration of the precious metals in the subsequent recovery fraction – compared to the pre-shredded PCBs (<8mm) the shredded PCBs (<2,5mm) indicate 62% less precious metals. The results suggest that a manual sorting for the removal of the most precious metal containing components should be implied before shredding. In addition, the implementation of more sophisticated preprocessing technologies that have special emphasis on the recovery of precious metals as well as metals with trace concentration should be considered (CHANCEREL et al., 2009). After the mechanical treatment a pyrometallurgical technology is traditionally used in order to upgrade the recovery of precious metals. The pyrometallurgical processing involves burning of the crushed PCBs in a furnace or in a molten bath and a subsequent retreatment and purification of the recovered materials via chemical processing (LUDA, 2011).

Currently, there are two state-of-the-art pyrometallurgical recycling plants in Europe (Umicore in Belgium and Boliden, Sweden) capable of recovering complex multi-metal combinations. They are able to recover both precious and special metals

(Platinum, Silver, Gold, Palladium, Rhodium, Ruthenium, Iridium, Copper, Lead, Tin, Bismuth, Selenium, Tellurium, Antimony, Arsenic, Indium, Nickel).

Another technology for the recycling of the PCB metal fraction is the hydrometallurgy. However, with hydrometallurgy the recovery of wide range metals is very complex and difficult to operate at an industrial scale (HAGELÜKEN and MESKERS, 2009). Usually, via hydrometallurgical processing focus on the recovery of selected metals and leave most of the special metals unrecovered (HAGELÜKEN and MESKERS, 2009).

5. REUSE OF ELECTRONIC EQUIPMENT

In addition to recycling, reuse is another option of the End-of-Life management of the electronics equipment.

Reuse is defined by the WEEE Directive as “any operation by which WEEE or components thereof are used for the same purpose for which they were conceived, including the continued use of the equipment or components thereof which are returned to collection points, distributors, recyclers or manufacturers” (WEEE, 2003).

As mentioned in section 1.4, in the WEEE Directive, the reuse and recycling targets are combined for each Member State. As a consequence, the reuse and recycling targets could be achieved only by recycling.

Reuse of electronic products is supplemented by the Waste Framework Directive (2008/98/EC). In particular, according to the waste hierarchy, reuse measures are given a priority over recycling. Fig. 41 illustrates the waste hierarchy.

Figure 41: Waste management hierarchy (source: WFD, 2008)

It is argued that reuse has many economical and environmental advantages, including decrease of waste generation and conservation of virgin materials and energy (CHANCEREL, 2010). Current reuse practices involve three different reuse alternatives of the electronic equipment – 1) reuse of working equipment; 2) reuse of equipment after repair and/or refurbishment; and 3) reuse of parts or components (CHANCEREL, 2010).

1) **Reuse of the working equipment** is the most efficient and environmentally sound way of treatment of End-of-Life equipment (KNOTH et al., 2005). However, reuse involves also some drawbacks. According to CHANCEREL (2010), when the waste electronic equipment is shipped from countries with developed waste collecting systems and recycling infrastructure to countries with lower environmental standards and weak waste management infrastructure both sides are imposed to some disadvantages.

On the one hand, by exporting the electronics equipment, valuable resources are being lost for the domestic economy. On the other hand, at some point the reused equipment reaches its final stage of life. When they are not properly treated (in countries without proper waste management practices) hazards to human health and environment are posed (CHANCEREL, 2010).

2) If the equipment is declared as feasible for reuse, it is prepared for **repair and/or refurbishment**. Missing parts of the equipment are replaced, scratches are removed and the product is ready to be reused (KNOTH et al., 2005).

3) The third alternative involves the **reuse of parts and components**. Regarding a PCB, dismantled components could be applied in new products with the same application or in a different one. Furthermore, parts or components could be used as spare parts in e.g. repairing shops (EFSOT, 2012).
However, the reuse of components has some bottlenecks. Firstly, there is a bad image of the reused components because of the uncertainty about their life span and reliability during the second use time. Additionally, because of the technical and the quality reasons, electronics components are not accepted back by the electronics industry in order to be applied in new products. There are no agreed quality standards for the recovered components (EFSOT, 2012).

The disassembly could also be an obstacle for the components reuse – in general product design does not allow easy, fast and efficient disassembly of the discrete components. For reuse purposes, the disassembly process of electronics components from a PCB includes three actions - identification of the components (through visual inspection or automatic comparison of the codes of the elements on the PCB with a database). For the desoldering and removal of the components two alternatives are possible – the traditional manual removing or desoldering with the help of infrared radiation, hot gas or vapor (EFSOT, 2012). For the removal of components using the BGA packaging the only possible methods is the use of specialized equipment as infrared radiation, hot gas or vapor. Fig. 42 illustrates the infrared and vapor techniques for the desoldering of BGA components.

Figure 42: Desoldering techniques for BGA components – infrared radiation (left) and vapor (right) (source: DCE, 2012)

A critical aspect is the prevention of a thermal shock (i.e. high temperatures) when desoldering the components, because the die could be damaged if exposed to higher temperatures. The last step involves the quality control. Important aspect here is that the packages and the connection lead should not have been damaged. Leads have to fulfill co-planarity[15] requirements. Usually, a visual inspection involves a scanning electron microscope (KEY et al., 2009).

[15] Co-planarity is a measurement of the distance between the highest and lowest lead and the surface. Co-planarity is critical for good solder fillets; even if one lead is significantly higher or lower than the plane, it could lead to open solder joints (source: SAMTEC, 2012)

6. SUMMARY AND DISCUSSION

In the chapters above, the technological innovations in the selected electronics equipment have been discussed. In order to identify the impact of the innovations on the recycling, the material content of the equipment was analyzed, including the valuable as well as the hazardous materials. In addition, the revenues from the recycling of the mass-relevant materials were calculated and compared to the value of materials in low concentration.

In the following part, a brief summary is presented with a link to the expected impact of the innovations on the recycler and disassembly.

6.1. Cathode ray tube

Flat panel displays (FPD) demised the CRT technology that has been dominant for many years. According to the conventional recycling, at the End-of-Life stage CRT-glass has been closed loop processed and reused for the production of new CRT as a raw material thereafter. However, because of the rapid market penetration of FPDs, the demand for new CRT glass has sharply decreased. According to MICHELS et al. (2010), the peak in CRT arisings is expected to occur between 2012 and no later than 2018. Until now, only 20% of the EOL CRT glass has been open loop recycled. Assuming the decreased demand for the new CRT glass in Europe and the high costs of shipping the CRT to Asia, the recycler will be enforced to find alternatives and new applications for the CRT-glass.

6.2. Liquid crystal display

LCD displays have entered the TV-set and computer market since many years. Nowadays they hold the dominant position in the TV-, notebook and mobile phone industry. As mentioned in section 2.2.1., LCD monitors are non-emissive, thus they need a backlight as a light source. Cold cathode fluorescent lamps (CCFL) have been the primary backlight technique which is used for many years. Currently, light emitting diodes (LED) are increasingly implemented as an alternative backlight source and are expected to become the dominant backlight technology for LCDs, not later than 2012 (MCDONNELL and WILLIAMS, 2010). From the End-of-Life perspective, the substitution of CCFLs with LEDs is not only advantageous because of the absence of mercury in the lamps, but also LEDs don't tend to break so easily as CCFLs, thus do not endanger the working environment at the recycling plant. The LEDs are semiconductor devices that contain metals such as gallium, indium and arsenic as well as a combination of rare-earth metals such as Scandium (Sc), Cerium (C) and Yttrium (Y) in the phosphors. In a white LED (one mm²) the content of indium amounts to 0,17mg and that of gallium to 0,53mg (ANGERER et al., 2009).

At the moment, there is no experience with recycling LEDs. According to the current state of knowledge, recycling and recovery of the core semimetals as well as of rare-earth metals are not economically viable yet (IRREK and BARTHEL, 2010).

6.3. Mass-relevant materials versus materials with low concentrations in CRT and LCD equipment

End-of-Life PC monitors and TV set displays fall under the legal regulations of the WEEE and RoHS Directives.

As discussed previously, the CRT and LCD equipment belong to equipment categories 3 (IT and telecommunications equipment) and 4 (Consumer equipment) of the WEEE Directive, hence the recovery targets for both type appliances amount to 75% and those for reuse and recycling to 65%.

CRTs and LCDs are composed of materials in different mass-%. In both, CRTs and LCDs the plastics fraction has a significant share. Current state-of-the art recycling methods are capable of recycling glass and metal fraction, however in order to achieve the recovery and recycling targets, the plastics fraction should also be considered for treatment.

As the case of LCD equipment, current recycling practices focus only on the recovering of the mass-relevant fractions (ferrous and non-ferrous metals, glass plastics and PCBs). Nevertheless, LCDs contain valuable resources in small concentrations (indium in the form of indium tin oxide, as well as gallium and some rare earth elements in the LED backlight) which is at the moment not being recovered due to high recovering costs and still low cost of the virgin resources.

In the following, the recycling of plastics from CRT and LCD appliances is being summarized as well as an assumption of the average revenues from plastics recycling are given. Additionally, the average value of indium in LCD appliances is given.

6.3.1. Plastics from CRT and LCD appliances

As discussed in the previous chapter (2.1.2.2 and 2.2.2.5), CRT and LCD equipment have complex structure and material composition. Regarding the CRT equipment, the share of plastics in monitors accounts for 17,5 mass-% and in TV sets for 16,5 mass-%. LCD appliances contain 30 mass-% plastics. In order to achieve the recovery (75%) and recycling and reuse (65%) targets determined by the WEEE Directive, the plastics fraction should also be implied in the recycling.

A main drawback for the recycling of plastics is the presence of the brominated flame retardants and more precisely the content of polybrominated diphenyl ethers (PBDE) (Deca-, Penta- and OctaBDE) and of polybrominated biphenyls (PBB) (SCHLUMMER et al., 2007). The presence of these flame retardants has an incline to the formation of the highly toxic and in the environment persistent polybrominated dibenzodioxins and dibenzofurans. With the introduction of the RoHS Directive in 2006 the PBDE and PBB have been restricted and since then the Member States have to make sure that the new marketed electronics appliances do not contain these hazardous substances above the defined maximum concentration values of the RoHS Directive.

However, in a comparison study WÄGER et al. (2010) investigated the flame retardant concentrations in CRT monitors and TV sets as well as in LCD appliances. The results indicate that in CRT monitors the concentration of OctaBDE (in ABS) and in CRT TV sets the concentration of DecaBDE (in HIPS) exceeds the MCV of the RoHS Directive. In contrast, in LCD appliances the concentrations of PBDE and PBB are found to be RoHS conform. The absence of hazardous substances in LCD in contrast to the CRT equipment is an important aspect regarding the potential of plastics recycling.

Main drawback for plastics recycling is the presence of hazardous substances that require more sophisticated treatment practices, inclusive identification of the polymer types as well as of halogens and cadmium. Further, the contaminants could be extracted from the plastics, however such practices are still in research and development phase. An alternative treatment for the plastic fraction includes thermal treatment in municipal solid waste incinerator with energy recovery or in cement kilns. However, regarding the incineration alternative, it has to be made sure that the incinerator plants have state-of-the-art off-gas cooling and they are operated at optimal incineration conditions in order to avoid the formation of polybrominated dibenzodioxins and dibenzofurans (SCHLUMMER et al., 2007).

The relevance of the absence of flame retardants (FR) as well as of other hazardous substances in the plastics is pointed out by SALHOFER et al. (2012). It is found out that the recycling of the FR-free ABS, ABS/PC and PMMA has a substantial market potential. The revenues from the recycling of the plastic fraction amounts to 613, 9 €/t LCD monitors and to 347 €/t LCD TV sets.

6.3.2. Other mass-relevant materials in LCD equipment

Additionally to the high share of plastics, LCD equipment contains approximately 41 mass-% steel and 3 mass-% aluminium. The PCBs make about 10 mass-% of the total weight of the equipment. Tab. 25 illustrates an estimation of the revenues from steel, aluminum and PCB recycling of LCD monitors and TV sets.

Material	TV LCD concentration mass-%	Monitor LCD concentration mass-%	Price of secondary row material (2012) €/t	Revenu e TV (€/t)	Revenue monitor (€/t)
Steel	41	38	100	41	38
Aluminium	3	2	500	13	10
PCB	10	14	3000	300	420

Table 25: Mass-relevant materials in LCD TV set and monitors (source: BÖNI and WIDMER, 2011)

Considering the secondary row material prices of the respective materials, a total revenue from the three fractions amounting to 354 €/t from LCD TV sets and 468 €/t from LCD monitor is estimated.

6.3.3. Materials in low concentration

As discussed in a previous section (2.2.2.3), transparent indium tin oxide (ITO) layer is used in the LCD panels to control the liquid crystals (BÖNI and WIDMER, 2011). ITO consists of up to 78 mass-% indium. According to the estimation of indium concentration in an LCD equipment, the average indium content in LCD monitor (21'') amounts to 0,72 grams and in LCD TV set the average content amounts to 2,26 grams (ANGERER et al., 2009).

In fig. 43 the historical development of indium prices is presented (BLOOMBERG, 2012).

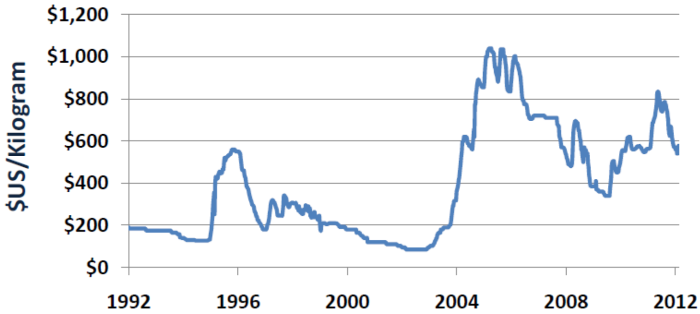

Figure 43: Historical indium prices 1992-2012 (source: BLOOMBERG, 2012)

The average indium price for 2012 was approx. 600 USD (464,5 Euro) per kilogram. Assuming that the average weight of 21'' LCD monitor is 7 kg and that of 40" TV set is about 10 kg, then the average content of indium in LCD monitors amounts to 103 gram/ton. The average indium content in LCD TVs amounts to 226 gram/ton.

Considering the average indium content in LCD monitor and in a TV set as well as the indium price in 2012, the indium value in a ton monitors amounts to 47,8 €/ton. In LCD TV sets the indium value is about 104 €/ton.

Currently, indium is not being recovered yet. The low indium concentration in an appliance and hence the value of indium per ton make the recycling of indium economically unviable. However, as can be seen from fig. 44 the indium price follows an increasing trend.

In addition, indium represents an important resource for the next generation technologies, not only being used for ITO, but also in photovoltaic panels and white LEDs. Tab. 26 illustrates the estimated static life of indium reserves and resources with reference year 2007.

<table>
<tr><th>Productuion in t (2009)</th><td colspan="4">600</td></tr>
<tr><th>Reserves in t (2007)</th><td>11.000</td><th colspan="2">Resources in t (2007)</th><td>16.000</td></tr>
<tr><th>Reserves-to-production ratio</th><td>18 years</td><th colspan="2">Resources-to-production ratio</th><td>>25 years</td></tr>
<tr><th>Reserves regional concentration (2007)</th><td colspan="4">China: 73%
Peru: 3%
USA: 2.5%</td></tr>
<tr><th>Next generation technology</th><th colspan="2">Demand 2006 in t</th><th colspan="2">Demand 2030 in t</th></tr>
<tr><th>Thin-film Photovoltaic</th><td colspan="2">1</td><td colspan="2">285</td></tr>
<tr><th>ITO (Displays)</th><td colspan="2">230</td><td colspan="2">1.580</td></tr>
<tr><th>White LED</th><td colspan="2">3</td><td colspan="2">46</td></tr>
<tr><th></th><td colspan="2">234</td><td colspan="2">1.911</td></tr>
</table>

Table 26: Estimation of indium reserves and resources in tons (2007) (source: adapted from LUTZ, 2010)

Considering that indium is a scarce resource (reserves in 2007 amounts to 16.000 t), the absence of virgin indium in Europe as well as the rising indium demand in the next decades (from 234 tons in 2007 to 1.911 tons in 2030), it would be important to put more effort in the development of economically viable and environmentally sound indium recovering methods.

The limited reserves-to-production, resources-to-production ratio as well the volatile indium's price fluctuations motivated the search for ITO alternatives. Current research focuses on Antimony tin oxide (ATO), carbon nanotubes and conductive polymers such as poly-3, 4-ethylenedioxythiopene (PEDOT). Carbon nanotubes are seen as the big opportunity for a wholesale replacement of ITO because of their excellent electronic properties (NANOMARKETS, 2010). However, little is known about the behavior as well as environmental, health and safety impacts of carbon nanotubes at their End-of-Life stage.

There are research initiatives (e.g. RECYTUBE with project duration 2010-2013) that focus on the reusability and recyclability of nanotubes. As the project reaches its end stage, more information will be available for the characteristics of nanotubes in regard to their End-of-Life stage.

6.4. Organic light emitting diodes and flexible displays

Flexible displays and OLEDs have found already their way into the FPD market and are expected to become a main competitor to the LCD panels in the near future. The device architecture consists of many jointly laminated plastic layers. Little is known about recycling practices of flexible displays and OLEDs. Because of their multilayer plastic structure, it is assumed that a mono-material separation will be currently hardly accomplished with the current state of the art recycling methods. However, the issue of OLEDs recycling was not found to be called yet.

However, OLEDs don't use a backlighting due to their self-emissive nature, thus there are no hazardous materials expected in the equipment (e.g. OLEDs and flexible displays are mercury-free).

Like LCDs, OLED displays also use one or two layers of indium tin oxide (ITO) for the transparent anode. Large OLED displays are predicted to become the dominant technology for large display applications no later than 2018. It can be assumed that by then the recycling of OLEDs and recovery of indium will be largely improved or the substitutes for ITO would be available on the market (e.g. carbon nanotubes).

6.5. Power supply units

From a recycling point of view, the most relevant developments in the power supply units are twofold. On the one hand, as described in section 3.2.1, the changeover from linear- to switched-mode converting technology requires more complicated circuit with higher amount of electronics components. On the other hand, the switched-mode EPS operate on much higher frequency, thus the size of transformer and capacitors is incomparably smaller.

EPS are characterized with low mass of valuable materials (their printed circuit boards are defined as low-grade). Moreover, a disadvantage to the recycler is the time to dismantle a power supply unit in order to reach the circuit board.

6.6. Printed circuit boards and packaging techniques

PCBs are electronic components that are present in almost all electronic equipment. PCBs can be differentiated according to the substrate they use (rigid or rigid-flexible) as well as regarding their layers – single- or double-sided or multilayer. With respect to the material composition of populated PCBs they are comprised between 30 and 40 mass-% metals, 30 mass-% plastics and 30 mass-% ceramics (GUO et al., 2009; HONGZHOU et al., 2007).

In general, PCBs account for approximately 10 mass-% of the equipment; nevertheless, they are valuable sources for precious and special metals.
With respect to the metal fraction, PCBs consist of precious and special metals in different concentration. Precious metals can make up between 80% and 90% of the total economic value of PCBs in personal computers and mobile phones. PCBs from TV sets impart for 40% of the value of the PCBs (CHANCEREL, 2009). The metals with the highest value are found to be gold, silver, palladium and copper. In particular, gold was regarded as the metal with the highest value, making up to 76% of the total PCB value (YU et al., 2009). As a result, these four metals are the target metals for the recovery.

However, the innovations in PCBs and packaging techniques show clear trend towards miniaturization, system integration and decrease of the overall material content. In particular, the innovations strive at the substitution or reduction of gold. Regarding the first level packing, i.e. wire bonding and flip chip techniques, there is a general tendency towards substitution of gold. In case of wire bonding, the gold wires are being substituted with aluminium or nickel wires. In addition, wires made of carbon nanotubes are being tested as a substitute (CLUFF and PECHT, 1999; LI et al., 2010).

The flip chip packaging allows further miniaturization of the package. Moreover, the gold solder balls, which are used to connect the chip to the package, are being replaced with aluminium, copper or nickel (CLUFF and PECHT, 1999).

Regarding these trends, future PCB recycling and precious metal recovery will have to consider more sophisticated metal recovering technologies. Manual separation of the PCBs, shredding the PCBs at size that does not impact the concentration of precious metals in the subsequent recovery fraction should be taken into consideration. In addition, technologies that emphasize the recovery of precious metals as well as of the metals with trace concentration should be implemented (CHANCEREL et al., 2009).

6.7. Reuse

Regarding the steadily increasing amounts of WEEE, the reuse of electronic equipment and electronic elements becomes a key part of the End-of-Life solution toolkit. Emphasis on reuse is put through the national implementation of the WEEE

Directive that sets up reuse and recycling targets for IT and telecommunications equipment (category 3) as well as for the consumer equipment (category 4). Further, reuse is a core objective in the Waste Framework Directive. Moreover, according to the waste framework Directive, reuse should be given the priority over the other waste management alternatives (WFD, 2008).

As discussed in the earlier section 6.7, reuse concerns three different options – reuse as whole equipment; reuse of the equipment after repair or refurbishment; or reuse of electronic parts or components (KNOTH et al., 2005).

In general, the innovations that occur currently in the electronics equipment and components do not foster their reusability. However, an important aspect, concerning the innovations in the EPSs, is presented by the agreement of the manufacturers to harmonize the EPS for all data enabled mobile phones. Contemporary, EPSs are personalized and sold together with notebooks and mobile phones. Hence, their lifetime is mostly restricted to that of the end-appliance they are sold with. The harmonization would give opportunity for the reusability of the EPS and for the extension of the EPS' active life time as long as they are technically intact (MONIER et al., 2007).

With respect to the reuse of electronic components, the innovations in the packaging technologies pose some drawbacks to their large scale reuse. In order to reuse the electronic components, firstly they have to be desoldered. Current innovations in the packaging involve the substitution of through-hole technology (THT) and surface mounted technology (SMT) with the advanced ball grid array (BGA) packaging (KOLLIPARA and TRIPATHI, 2005; KWAK and HUBING, 2007). BGA elements use small solder balls instead of pins. In order to prepare them for reuse, the BGA elements have to be desoldered and this is only possible with specialized equipment – infrared radiation, hot gas or vapor. Additionally, after the BGA removal, a visual inspection via X-ray transmission radiography or cross-section acoustic microscopy (C-SAM) is required in order to prove the quality of the component (GHAFFARIAN, 2003).

7. RECYCLING AND REUSE IN PRACTICE

In the literature review above the latest technological trends and innovations in the field of consumer electronics and microelectronics were outlined. In order to gather more in-depth knowledge about the impacts of the innovations in electronics on the recycling and reuse, expert interviews were conducted within Mai 2012.

7.1. Research method

The research method chosen to gather details on the topic was a qualitative expert interview.

Qualitative interviews are part of the qualitative research methods. The interviews are classified according to their structure. An open interview follows a free format and gives an opportunity of choosing the interview direction. Structured interviews involve a list of predetermined questions about a selected topic. The structure of the semi-structured interviews is in-between of open and structured interviews – it has a "schedule in mind" and at the same time the interviewee has the opportunity to answer freely (for more details on qualitative research methods, see BOGNER et al., 2005; POPOVA, 2010).

In order to be able to gather unexpected and new information, the research method chosen for this master thesis was the semi-structured interview. Questionnaires with open questions were defined, in order to obtain more detailed information based on personal experience (POPOVA, 2010).

The selected interview partners are experts with many years practical experience in the field of recycling and reuse of WEEE. The experts can be divided into the following two groups – experts belonging to a recycling facility (1) and experts belonging to a dismantling and reuse facility (2).

Interview partner from the recycling companies include:

Dipl. Ing. Barbara Pramreiter, MBA – operator of the recycling facility at Maculangasse, Saubermacher Dienstleistung AG, Vienna;

Franz Neudorfer, MBA – managing director of STENA Technoworld GmbH, Stockerau, Austria. STENA Technoworld is a part of the Stena Metall Group, a Sweden family owned group, operating at international level. The facility in Stockerau operates in the field of WEEE dismantling. After the WEEE disassembly, the fractions are subsequently processed in other STENA' facilities in Europe;

Mag. Alfred Ledersteger – active in the management of materials flow and recycling, Saubermacher Dienstleistung AG, Feldkirchen bei Graz;

Dipl. Ing. Markus Spitzbart from D.R.Z Wien was the interview partner. D.R.Z Wien is a facility, acting in the field of dismantling, recycling and reuse of WEEE.

7.2. Research process

The interview process can be classified in the following four parts:

1. **Theoretical analysis and creation of the questionnaires** - after the literature on the topic of innovations in electronics was examined, two questionnaires, concerning recycling and reuse of electronics equipment were constructed. Each questionnaire consisted of seven open questions. The questionnaires are included in the appendix.
2. **Expert research and contact** - in order to schedule a date for the personal interview, the experts were researched and contacted via telephone or Email.
3. **Interview** - A total of four persons were interviewed. The interviews took place within the premises of their facility. One interview was conducted via phone call. The interviews lasted approximately 30 minutes.
4. **Summary of research** - The findings of the research are summarized in the next section.

7.3. Findings

In the following, the findings from the semi-structured interviews are presented. Below each question the gathered information is summarized.

What recycling method do you use for flat panel displays (especially for the CCFL's disassembly and treatment? How do you process the liquid crystals? Do you recover indium from ITO? How do you evaluate the substitution of indium with carbon nanotubes and PEDOT?

The facilities that have been visited use dry processing[16] for the LCD treatment. The LCD panel is being crushed and subsequently sorted into separate fractions – ferrous, non-ferrous (aluminium, plastics, PCBs) and powder (fluorescent powder, glass dust and metal dust). In order to ensure that no mercury emissions are being released, the facility is maintained under negative pressure.

With respect to indium recovery, the findings indicate that indium is not being recovered at the present moment. The substitution of indium with carbon nanotubes or indium is still in its research phase, hence there is no experience with its impact.
Furthermore, it has been revealed that liquid crystals from LCDs are not being recovered yet.
At the moment, the plastics from the LCD equipment represent the most valuable resource for the recyclers.

Have you had experience with OLED technology and how do you process OLEDs?

Equipment based on OLED technology is not being observed at the waste stream yet. In general, little is known about OLEDs and their recycling possibilities. As the technology becomes more present at the market and subsequently more OLED

[16] The processing is being realized in the so called "Blubox" (more information can be found on the manufacturer internet site: http://www.blubox.ch)

equipment reaches its End-of-Life phase, it will motivate research initiatives in order to gain more in-depth knowledge about this kind of technology and its processing.

How does the technological changeover in the display technologies impact their recycling? Do the innovations in the materials' content facilitate the recycling?

The innovations in LCD backlighting, namely the substitution of mercury containing CCFLs with LEDs are considered as favorable and has twofold benefit. The absence of hazardous materials in the equipment represents a main advantage, considering that the contamination risk for the employees and the environment is therefore excluded.

Furthermore, the disassembly is accomplished at faster rate; hence the processes have enhanced efficiency.
However, the introduction of LEDs will pose new challenges to the materials' recovery. Due to financial reasons, at the moment, LEDs are not being recycled in order to recover metals, e.g. indium, gallium and some rare earth metals.

With respect to newer display technologies, i.e. OLED and flexible displays, it is expected that, due to their complex multilayer structure, a mono-material separation and recycling would bring some disadvantages. In general, more research in the field is needed.

Can further miniaturization make recycling uneconomical?

Miniaturization affects the absolute precious metal content and also involves the use of multiple different materials. The interview findings indicate that the miniaturization decreases the level of recycling. The trend towards continued size reduction of equipment (elements and subassemblies) complicates the disassembly and the subsequent recycling.

Is there any industry trend for reducing the valuable materials in the electronics equipment?

In general, there was not much input provided on this subject.

From a recycling point of view which End-of-Life solution is more economically and environmentally friendly – reuse or recycling?

In general, recyclers are not interested in End-of-Life options deviating from recycling. When the equipment is exported out of the European borders and reused in countries with lower waste management infrastructure, valuable resources are being lost. In addition, the subsequent processing of reused equipment in respective countries poses environmental drawbacks.

Which are the target metals from the printed circuit boards' recycling?

Currently, gold, silver, palladium and copper are the metals that are being mostly recovered from the PCBs.

Are there any measures that could be launched in order to enhance the reuse of electronics?

A modular design would not only enhance the disassembly efficiency, but more importantly would promote better refurbishment and higher reuse opportunities for the product, thus will prolong the product use phase and deviate it from the waste stream. In addition, equipment constructed with modular design can be easily prepared for reuse. In this respect eco-design should be promoted and made compulsive for the manufacturers.

How feasible is refurbishment and what is the life expectancy of a refurbished device (phone, TV set, laptop)?

The design of electronics doesn’t allow easy refurbishment and preparation for reuse. There are too many screws and the manufacturing involves many glues and fixing tapes that make the removal of the different elements difficult.

What is the impact of the innovations in electronics packaging on the reuse of electronics components?

Not much input could be revealed on this subject.

How do you estimate the consumer’s inclination towards reused electronics components?

In general, the consumer’s inclination to chose in favour of reused products is determined by the market price of new equipment. When refurbished equipment reveals similar prices as the new one, then it is more likely that the consumer will prefer the new one. However, there is an enhanced potential for reuse when the equipment is high-value. It has been disclosed that some consumer prefer to buy the reused equipment that has a higher value than a new one with lower value.

Are there any drawbacks in the electronics components disassembly that can make reuse technically unreliable or uneconomical?

In general, the way how electronics equipment is constructed today makes the disassembly difficult. Furthermore, electronics equipment becomes more complex, hence in order to replace a component particular knowledge and experience is demanded.

How does the miniaturization of the electronics components impact their reuse?

Theoretically, the miniaturization presents no difficulty for the reuse of electronics components. In fact however, it has been disclosed that it is difficult to reach and update the different components. This is due to the equipment construction that doesn’t allow easy disassembly and separation into different subassemblies and components.

How do you estimate the quotient between reused and recycled flat screens in Austria and in Europe?

There has been no information on the subject.

8. CONCLUSION

The IT-, communication and consumer equipment markets are characterized by dynamic development and rapid technology changes, resulting in ever increasing waste streams of electronics equipment. Therefore, the scope of this master thesis has been to investigate the innovations that have occurred in display technologies, printed circuit boards, packaging techniques and external power supplies for notebooks and mobile phones and to trace the most relevant changes within each technology with respect to their material content and subsequent recycling and reuse.

Several innovation trends have been observed.

Innovations in the display and monitor technologies are developing at a fast rate, leading to the demise of the CRT technology and hence posing challenges to its recycling and future applications within Europe.

Display technologies as OLED and flexible displays are slowly entering the electronics market, however, little is known about their exact material content and moreover about their recycling options. Currently the stock of OLEDs, reaching the End-of-Life stage is not significant and thus no specific recycling experience has been observed (in theory as well as in the practice).

With reference to LCD equipment, the most prominent innovations have been presented by the technology changeover with regard to the backlighting. The substitution of CCFLs with LED has not only advantages to the dismantling and thus recycling, but also the absence of hazardous materials, i.e. mercury, excludes the risk of human and environmental contamination.

However, a main drawback of the current recycling practices is the mass-oriented recovery. Currently, recycling strives to recover the most mass-relevant materials. On the one hand, the current legislative framework sets incentives for “mass-relevant” recycling; on the other hand, as it was shown, there is also an economic stimulus for the recycling of ferrous and nonferrous metals, plastics and PCBs. With respect to the materials with low concentration – indium from the ITO and gallium scandium, cerium, yttrium from the LEDs, there have been no recycling practices in Europe yet. Additionally, current technologies are not sophisticated enough to recover economically viable metals in low concentrations.

However, there is no regional concentration of indium and of rare earth metals in Europe. Considering the scarcity of these natural resources as well as the ambition of Europe towards resource autarky, the recovery of these elements should be integrated in the waste management scheme of the EU – both in the legal framework and in the fostering of research and development initiatives concerning their recovery.

Currently, printed circuit boards and packaging technologies are subject to advanced developments. A major trend towards minimization and integration of the electronics elements has been observed. The innovations in this area allow mass reduction of the overall equipment, as well as of the total content of precious metals. Gold has been recognized as the metal with the highest intrinsic value and hence represents the metal with superior interest for recovery. However, there is a growing tendency of substituting gold with other metals (aluminium and copper). Additionally, the use of carbon nanotubes in the microelectronics is under substantial research and is expected to enter the microelectronics market in near future. The impact of these innovations on the overall PCB metal content is still unexplored and is to be specified in future studies.

Referring to reuse, little is done at the moment. Reuse of electronics equipment and elements is regulated by the WEEE Directive. The Directive sets reuse and recycling targets for each Member State. However, the targets are combined and hence Member States can reach them by recycling alone. Nevertheless, since the equipment is often discarded while it is still technically intact, a more sophisticated reuse practices should be considered. A starting point for reuse could be the design of the equipment. For instance, harmonization of the external power supplies for data enabled telephones, which was launched by the European Commission and fourteen major electronics manufacturers, is a good example of an initiative that can foster reuse and thus minimize waste streams.

As has been seen, the legislation regarding the WEEE contributes to some extent to the recycling and reuse of equipment. However, in order to close the cycle, the whole lifecycle of the product should be reconsidered. There is a huge improvement potential at the beginning of the product's lifecycle. Here, the design and manufacturing can substantially contribute to the reuse and recycling when considering material choices, the quantity of different material as well as implementing concepts such as eco design, design for recycling and design for the environment. The implementation of these concepts in the design of electronics products should be fostered in order to facilitate the dismantling, recycling and recovering of materials, as well as the reuse of the products or components.

Finally, further research is needed in order to investigate the unanswered questions in this thesis. The impact of the use of carbon nanotubes on the recycling is a topic that needs more detailed analysis. There is currently little information on the behavior of carbon nanotubes at their End-of-Life phase. In addition, it would be interesting to examine the impact of the introduction of the new packaging technologies on the overall precious material content. Due to limitations-, in the present study only assumptions about the decrease of precious metal content, in particular of gold, have been made.

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FIGURES

TABLES

APPENDIX

Questionnaire "Recycling"

Number	Question
1	What recycling method do you use for flat panel displays (especially for the CCFL' disassembly and treatment? How do you process the liquid crystals? Do you recover indium from ITO? How do you evaluate the substitution of indium with carbon nanotubes and PEDOT?
2	Have you had have experience with OLED technology and how do you process OLEDs?
3	How does the technological changeover in the display technologies impact their recycling? Do the innovations in the material content facilitate the recycling?
4	Can further miniaturization make recycling uneconomical?
5	Is there any industry trend for reducing the valuable materials in the electronics equipment?
6	From recycling point of view which End-of-Life solution is more economically and environmentally friendly – reuse or recycling?
7	Which are the target metals from the printed circuit boards' recycling?

Questionnaire „Reuse“

Number	Question
1	Are there any measures that could be launched in order to enhance the reuse of electronics?
2	How feasible is refurbishment and what is the life expectancy of a refurbished revice (phone, TV set, laptop)?
3	What is the impact of innovations in electronics packaging on the reuse of electronics components?
4	How do you estimate the consumer's inclination towards reused electronics components?
5	Are there any drawbacks in the electronics components disassembly that can make reuse technically unreliable or uneconomical?
6	How does the miniaturization of electronics components impact their reuse?
7	How do you estimate the quotient between reused and recycled flat screens in Austria and in Europe?