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Recycling critical raw materials from waste electronic equipment

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1 Background and objectives

Against the backdrop of the importance of certain metals and other raw materials for many future technologies and the concurrent scarcity of these resources, the European Commission has classified a selection of fourteen raw materials as being particularly significant and critical (EC 2010). In view of the potential or expected difficulties attached to the supply of these critical raw materials, recovery of the raw materials from waste products is all the more important. This is the starting point for the project "Recycling critical raw materials from waste electronic equipment". The project's aims are to produce a life cycle inventory of the occurrence of the critical raw materials in four selected groups of electronic devices – flat screens, LED lights, notebooks and smartphones – and to develop recycling options for the waste equipment to recover the critical raw materials. Studies by the Oeko-Institut have shown that, for the four product groups being investigated, the following metals or groups of metals from the 14 "critical" raw materials identified by the EC study are of particular importance:

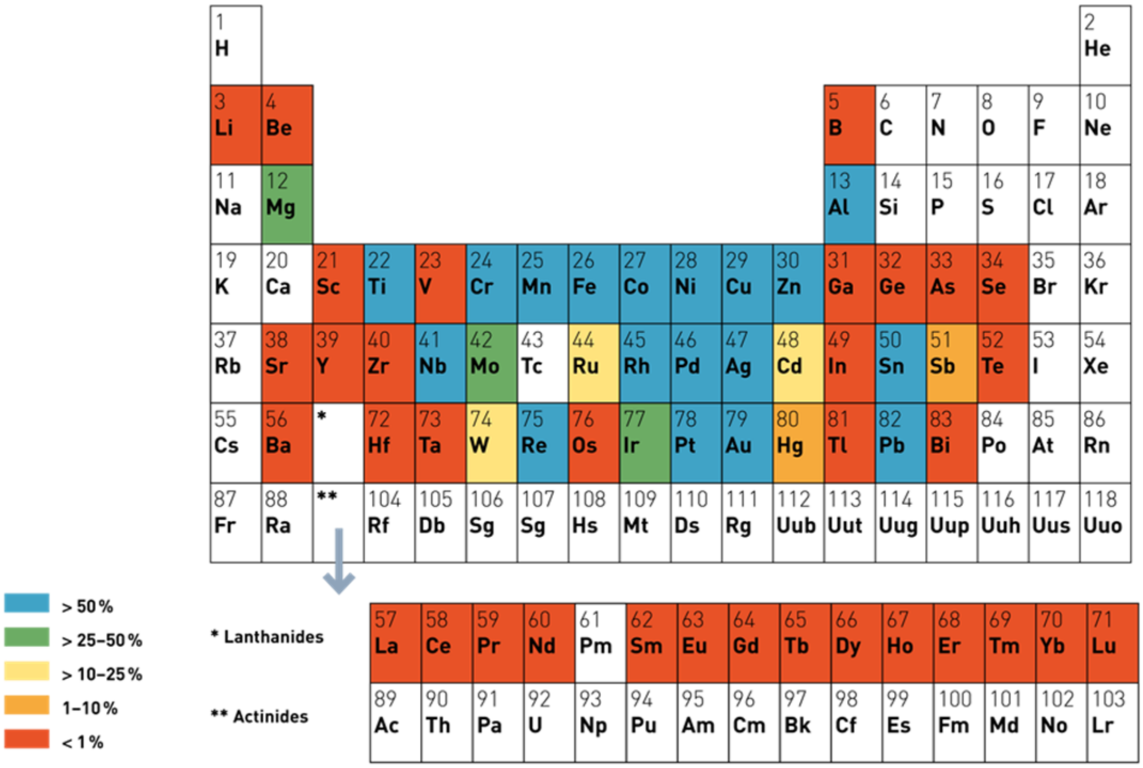
- Cobalt,
- Gallium,
- Germanium,
- Indium,
- Platinum group metals,[1]
- Rare earths,[2]
- Tantalum.

The following figure presents an overview of the current end-of-life recycling rates for 60 metals (Graedel et al. 2011). These ranges of values represent the global situation, however, and include all uses of the metals.

[1] The platinum group metals comprise the elements platinum, palladium, iridium, rhodium, ruthenium and osmium.

[2] The rare earths (often also called rare earth metals) include the elements yttrium, scandium and what are known as the lanthanides (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium).

Figure 1: Global end-of-life recycling rates for 60 metals (Graedel et al. 2011)



Many of the critical metals examined in this study, especially the rare earths (lanthanides plus scandium and yttrium) as well as tantalum, gallium and indium show total end-of-life recycling rates of less than 1%. The recycling situation for precious metals (platinum, palladium, gold, silver) and cobalt is significantly better with rates above 50%. There are already advanced recycling methods for these metals and functioning collection systems, at least for some applications (e.g. industrial catalysts, special alloys).

The study for the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection (Landesamt für Natur, Umwelt und Verbraucherschutz Nordrhein-Westfalen) will also continue to examine the important precious metals gold and silver. It requires great effort to extract these sought-after and valuable metals from the natural ores. They are therefore important drivers for recycling operations, particularly in the field of electronic products. Many experts classify silver as a critical raw material, even though this is not on the EC's list of 14 raw materials (Buchert et al. 2011). The aim of this study for the North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection is to produce an analysis of the critical metal potential for the selected product groups and from this, identify shortcomings in the recycling infrastructures and technologies in order to prepare preliminary suggestions and recommendations for action for a future optimised recycling industry in North Rhine-Westphalia.

2 Flat screens

Large-sized flat screens are primarily used in the field of TV appliances and computer monitors. Additional application areas include digital displays, digital picture frames, tablet PCs and, for smaller formats, mobile phones, smartphones, e-book readers and numerous other devices. The analysis below deals primarily with flat screens for TV and computer applications.

Three different display technologies are currently in use:

Table 1: Display technologies and their principal areas of application

Display technology	Main areas of application	Background illumination
LCD (Liquid Crystal Display)	Desktop PCs, notebooks, TV sets	Yes
PDP (Plasma Display Panel)	TV sets	No
OLED (Organic Light Emitting Diode)	Mobile phones, notebooks	No

The following components are of particular importance for critical raw materials.

- Display
- Background lights
- Assembled PCBs

The following sections present a detailed examination of these components with respect to the critical resources which they contain.

2.1 Indium

Indium is used in the form of indium tin oxide (ITO) as electrode material in flat screens. The advantage of indium tin oxide is that it is transparent, conductive and largely heat-resistant. The ITO layers applied in screens consist of 90% In_2O_3 und 10% SnO_2, corresponding to a percent by weight of indium of 78% (Böni & Widmer 2011). Whilst two layers of ITO are applied to LCD displays, OLED displays only have one layer. The literature gives different and often very contradictory data on the film thickness and indium content of flat screens (see Table 2). In LCD displays with LED background illumination, indium is also used as a component of the LED semiconductor chip which is largely composed of indium gallium nitride. The resulting additional quantities of indium per display are given inTable 8. They are about one order of magnitude lower than the percentages by weight of indium attributable to ITO as an electrode material.

Table 2: Published values on film thickness and indium content of LCD displays.

	ISI 2009	Socolof et al. 2005	Martin 2009	Becker et al. 2003	Becker et al. 2003	Bogdanski 2009	Bogdanski 2009	Böni & Widmer 2011
mg ITO/ m^2	4,000	7,176	700	192	240	72	192	300
nm/layer	1,667	2,990	292	80	100	30	80	125
mg In/m^2	3,120	5,597	546	150	187	56	150	234

Source: Böni & Widmer 2011

FEM & IUTA 2011 determined a mean indium content of 174 g/t of display waste for the display recycling stream. If this value is related to the individual display devices, then this approximation indicates mean quantities between 464 and 864 mg/m^2 (see Table 3), so that in what follows a mean value of 700 mg/m^2 will be assumed for LCD displays. A comparable value will be assumed for plasma screens which have a market share of just 10% in the TV sector.

Table 3: Approximation calculation of indium content in LCD displays

	Mean weight of display [g]	Mean content of In [g/t]	Mean In content per device [mg]	Mean screen area [cm^2]	Mean content of In [mg/ m^2]
Notebooks	250	174	43.5	552	788
LCD monitors	300		52.2	1126	464
LCD televisions	1800		36.3	3626	864

Data sources: FEM & IUTA 2011, Displaybank 2011 (size of displays)

This enables the following mean indium contents to be estimated for the selected display devices:

Table 4: Mean indium content of different display devices

	Mean screen area [cm^2]	Mean In content per device [mg]
Notebooks	552	39
Computer monitors	1,126	79
Televisions	3,626	254

These values correspond closely with the data on the indium content of notebook displays for 15.4 inch screens (686 cm^2) provided by the manufacturers. According to data from Prakash et al. (2011) these contain around 0.5 g of indium tin oxide, corresponding to an indium content of 0.39 g.

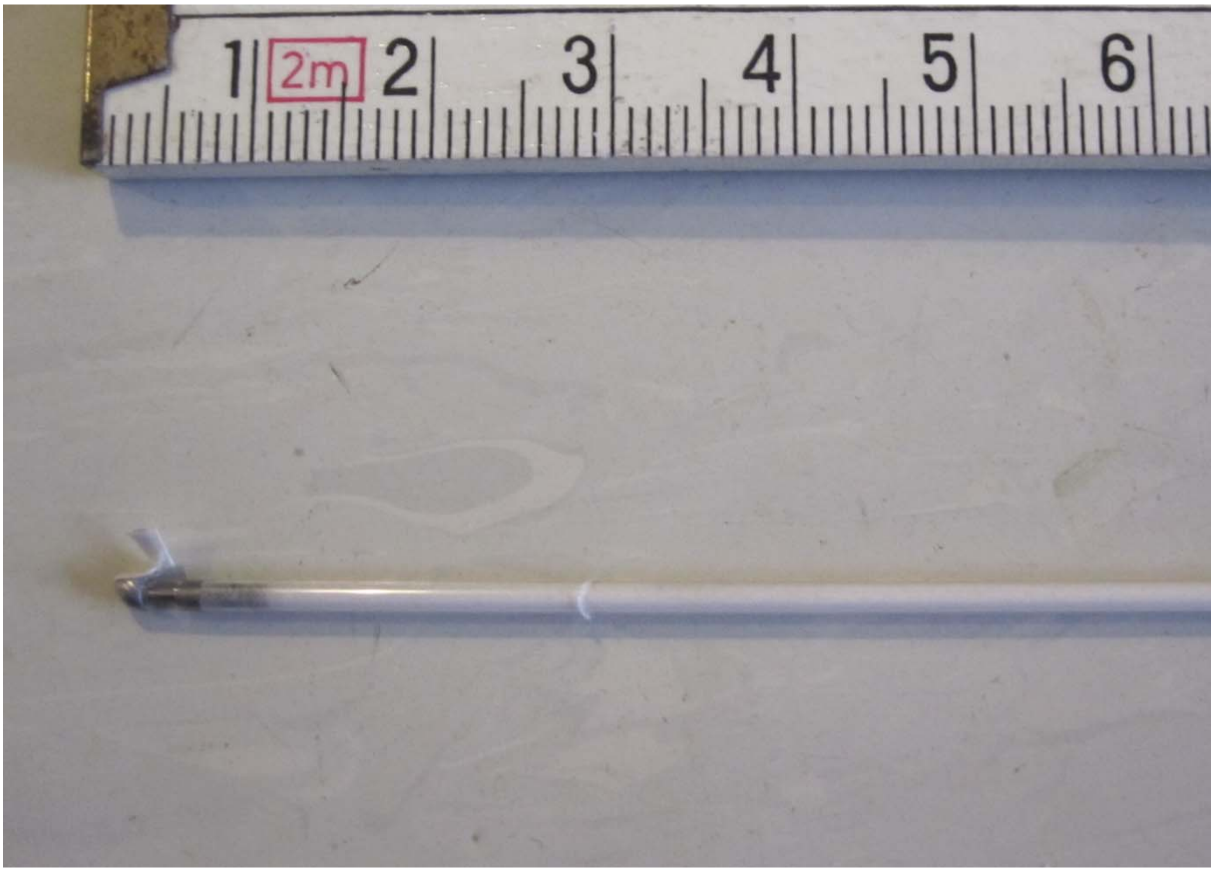
2.2 Rare earths

Rare earths (also known as rare earth metals) are used in the luminescent material in visual display units. Depending on the display technology, the rare earths are either used in the displays themselves (PDP and OLED technology) or the background illumination (LCD technology). The available data on the use of rare earths in this context is of a very general nature, as all information on the quantities and concentrations for specific products is usually covered by trade secrets. The following statements can nevertheless be made:

- For luminescent material a distinction can be made between the support matrix and the actual luminescent substances (activators). In addition to compounds without rare earths, compounds with yttrium (Y_2O_3), cerium ($CeMgAl_{11}O_{19}$) and lanthanum (La_2O_3) are used in the support matrix (Schüler et al. 2011). Data from the US Department of Energy (US DoE 2010), Guarde et al. (2010) and Gambardella et al. (2010) show that these three metals exhibit the largest proportions of all rare earths in luminescent materials. Gambarella et al. (2010) specify the proportion of yttrium, lanthanum and cerium in all rare earths used in luminescent materials as 69.2%, 11.0% and 8.5%, followed by europium (4.9%), terbium (4.6%) and gadolinium (1.8%).
- Europium, terbium and gadolinium are used in different compounds for the actual luminescent substances. Samarium, erbium, dysprosium, thulium and lutetium play a quantitatively more minor role (Schüler et al. 2011; Gambardella et al. 2010).
- According to Rieger (2009) the following rare earth compounds are used in plasma displays:

  Red: $(Y, Gd)BO_3:Eu$
  $(Y_2O_3:Eu^{3+})$
  Green: $(Y, Gd)BO_3:Tb$
  Blue: $BaMgAl_{10}O_{17}:Eu$
- Cold cathode tubes (CCFL) are used for the LCD background illumination, especially in older devices. Whilst only one or two lamps are generally used in notebooks, televisions are fitted with up to 82 tubes (FEM & IUTA 2011). The cold cathode tubes in a notebook have a diameter of approx. 1.5 mm and weigh less than 1 g (see Figure 2).

Figure 2: CCFL tubes from a notebook screen (photo Oeko-Institut)



Estimating quantities per unit can only be done using data which is generally available and may display considerable uncertainties, especially for combinations. Nevertheless, an estimate for LCD screens with CCFL background illumination in particular can be made on the basis of the following data:

Table 5: Assumptions and data for estimating the percentage of rare earths in the CCFL background illumination of LCD screens

	Mean weight of a CCFL tube [g]	**Mean number of tubes per device**	**Percentage weight of luminescent substances in tubes [%]**	**Percentage weight of the luminescent substances [%]**						
				Y	**Eu**	**La**	**Ce**	**Tb**	**Gd**	**Pr**
Notebooks	1	1	2.1	8.72	0.64	0.54	0.36	0.18	0.05	< 0.01
Monitors	1.5	6								
Televisions	4	15								

Data sources: Measurements and estimates made by Hamidovic, 1997, cited in Martens 2011, Guarde et al. 2010.

Based on these data, the following quantitative estimates can be made:

Table 6: Estimated mean weights of rare earth metals in LCD displays with CCFL background illumination

	Yttrium [mg]	Europium [mg]	Lanthanum [mg]	Cerium [mg]	Terbium [mg]	Gadolinium [mg]
Notebooks	1.8	0.13	0.11	0.076	0.038	0.011
Monitors	16.0	1.20	1.00	0.680	0.340	0.095
Televisions	110.0	8.10	6.80	4.500	2.300	0.630

Newer LCD monitors are sometimes already fitted with background illumination based on white LEDs (see Section 5). In 2010 the market share of LCD monitors and LCD televisions fitted with LEDs was around 30% whereas around 90% of all new notebooks were already equipped with LED background illumination (Young 2011). Like CCFL tubes, white LEDs also make use of a luminescent substance which converts the short-wave light produced in the LED into the visible spectrum. The support matrix is usually made from yttrium aluminum garnet (YAG) with substantial admixtures of gadolinium. The doping consists of a few percent by weight of cerium and sometimes europium. The actual LED semiconductor chip which produces the light is composed of indium gallium nitride (see also Section 5.1). This results in a somewhat different composition for the rare earths in LCD monitors, LCD televisions and notebooks with LED background illumination in comparison to Table 6, as shown in Table 8 (indium and gallium are included in this list). This table makes use of the proportions of critical metals in white LEDs specified in Table 7 (see also Table 30 in Section 5.1). The number of white LEDs in a monitor required for the projection is a quantity which varies depending on the manufacturer and can therefore only be estimated for a general survey. Based on model data in Young (2011), estimates of 100 LEDs for an LCD PC monitor, 150 LEDs for an LCD television and 50 LEDs for a notebook display have been made (see Table 7).

Table 7: Assumptions and data for estimating the content of rare earths (incl. indium and gallium) in the LED background illumination of LCD screens.

	Mean number of white LEDs per device	Luminescent substance: Weight per LED [µg]					Semiconductor chip Weight per LED [µg]	
		Y	Eu	Ce	Tb	Gd	In[3]	Ga
Notebooks	50	32.0	0.6	2.0	0.0	32.5	29.0	32.5
Monitors	100							
Televisions	150							

Table 8: Estimated mean weights of rare earth metals (incl. indium and gallium) in LCD displays with CCFL background illumination

	Yttrium [mg]	Europium [mg]	Cerium [mg]	Terbium [mg]	Gadolinium [mg]	Indium[1] [mg]	Gallium [mg]
Notebooks	1.6	0.03	0.1	0.0	0.75	1.5	1.6
Monitors	3.2	0.06	0.2	0.0	1.50	2.9	3.3
Televisions	4.9	0.09	0.3	0.0	2.30	4.4	4.9

In addition to the rare earths in background illumination, some devices also contain permanent magnets based on rare earths (see Section 3.4). Loudspeakers in television sets are the main application of these. However, there is no available data on the frequency with which rare earth magnets are used in televisions nor on their unit weight, so these have been disregarded in this study.

2.3 Precious metals

Flat screens contain one or more printed circuit boards equipped with electronic components and connectors. Important amounts of precious metals are contained both in the components and connectors as well as in the solder.

Table 9: Weight and concentration of precious metals in PCBs in flat screens

	Weight per unit [g]	Ag [mg/kg]	Au [mg/kg]	Pd [mg/kg]	Source of data
PCB from an LCD monitor	400	1,300	490	99	FEM & IUTA 2011, Huismann et al. 2007
PCB from an LCD television	2,300	250	60	19	FEM & IUTA 2011, 2007

3 only part of the LED background illumination

The data in Table 9 can be used to estimate the total quantity in the PCBs of a notebook:

Table 10: Quantities of precious metals in the PCBs of flat screens

	Ag [mg]	Au [mg]	Pd [mg]
PCB from an LCD monitor	520	196	40
PCB from an LCD television	575	138	44

2.4 Summary of critical metals in flat screens

The results of the analyses in Sections 2.1 to 2.3 are shown in Table 12 and Table 13. It should be noted that these values are provided as an indication and cannot be applied to specific models or sizes. Many of the values have been derived from measurements on waste appliances. Differences may result due to modifications in product design in newer generations of devices which could not be included in these data because they are often covered by trade secrets or have not yet been calculated using aggregated data for an average product. Table 11 summarizes the quantities used for projecting the quantitative data on the PC and TV displays sold in Germany in 2010. The data on the relevant sales figures given in Section 2.5 are taken as a basis for extrapolating the quantitative data on the devices sold on the German market in 2010. Although these also include PC monitors with electron tube screens (CRT screens), their market share can, however, be considered negligible in the overall result. A value of 30% has been taken for the market share of TV sets and PC monitors with LED background illumination sold in 2010 (Young 2011). The concentrations of rare earth metals and of gallium and indium in LCD devices with LED background illumination are based on the data in Table 8. This makes the assumption that an average LCD monitor contains 100 white LEDs and an LCD television 150 white LEDs in the background illumination (see Young 2011). Data from LCD televisions has been used as a basis for calculating the additional potential of PDP television sets.

Table 11: Sales figures for equipment with LCD displays (Germany 2010), the market share of devices with background illumination using white LEDs (WLEDs) and the estimated number of WLEDs used in the background illumination per device (see also Section 5.3)

Device class	No. of devices sold in Germany in 2010	Market share of background illumination using WLEDs	Number of WLEDs per device
LCD PC monitors	2,576,000	30%	100
LCD TV sets	8,258,000	30%	150

Table 12: Mean weight of critical raw materials in LCD PC monitors (private market sector)

Metal		Content per LCD monitor (CCFL[4]) [mg]	Content per LCD monitor (LED[5]) [mg]	Content in all LCD monitors sold in Germany in 2010 [kg]	Occurrence
Silver	Ag	520	520	1,340	PCB and contacts (100%)
Gold	Au	200	200	505	PCB and contacts (100%)
Indium	In	79	82	206	Internal coating on display (100%)
Palladium	Pd	40	40	102	PCB and contacts (100%)
Yttrium	Y	16	3.20	32	Background illumination (100%)
Gallium	Ga	0.000	3.30	2.51	LED background illumination (100%)
Europium	Eu	1.200	0.06	2.23	Background illumination (100%)
Lanthanum	La	1.000	0.00	1.84	CCFL background illumination (100%)
Cerium	Ce	0.680	0.20	1.38	Background illumination (100%)
Gadolinium	Gd	0.096	1.50	1.33	Background illumination (100%)
Terbium	Tb	0.340	0.00	0.61	CCFL background illumination (100%)
Praseodymium	Pr	< 0.019	0.00	<0.05	CCFL background illumination (100%)

It can be seen from the above table that it is primarily silver (over 1.3 tons/year) and gold (around half a tons/year) that currently enter the use phase via all LCD PC monitors sold in Germany and present an interesting potential for the recycling industry after their use phase has expired. These metals are followed by indium (around 200 kg/year) and the precious metal palladium (around 100 kg/year). LCD monitors only contain minor amounts of the various rare earths and gallium.

4 LCD monitors (PC) with CCFL background illumination (approx. 70% of all new LCD monitors in 2010)

5 LCD monitors (PC) with LED background illumination (approx. 30% of all new LCD monitors in 2010)

The corresponding data for LCD TV sets are presented in the following table. Silver (over 4.7 tons/year), indium (over 2.1 tons/year) and gold (over 1.1 tons/year) come onto the German market in the ton range by means of LCD televisions annually. The content of gold alone is worth around 40 million euros at present-day market prices. Yttrium as a representative of the rare earths and the precious metal palladium are each sold in several hundred kilograms per year in LCD televisions in Germany. Gallium and the other rare earths display less significant quantities.

Table 13: Mean weight of critical raw materials in LCD televisions

Metal		Content per LCD television (CCFL[6]) [mg]	Content per LCD television (LED[7]) [mg]	Content in all LCD TVs sold in Germany in 2010 [kg]	Occurrence
Silver	Ag	580	580	4,748.35	PCB and contacts (100%)
Indium	In	260	260	2,157.86	Internal coating on display (100%)
Gold	Au	140	140	1,139.60	PCB and contacts (100%)
Yttrium	Y	110	4.8	647.02	Background illumination (100%)
Palladium	Pd	44	44	360.87	PCB and contacts (100%)
Europium	Eu	8.10	0.09	46.84	Background illumination (100%)
Lanthanum	La	6.80	0.00	39.33	CCFL background illumination (100%)
Cerium	Ce	4.50	0.30	26.96	Background illumination (100%)
Terbium	Tb	2.30	0.00	13.11	CCFL background illumination (100%)
Gallium	Ga	0.00	4.90	12.08	LED background illumination (100%)
Gadolinium	Gd	0.63	2.30	9.22	Background illumination (100%)
Praseodymium	Pr	< 0.13	0.00	<1.07	CCFL background illumination (100%)

2.5 Market data for flat screens

The German market for TV sets is mainly dominated by sales of flat screen TVs based on LCDs. According to CEMIX (2012), 8.3 million TVs in this product group were sold in 2010, 9.3% more than in the previous year (see table 14). This trend towards increasing quantities and also increasing revenue (almost 5.5 billion euros in 2010, up 3.9% on 2009) is partly fuelled by falling average prices. The market for plasma TVs is significantly smaller: sales and revenue from these in 2010 were only around 10% that of the LCD TV market. This is partly due to the higher average price of plasma TV sets along with the constant improvement in the image characteristics of LCD TVs. Plasma TV sets appear to have

[6] LCD televisions with CCFL background illumination (approx. 70% of all new LCD televisions in 2010)

[7] LCD televisions with LED background illumination (approx. 30% of all new LCD televisions in 2010)

become established in a small but stable niche in Germany over the last few years (GfK & gfu 2011, see Figure 3). Plasma screens are currently not used as PC monitors. They are usually produced for diagonals of around 37 inches and above and are therefore used almost exclusively in the TV sector.

The growth trend over the whole television market resulted in a stock of an estimated 50 million flat screen TVs in private households in 2010 (GfK & gfu (2011). This means that each household in Germany has around 1.5 televisions. In addition to expanding the available supply of HDTVs, the newly available 3D technology for TV sets (2010 sales: 200,000 units) and what are known as smart TV sets with internet connection (2010 sales: 2 million units) have raised the demand for new flat screen televisions. The planned end to the analogue TV satellite transmission service due to take place on 30 April 2012 also increases the demand for new TV sets. In view of these new technologies which are becoming established, a positive development in the market can be expected over the coming years (GfK & gfu (2011). In contrast, TV sets with electron tubes for the imaging components (CRT devices) scarcely featured amongst new purchases in 2010, continuing the long-term trend towards their disappearance from the market (see Figure 3).

Figure 3: Sales of TV sets in Germany, according to imaging technology (LCD, plasma and CRT TV sets), from GfK & gfu (2011)

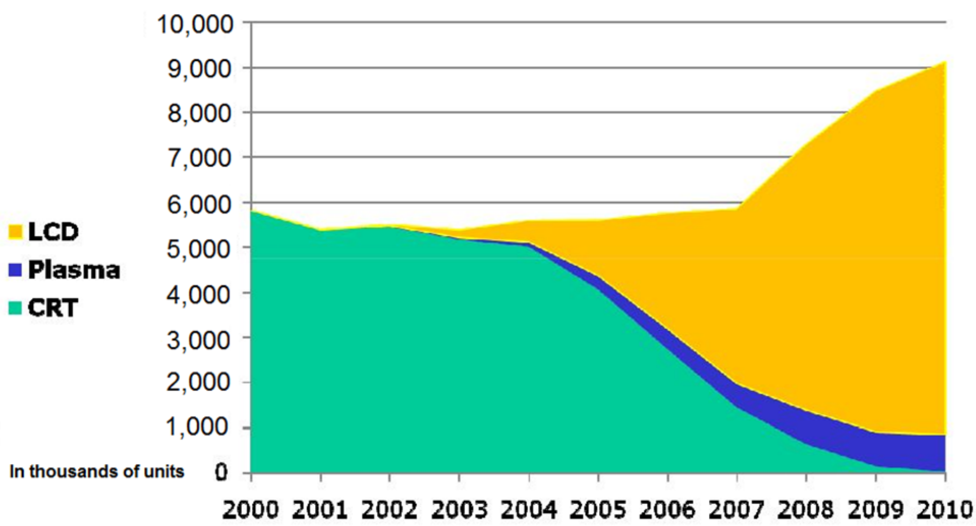


Table 14: Sales, percentage change against previous year and average price for TV sets (private market) in 2010 (CEMIX 2011)

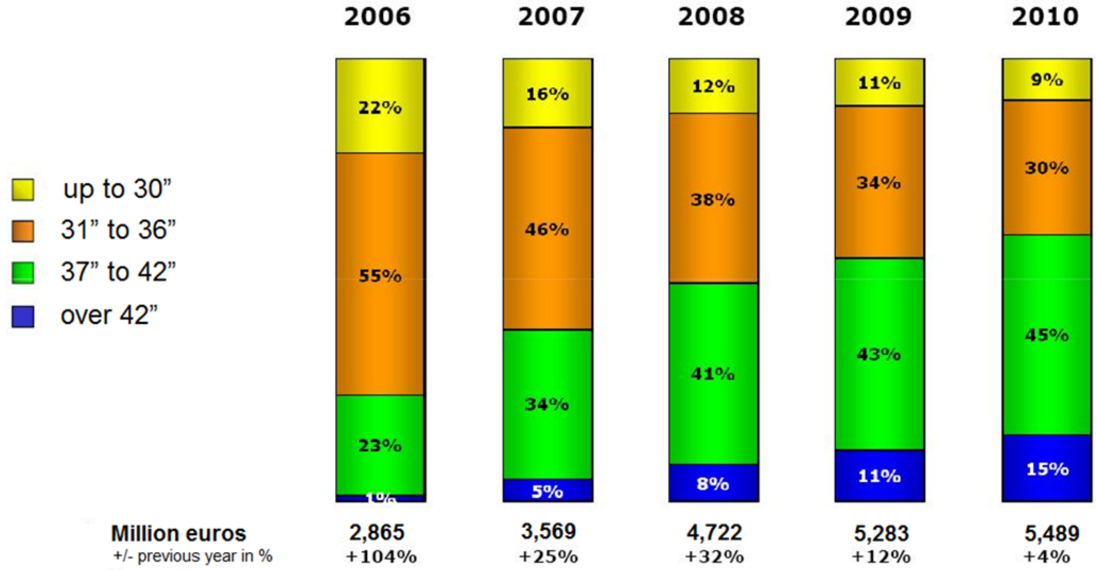
Product group	LCD TV screens	Plasma TV screens	CRT TV screens	PC monitors[8]
Sales in 2010 in 1,000s	8,258	812	34	2,576
Change compared to 2009	9.30%	8.00%	-77.10%	-20.80%
Average price in 2010 [€][9]	665	804	120	180

The trend towards larger format TV sets which has been apparent for several years is important for the use of raw materials. Figure 4 shows the development of the sales generated from TVs of different screen sizes over recent years. A clear trend towards larger TV screens can be seen. In contrast to PC monitors in which the screen size is restricted in a vertical direction due to the size of a typical PC workstation, from the viewpoint of the electronic entertainment industry there is also a use – and therefore a demand on the market – for TV screens which are significantly larger than before. The mean size of the LCD panel of a flat screen sold at the beginning of 2010 was around 3626 cm² for TV screens and around 1126 cm² for PC monitors, corresponding to approximately the size of a 37 inch TV screen and a 20 inch PC screen. This information is based on data on the relative proportions of different sizes of LCD panels on the world market (Displaybank (2011). In order to extrapolate to the total quantity of critical metals in LCD flat screens in the German waste management industry, it has been assumed in Section 2.4 that the types of flat screens of different sizes have similar proportions on the German market as they do on the world market. This gives rise to a matching average size of the screen areas.

8 CRT+TFT, private sector only

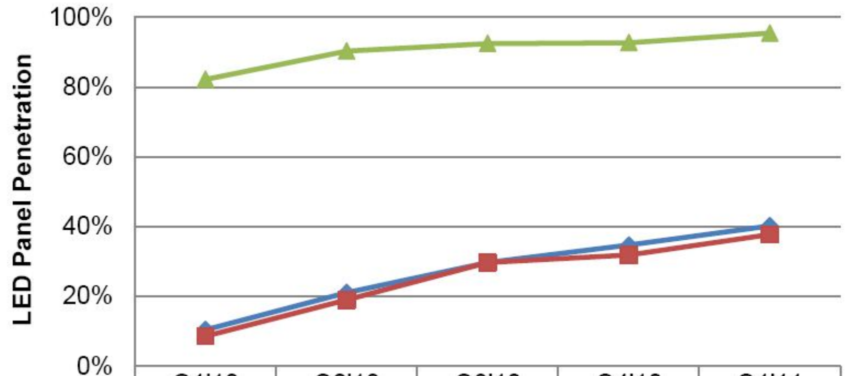
9 incl. VAT

Figure 4: Sales development of TV sets according to screen size in Germany



In contrast to plasma screens, background illumination is necessary for screens based on LCDs. Besides the cold cathode tubes (CCFL) mainly used in the past, this makes increasing use of white LEDs (WLEDs). Figure 5 shows the increasing proportion of devices with LCD screens over the past year in which WLEDs are used as background illumination (Young (2011). For flat screen TVs manufactured at the beginning of 2011 this had already reached 40%.

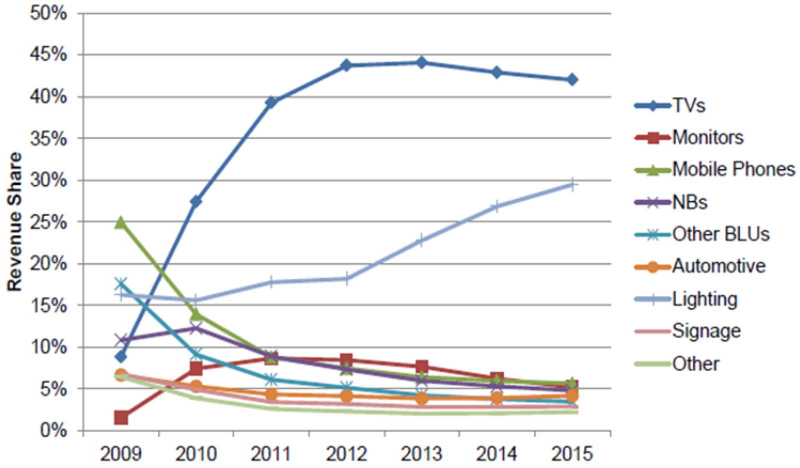
Figure 5: Market share of devices with LCD screens and LED background illumination (Young 2011)



	Q1'10	Q2'10	Q3'10	Q4'10	Q1'11
TVs	10%	21%	30%	35%	40%
Monitors	9%	19%	30%	32%	38%
NBs	82%	90%	92%	93%	95%

In 2010 the revenue generated by WLEDs used in flat screen TVs already outweighed all other applications for WLEDs, at a value of approx. 28% (see Figure 6). Further rapid growth is predicted over the next few years, to over 40% in 2012 (Young (2011)).

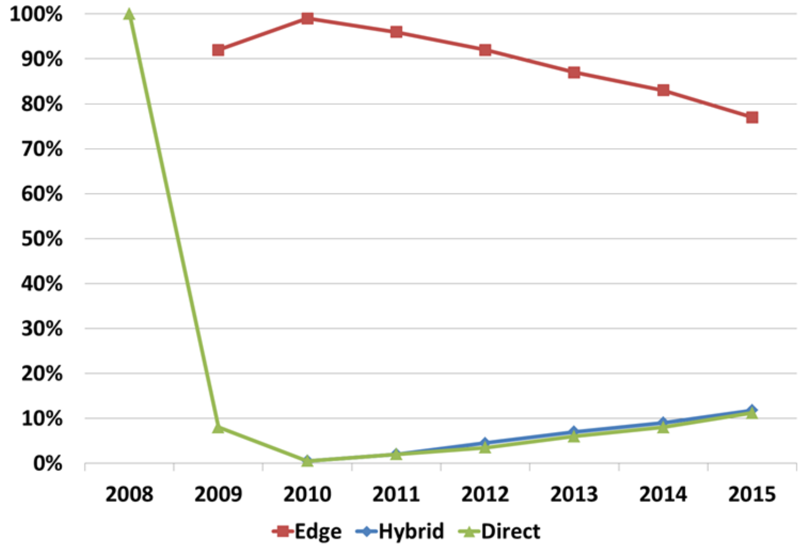
Figure 6: Market share and projection of market development for white LEDs according to application (Young 2011).



TV screens generally use an indirect method of illumination in which the WLEDs are placed in a strip at the edges of the monitor and the luminous flux is distributed over the whole surface by means of light guides. In contrast, monitors with what is known as direct background illumination have the LEDs distributed individually across the surface, each fitted with its own lens system to scatter the light. This requires at least three times as many LEDs as the indirect illumination (Young (2011). Hybrids of these two design principles are also manufactured.

Improvements in the luminous efficacy of white LEDs and the quality of the light guides plus increases in the transparency of the actual LCD film resulted in an approximate halving of the number of LEDs used in the background illumination of an LCD panel between 2009 and 2010. In 2010 this was around 100 LEDs per screen. However, it is likely that this current development towards fewer LEDs could fall off or even reverse because of the trend towards ever larger flat screens (see also Figure 4) which will require greater numbers of LEDs for their background illumination. Besides larger screens, 3D-capable flat screens also require enhanced background illumination. Both the main technologies used for 3D televisions, the shutter method and the use of polarization filters, reduce the brightness by 80% and 60% respectively. The reduction in brightness must therefore be compensated by stronger background illumination (Young (2011). These increased demands on the strength of the background illumination will in all probability be met primarily by direct illumination methods or hybrid designs. Although these designs only had a market share of a few percent in 2010, primarily determined by the high production costs, it is nevertheless anticipated that this will increase to around 15% each by 2015 (see Figure 7).

Figure 7: Market share of LCD TV sets with indirect ("edge"), direct ("direct") and hybrid ("hybrid") background illumination (Young 2011)



2.6 Service life and collection rates for flat screens

The lifespan of computer screens was estimated at an average of 6.6 years as part of the EU eco-design process (EuP 2007). This figure includes both the first use and the length of an average second use.

According to Zangl et al. (2009), television sets can be assumed to have an average service life of 10 years.

In 2008 319,983 t of the WEEE product category 3 (IT and telecommunication equipment) and 192,224 t of the WEEE product category 4 (consumer electronics products) were put on the market in Germany. In the same period 155,007 t of category 3 and 130,620 to of category 4 equipment were collected through the official return and collection systems for controlled recycling and disposal (BMU 2009). If it is assumed that these values can be applied to screens, then the collection rates in Germany for computer screens can be estimated at just 50% and for televisions at just 85%[10]. Compared with data at the EU level (40.5% for flat screens), Germany is therefore above the European average (Huisman et al. 2007). There is no reliable data on the whereabouts of the remaining devices. The following possibilities can be considered:

---

[10] These values do not include any delays from the use phase of the devices. They are purely an estimate of the actual collection rates.

- Delayed disposal (storage of old devices by the user)
- Disposal via domestic waste
- Export to other countries

With reference to the last point in particular, it is known that both television sets and computer monitors are frequently exported to Eastern Europe or West Africa where the devices are repaired and sold to local or regional markets (Prakash & Manhart 2010, Manhart et al. 2011).

2.7 Status of pre-treatment technology for flat screens

In accordance with Annex II of the Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment, liquid crystal displays with a surface of over 100 square centimeters and background illuminated displays with gas discharge lamps must be disposed of or recycled. Appropriate measures must be taken so that the wastes do not endanger human health or damage the environment. The Directive 2002/96/EC provides explicitly for removal of the mercury especially for gas discharge lamps.

In Germany and the EU, flat screens are therefore fed into a separate recycling process after collection, primarily for the purpose of recovering the mercury from the gas discharge lamps (LCD displays with CCFL background illumination).

To achieve the best recovery, the tubes have to be removed manually. Although a variety of companies carry out this procedure, it should only be undertaken in accordance with stringent health and safety standards due to mercury emissions from damaged lamps. In general, when using this procedure it must be assumed that during disassembly 5-20% of the capillary tubes will be damaged so that mercury escapes (Böni & Widmer 2011).

The complete manual disassembly of LCD screens with CCFL background illumination[11] produces the following fractions:

- Plastics fraction (sometimes subdivided according to different types of polymers)
- Sheet steel and aluminum
- Printed circuit boards
- CCFL lights
- Displays

[11] The flat screens entering the waste stream are currently mainly LCD screens with CCFL background illumination. Newer technologies such as LCD displays with LED background illumination or OLED screens are not yet of any quantitative importance in the waste stream.

The plastics fraction, steel, aluminum and PCBs are passed on to the relevant markets for materials recycling. The recovery of precious metals from PCBs is discussed in Sections 3.9 and 6.1. The CCFL lights are sent to general lamp recycling where the proper treatment of mercury is a priority. In addition, the glass and some of the metallic components in the sockets are sent to materials recycling. The luminescent substances themselves and any contaminants from broken glass, mercury and other materials are usually deposited underground (Martens 2011). The rare earths contained in the luminescent materials are currently not recycled (see Section 6.3).

Instead of manual disassembly, the complete or partly disassembled display unit can be sent for mechanical pre-treatment where the devices are shredded in an airtight sealed shredder and the mercury eliminated from the process air. However, this process also fails to address all the issues as, according to Böni & Widmer (2011), the whereabouts of all the mercury is not conclusively explained.

A further option is thermal treatment of the whole or partially disassembled display units (Böni & Widmer 2011, Martens 2011).

The displays are usually recycled thermally in waste incineration plants or in the Waelz kiln process for steel mill dust. The organic components (liquid crystals, polarization filters, resins) are incinerated and the glass along with the oxidized metals bound in an inert slag (Martens 2011). The indium contained in the displays is lost through dissipation.

2.8 Potential for optimization in the recycling chain

From a resource point of view, manual pre-treatment with complete removal of the assembled PCBs and subsequent recovery of the precious metals is to be recommended (see Section 6.1). This allows utilization of the synergies associated with the common process of manually removing the mercury-containing CCFL lamps.

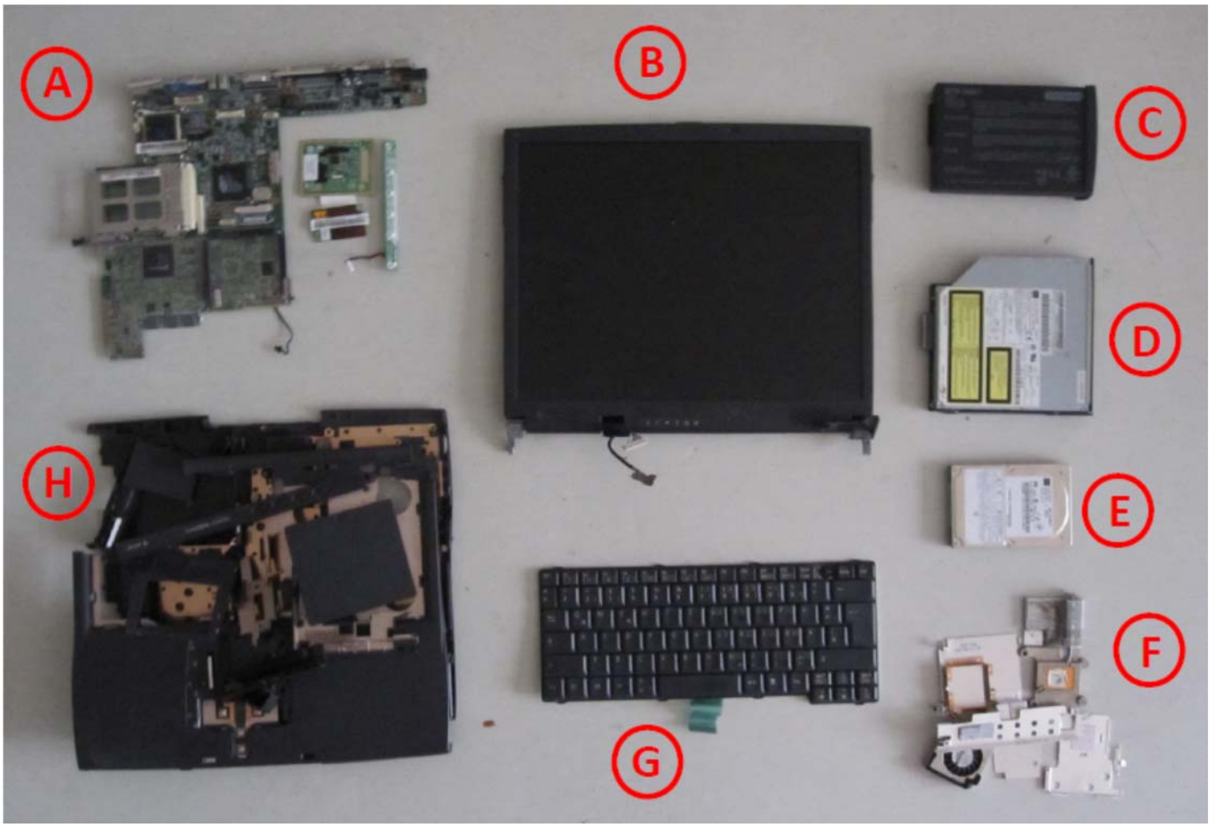
There are currently no suitable separation and refining processes for recovering the indium from the display units and the rare earths from the background illumination (see Section 6.3 and 6.4), so that these substances have not been included in materials recycling so far. In view of the emerging developments in this field, it is worth considering storage of the display units and the luminescent material for recycling at a later date. These measures can be deemed practicable as both fractions already occur in a concentrated form in the disassembly process[12].

[12] The principal source of luminescent materials is, however, not the background illumination from flat screens but other illuminants (including fluorescent tubes) and screen technologies (cathode ray tubes).

3 Notebooks

Notebooks are composed of several components and 1,800 to 2,000 individual parts (Manhart & Griesshammer 2006). Taken together, these contain a wide range of elements. The following figure gives an overview of the important components of relevance from a recycling perspective:

Figure 8: The main notebook components of relevance from a recycling perspective (photo Oeko-Institut)



A: Motherboard & smaller PCBs (e.g. touchpad)

B: LCD screen

C: Battery pack

D: Optical drive (CD / DVD / Blu-ray)

E: Hard disk drive

F: Steel plates, cooling elements & fans

G: Keyboard

H: Plastic components

In terms of scarce resources, the main items of importance are the PCBs (A), the LCD screen (B), the battery pack (C), the hard disk drive (D) and the optical drive (E)[13].

These components and the scarce resources they contain will be examined in detail in the following sections.

3.1 Precious metals

Notebooks contain various PCBs which are equipped with a variety of electronic components and connectors. Significant amounts of precious metals are contained both in the components and in the connectors and solder. The following list gives an overview of the main applications of the precious metals in assembled PCBs:

- Gold: contacts, bonding wires, microchips
- Silver: (lead-free) solder
- Palladium: capacitors

Gold, silver and palladium can be recovered with a high level of efficiency in the refining process. As the financial returns for the copper and precious metal smelting works are linked to the material value of the PCBs supplied, very precise analysis data are available for the different types of assembled PCBs.

Table 15: Weight and concentration of precious metals in PCBs in notebooks

Components	Weight per unit [g] [14]	Ag [mg/kg]	Au [mg/kg]	Pd [mg/kg]	Data source
Motherboard	310	800	180	80	Umicore 2011
Memory cards	20	1,650	750	180	Umicore 2011
Small PCBs	28	800	180	80	Umicore 2011
Hard disk drive PCB	12	2,600	400	280	Umicore 2011
PCB for optical drive	25	2,200	200	70	Umicore 2011
Display PCB	37	1,300	490	99	Chancerel & Rotter 2009

The data in Table 15 can be used to estimate the total quantity in the PCBs of a notebook:

13 Some of the remaining components are of importance for less critical raw materials. For example, notebook housings are partly lined with copper foil which cannot be properly separated from the plastic in the standard pre-treatment processes.

14 Source for weight data: Oeko-Institut research and measurements.

Table 16: Quantities of precious metals in the PCBs of a notebook

	Ag [mg]	Au [mg]	Pd [mg]
Motherboard	248	56	25
Memory cards	33	15	4
Small PCBs	22	5	2
Hard disk drive PCB	31	5	3
Printed circuit boards for optical drive	55	5	2
Display PCB	48	18	4
Total	**438**	**104**	**39**

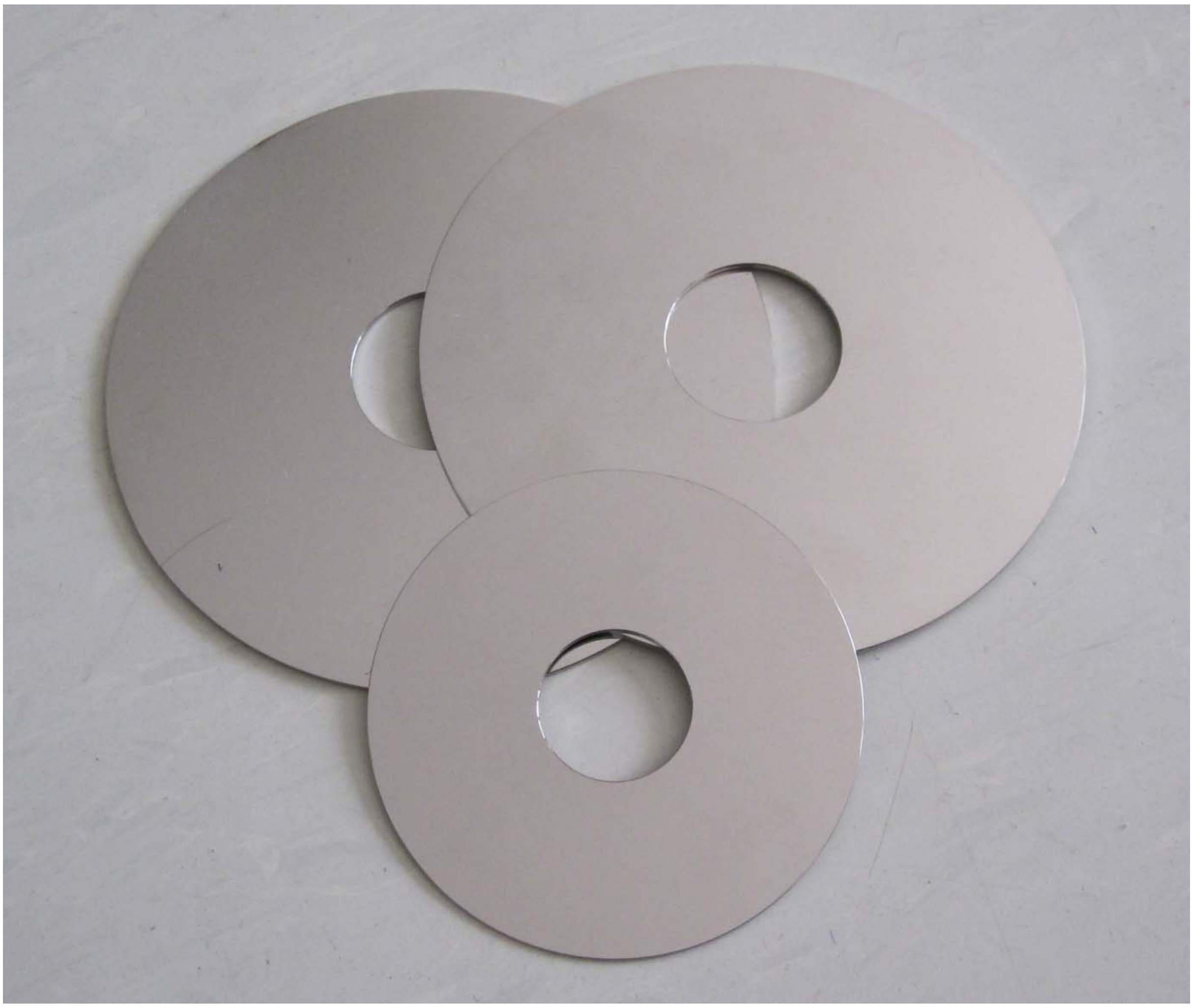
Besides the PCB, the hard disk drive platters also contain a certain amount of precious metals. These are mostly located on the surface of the storage medium. Notebooks usually use hard disks with a 2.5 inch format. However, some newer devices are equipped with semiconductor flash memories. These *Solid State Disk (SSD)* storage media are still more expensive than hard disks and, in addition, do not yet have the same storage capacity. However, they have the advantage of being less susceptible to physical stress (knocks, bumps, etc.). They also run on less electricity, which has advantages especially for mobile devices in terms of increasing battery life. With falling unit prices and higher storage capacities it can be anticipated that notebooks will increasingly be fitted with SSDs in the future[15].

Hard disk drive platters can generally be divided into those based on either glass or aluminum in terms of their substrate material. Whilst aluminum-based platters are usually used in a 3.5 inch format, 2.5 inch hard disk drives are primarily equipped with two or three glass-based platters[16]. A single glass-based platter of 2.5 inch format weighs around 4.8 g.

15 There is currently no reliable data on the material composition of solid state disks. However, as far as critical raw materials are concerned, it can be assumed that these semiconductor storage devices are important in terms of precious metals. The effect on the total quantities of precious metals in notebooks cannot be established at present. However, as some components containing precious metals become unnecessary (hard disk drive PCB), the simplified assumption is made that the quantity of precious metals remains unchanged. However, there are changes in the content of rare earths, as SSD drives do not contain permanent magnets (see Section 3.4).

16 As hard disk drives with two data platters have flatter profiles than hard disk drives with three platters, modern slim notebooks mainly use hard disk drives with two data platters.

Figure 9: Hard disk drive platters with 3.5 and 2.5 inch format (photo Oeko-Institut)



Analysis data for precious metals are available from Umicore for both types:

Table 17: Precious metal concentrations in hard disk drive platters

	Ag [mg/kg]	Au [mg/kg]	Pt [mg/kg]	Pd [mg/kg]	Rh [mg/kg]	Ru [mg/kg]
Aluminium-based	850	21	0	14	0	<7
Glass-based	<3	<6	38	<2.3	<3	<6

Source: Umicore 2011

These figures enable the following total concentrations to be estimated for hard disk drive platters in notebooks:

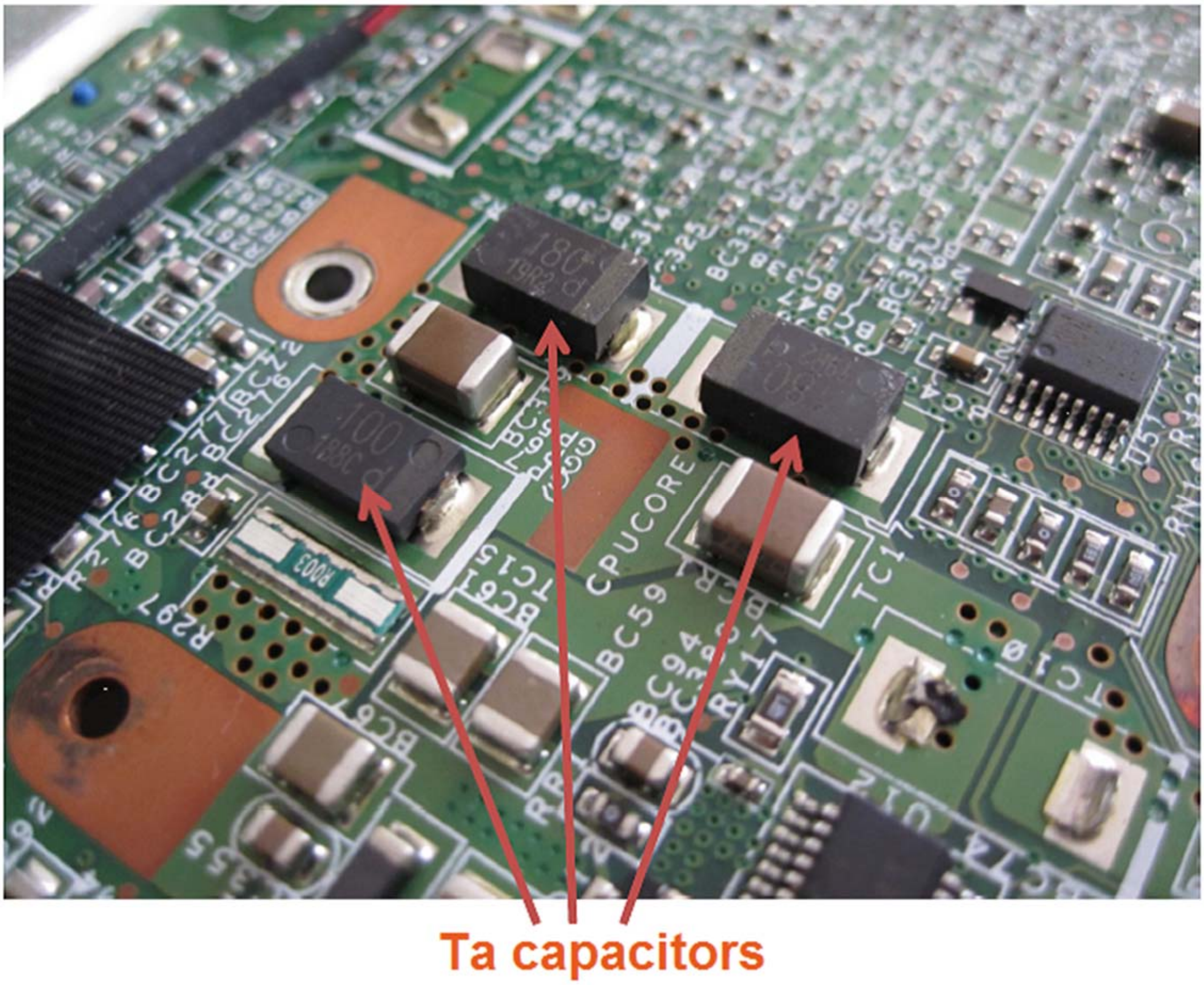
Table 18: Quantity of precious metals in the hard disk drive platters of a notebook

Ag [mg]	Au [mg]	Pt [mg]	Pd [mg]	Rh [mg]	Ru [mg]
< 0.1	< 0.1	0.4	< 0.1	< 0.1	< 0.1

3.2 Tantalum

Assembled PCBs contain a range of other metals in addition to the precious metals. In terms of critical raw materials, tantalum is of particular importance. Tantalum is used in high-capacity capacitors. As it cannot be recovered in the refining process for precious metals, there are no data comparable to that in Table 15 and Table 16. Although some older sources specify a percent by weight of 0.0157% or 4.71 g for a desktop PC (ACRR, undated) nothing is really known about the basis for this value. Furthermore, this value relates to device generations from the 1990s and should therefore be viewed with caution.

Figure 10: Tantalum capacitors on the motherboard of a notebook (photo Oeko-Institut)



On the other hand, it is known that Ta capacitors have typical Ta concentrations between 24.4% and 42.6% and a mean value of 36.7% (ZVEI 2003). A Ta percentage weight of 28% was determined from Ta capacitors in post-consumer recycling (Schöps 2011). The Ta capacitors on all the PCBs in a notebook had a total weight of 4.63 g, corresponding to a total quantity of Ta of around 1.7 g for a mean Ta content of approx. 36.7%. It should be noted that the analysis only includes capacitors with a minimum size of approx. 2 x 2 x 3 mm. The Ta content might be slightly higher if all the smaller Ta capacitors were to be included. It should also be noted that – depending on prices of raw material – Ta capacitors could be partly substituted by other types of capacitors. It can therefore be assumed that the Ta content of notebooks will vary significantly depending on the year of manufacture and device generation.

3.3 Indium

Indium is present in LCD displays in the form of indium tin oxide (ITO). The available data for the indium content of displays and the uncertainties associated with it are described in more detail in Section 2.1 An indium content of 700 mg/m^2 of LCD display surface is assumed in what follows.

The total indium content for a display surface of 552 cm^2 for a 14-inch LCD screen is therefore around 39 mg.

3.4 Rare earths

In notebooks, rare earths are primarily used in permanent magnets and lights. The rare earths in the display lights are dealt with in detail in Section 2.2.

Permanent magnets based on rare earths – also known as neodymium iron boron (NIB) magnets – are used in the following components of notebooks:

- Voice coil accelerator in the hard disk drive (see Figure 10)
- Spindle motor for the hard disk drive (see Figure 11)
- Spindle motor for the optical drive (see Figure 11)[17]
- Loudspeaker

The weights of the magnets are shown in Table 19.

[17] From a technological viewpoint, optical drives are divided into CD, DVD and Blu-ray drives. However, the design and principal mechanical and electronic layouts only have minor differences so that the values given here can be considered representative for all the types.

Table 19: Applications and weights of rare earth magnets in notebooks

Magnet application	No. of magnets per notebook	Mean total weight per notebook [g]
Voice coil accelerator for a 2.5 inch HDD	usually 2, sometimes 1	3.0
Spindle motor for HDD	1 ring magnet	1.1
Spindle motor for optical drive	1 ring magnet	1.6
Loudspeaker magnets	2	2.5

Figure 11: Rare earth magnets from the voice coil accelerator (photo Oeko-Institut)

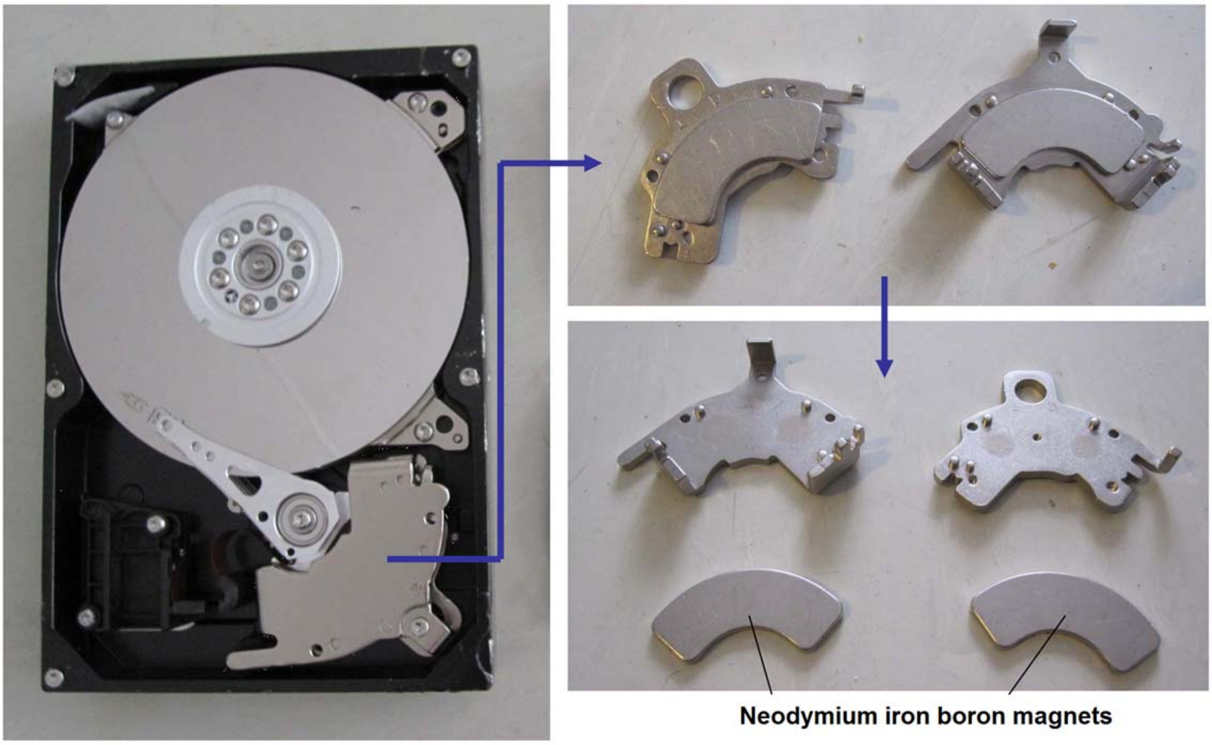
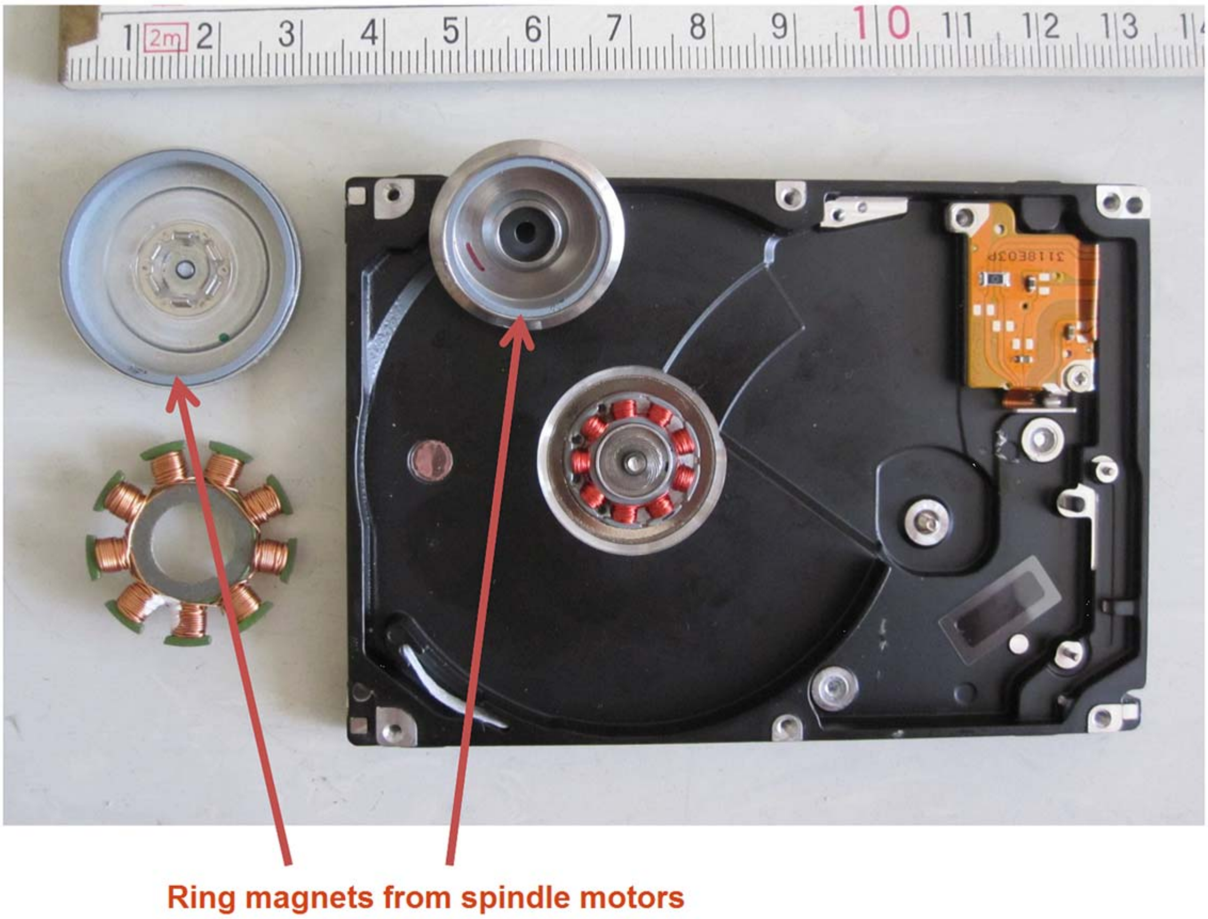


Figure 12: Opened spindle motors with ring magnets from the optical drive (left) and hard disk (right) (photo Oeko-Institut)



The rare earth percentages of these magnets are specified by VAC (2011) as shown below:

Table 20: Concentrations of rare earths in magnets in notebooks

	Nd [%]	Pr [%]	Dy [%]
Magnets for voice coil accelerator	29% together		2.3%
Ring magnets for spindle motors	29%	0%	0%
Loudspeaker magnets	31% together		0%

Source: VAC 2011

It should be noted with regard to the data on neodymium and praseodymium in the magnets from the voice coil accelerator that some manufacturers partially replace neodymium with the slightly cheaper praseodymium for cost reasons. However, according to Hatch (2011), this is only practical up to a mixing ratio of a maximum of 3:1 as at higher praseodymium levels the properties of the magnets would suffer. In what follows it is assumed that the mean ratio of neodymium to praseodymium is 5:1.

The following concentrations can therefore be estimated for magnets in notebooks:

Table 21: Amounts of rare earths in magnets in notebooks

	Nd [mg]	Pr [mg]	Dy [mg]
Magnets for voice coil accelerator	725	145	60
Ring magnet from the HDD spindle motor	319	0	0
Ring magnet from the spindle motor in the optical drive	464	0	0
Loudspeaker magnets	646	129	0
Total	**2,136**	**274**	**60**

3.5 Cobalt

Cobalt is used primarily in the notebook batteries. The battery pack used in notebooks usually has six to eight lithium-ion battery cells (see Figure 13).

Figure 13: Battery cells from the battery pack (photo Oeko-Institut)

Other types of batteries such as e.g. NiMH are only of secondary importance in notebooks. The positive electrode in lithium-ion cells in notebooks consists of lithium cobalt oxide ($LiCoO_2$) in most cases (Lauwigi et al. 2011). Although variations in the cobalt content can arise depending on the technology and design, Hagelüken & Buchert (2008) specify a mean content of 65 g per battery pack for a notebook. These data are supported by analysis results from Umicore Battery Recycling (2011), according to whom mixed lithium-ion battery packs of small and medium sizes display a mean cobalt content of 13.8%. For a unit weight of approx. 350 g per notebook battery pack, the Co content of just below 50 g is therefore in the same order of magnitude.

3.6 Summary of critical metals in notebooks

The results of the analyses in Sections 3.1 to 3.5 are shown in Table 23. It should be noted that these values are provided as an indication and cannot be applied to specific models or sizes. Many of the values have been derived from measurements on waste appliances. Differences may result due to modifications in product design in newer generations of devices which could not be included in these data because they are often covered by trade secrets or have not yet been calculated using aggregated data for an average product. For the extrapolation to the number of devices sold in Germany in 2010 (Table 23) it was borne in mind that the background illumination of the notebooks now being sold is partly based on CCFL tubes and partly on white LEDs. Table 22 summarizes the values used for these extrapolations. The values given in Section 2.2 were taken as the basis for the sales figures for notebooks and the market share of new notebooks with LED background illumination. The mean number of white LEDs incorporated in an LCD notebook display is specific to the manufacturer. There are therefore no generally valid figures available. However, on the basis of the sample case studies on different background illumination technologies in LCD displays (Young 2011), an assumption of 50 WLEDs per notebook display would seem to be a good guideline.

Table 22: Sales figures for notebooks used in the private sector (Germany 2010), the market share of devices with background illumination using white LEDs (WLEDs) and the estimated number of WLEDs used in the background illumination per device (see also Section 3.7)

Device class	No. of devices sold in Germany in 2010[18]	Market share of background illumination using WLED in 2010	Number of WLEDs per device
Notebooks (private sector)	7,097,000	90%	50

The following table displays the amounts of critical raw materials in notebooks sold in Germany in 2010. The greatest quantitative importance is shown by cobalt (over 460 tons/year), neodymium (15 tons/year), tantalum (12 tons/year), silver (3 tons/year) and praseodymium (almost 2 tons/year). However, indium, the precious metals gold, palladium

[18] These sales figures only include the private sector.

and platinum plus additional rare earths such as dysprosium are of interest for the recycling industry. It is important to stress that this only includes the potential in notebooks sold to private customers: i.e. the total number of notebooks sold (an important group of devices for the business sector) is considerably greater than the 7,097,000 units per year mentioned above for Germany in 2010 and therefore also the total potential of critical metals. Lastly it should be emphasized that e.g. copper is contained in considerably larger quantities in notebooks. Copper plays an important role in the recycling industry, both for technical reasons (collecting agent for precious metals in the refining process) and for economic reasons. As a whole the data for notebooks confirm the large potential of this group of products for the recycling of critical metals.

Table 23: Mean content of critical raw materials in notebooks (incl. LCD monitors)

Metal		Content per notebook (CCFL[19]) [mg]	Content per notebook (LED[20]) [mg]	Content in all notebooks sold in Germany in 2010 [kg]	Occurrence
Cobalt	Co	65,000	65,000	461,305	Lithium-ion batteries%)
Neodymium	Nd	2,100	2,100	15,159	Spindle motors (37%), voice coil accelerators (34%), loudspeakers (30%)
Tantalum	Ta	1,700	1,700	12,065	Capacitors on the motherboard (90%), capacitors on other PCBs (10%)
Silver	Ag	440	440	3,106	Motherboard (57%), other PCBs (43%)
Praseodymium	Pr	270	270	1,945	Voice coil accelerators (53%), loudspeakers (47%)
Gold	Au	100	100	736	Motherboard (54%), other PCBs (46%)
Dysprosium	Dy	60	60	426	Voice coil accelerators (100%)
Indium	In	40	40	286	Display & background illumination (100%)
Palladium	Pd	40	40	280	Motherboard (64%), other PCBs (36%)
Platinum	Pt	4	4	28.40	Hard disk drive platters (100%)
Yttrium	Y	1.80	1.60	11.50	Background illumination (100%)
Gallium	Ga	0.00	1.60	10.30	LED background illumination (100%)
Gadolinium	Gd	0.01	0.75	4.80	Background illumination (100%)
Cerium	Ce	0.08	0.10	0.69	Background illumination (100%)
Europium	Eu	0.13	0.03	0.28	Background illumination (100%)
Lanthanum	La	0.11	0.00	0.08	CCFL background illumination (100%)
Terbium	Tb	0.04	0.00	0.03	CCFL background illumination (100%)

3.7 Market data for notebooks

The market for notebooks and other mobile terminal devices varies greatly over time, partly because it is controlled by private demand. This responds very quickly to price fluctuations, technical innovations and the appearance of new classes of products on the market, such as tablet PCs and smartphones. In recent years notebooks and other mobile terminal devices have developed into the driving forces on the German computer market. According to CEMIX (2011), sales of mobile computers in the private sector have risen by a factor of 3-4 since 2005 and were running at around 1.8 million units in the first quarter of 2011 in comparison to a figure of around 630,000 devices in the same quarter in 2007 (see Figure 14). Over the same period the average price of a notebook dropped by about half which, along with the

[19] with CCFL background illumination (approx. 10% of all new notebooks in 2010)

[20] with LED background illumination (approx. 90% of all new notebooks in 2010)

increasing performance, has pushed up demand. In total, 7,097,000 notebooks were sold to the private sector in Germany in 2010 (see Table 24), although this figure includes the tablet PCs which were available on the market for the first time in this year (CEMIX (2011). It is not only the private sector where notebooks are dominant. According to data from the Gartner market research company, if the business sector is included, around 68% of the approximately 9 million computers sold in Germany is made up of notebooks (Gartner 2011a). It should be noted that, in contrast to CEMIX, Gartner has excluded tablet PCs from the computer statistics.

Figure 14: Quarterly sales volume, average price[21] and revenue from notebooks[22] (CEMIX)

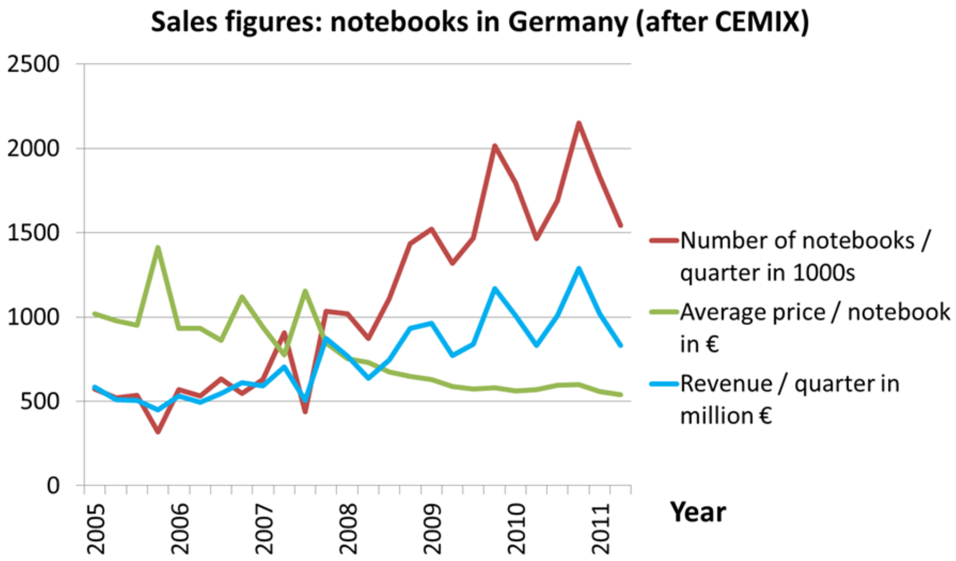


Table 24: Sales, percentage change against previous year and average price for notebooks on the German market (private sector) in 2010, from CEMIX (2011)

Product group	Notebooks
Sales in 2010 in 1000s	7,097
Change compared to 2009	12.3%
Average price in 2010 [€][23]	583

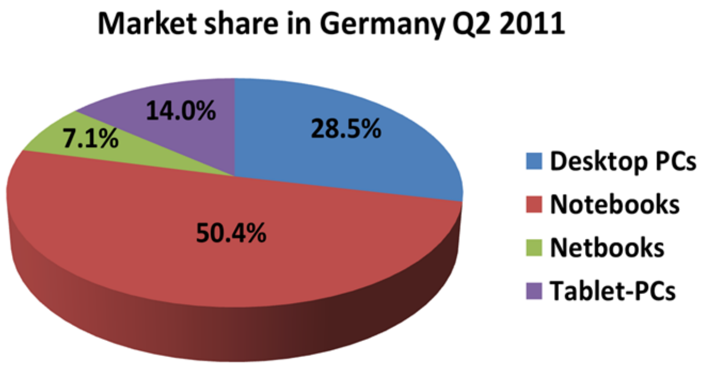
However, since about the middle of 2010, these have captured the mobile computer market along with smartphones. According to Young (2011), even in 2010 8% of sales worldwide were due to tablet PCs (see Figure 16), while in Germany in the second quarter of 2011 their

[21] including VAT

[22] private sector only

market share had already risen to 14% (see Figure 15). In comparison, the German market share for traditional desktop PCs was only 28.5%, with 50.4% for notebooks and 7.1% for netbooks. Considering only the traditional PC business, notebooks and netbooks together account for around two thirds (Heise 2011, in agreement with Gartner 2011a).

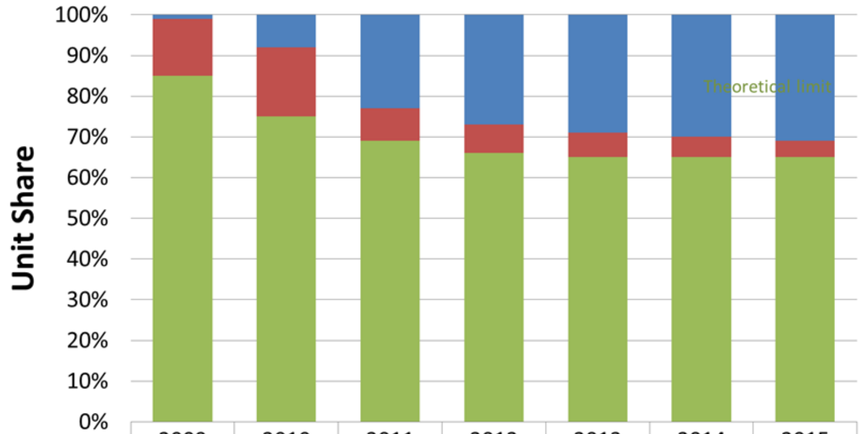
Figure 15: Percentages of different types of computer on the German market, 2nd quarter, 2011 (from Heise 2011)



According to Young (2011), tablet PCs are likely to have a market share of up to 30% in 2013 (see Figure 16). The market for netbooks, however, which still accounted for approx. 17% of sales worldwide in 2010, already appears to be heading for saturation. It is anticipated that the market share will fall to only around 5% by 2013 (Young 2011). This development also reflects the decision by many private consumers who increasingly choose to purchase a tablet PC rather than a notebook. In Germany, sales of computers in the private sector (minus tablet PCs) in the third quarter of 2011 dropped by 17% compared to the previous year. The notebook sector suffered an even larger decline whilst sales of desktop PCs remained somewhat more stable (Gartner 2011b). Gartner does not predict any recovery of the market for the remainder of 2011. Due to ongoing floods in Thailand, bottlenecks in the supply of hard disk drives and other electronic components could lead to price increases for all types of computers and, as a consequence, to a continuing fall in demand and sales.

[23] incl. VAT

Figure 16: Percentage[24] of notebooks, netbooks and tablet PCs in sales of mobile computers (Young 2011)



	2009	2010	2011	2012	2013	2014	2015
Tablets	1%	8%	23%	27%	29%	30%	31%
Netbooks	14%	17%	8%	7%	6%	5%	4%
NBs	85%	75%	69%	66%	65%	65%	65%

Unlike LCD TV sets, notebooks already mainly use white LEDs for the background illumination. The corresponding market share was around 92% worldwide in 2010, with an ongoing slightly upward trend (see Figure 5, Young 2011). An interesting point in relation to the use of critical raw materials is the fact that tablet PCs require an approximately 60% brighter background illumination than do traditional notebooks. This means that relatively more LEDs are required per device. The increasing degree of resolution of the screens used in tablet PCs also requires brighter background illumination (Young 2011).

3.8 Service life and collection rates for notebooks

The service life of notebooks was estimated at an average of 5.6 years as part of the EU eco-design process (EuP 2007). This figure includes both the first use and the length of an average second use. In 2008 319,983 t of the WEEE product category 3 (IT and telecommunication equipment) were put on the market in Germany. In the same period 155,007 t of this category were collected through the official return and collection systems for controlled recycling and disposal (BMU 2009). If it is assumed that these values can be applied to notebooks, then the collection rates can be estimated at just 50% for notebooks in Germany[25]. There is no reliable data on the whereabouts of the remaining devices. In

[24] Projected from 2011

[25] This value does not contain a delay due to the use phase of the equipment. It is therefore merely an estimated value for the actual collection rate.

general it can be assumed that the whereabouts of notebooks is subject to similar dynamics as that of flat screens (see Section 2.6).

3.9 Status of pre-treatment technology for notebooks

Annex II of the Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment lists those materials and components which need to be handled separately during the disposal of waste equipment. The following components are of importance in notebooks:

- Printed circuit boards with a minimum surface area of 10 cm^2;
- Displays including their gas discharge lamps (and the housing if applicable)[26];
- Batteries.

Waste disposal companies in the EU are therefore legally obliged to manually remove the visual display unit and the battery pack in an initial "detoxification" stage and send these for separate treatment. In many cases the motherboard is not removed manually but fed into a mechanical pre-treatment (usually a shredder with subsequent mechanical sorting) along with the remaining device components. A more thorough manual disassembly is only carried out by a few, mainly smaller companies.

The standard detoxification stages and mechanical pre-treatment and sorting produce the following fractions:

- Lithium-ion batteries (un-shredded)
- Visual display unit (un-shredded)
- Plastics fraction (sometimes subdivided according to different types of polymers)
- Steel fraction
- Aluminum fraction
- Printed circuit boards
- Light shredder fraction (glass, elastomers, miscellaneous materials)

The lithium-ion batteries are sent to a pyro-metallurgical refining process for recovery of the cobalt and nickel (see Section 6.2). The display units are disposed of as described in Section 2.7. The plastics fraction, steel, aluminum and PCBs are passed on to the relevant markets for materials recycling. The main economic aim of the particularly important PCB fraction is to recover the copper, gold, silver and palladium. Although a range of additional metals are

[26] The directive stipulates a threshold of 100 sq. cm display surface. All displays larger than 100 sq. cm must be given special treatment.

obtained, some with good recovery rates, other critical metals such as tantalum are lost in this process (see Section 6.1). Successful recovery of tantalum would require a prior separation and removal of the tantalum capacitors which is currently only carried out on a pilot scale by a very few companies (see Section 6.5).

For the mechanical pre-treatment and sorting processes in general it should be noted that these are only able to separate the complex intermix of materials in a very inadequate manner, so that many components containing important resources are only partially sorted into the correct fractions. This leads to high losses of critical raw materials[27]. For one shredding company which can be viewed as fairly representative, Chancerel & Rotter (2009) have shown that, in the mechanical treatment process, 74.4% of the gold and palladium and 88.5% of the silver end up in fractions from which precious metals cannot be recovered. If it is assumed that more careful pre-treatment methods are used in some plants (e.g. manual removal of the motherboard), then losses of precious metals can be estimated at approximately 70%.

Due to their data content, special attention is often paid to the disposal of hard disk drives which are of particular importance for raw materials. Customers often make a guaranteed deletion of data as one of the terms of contract for the waste disposal company. Data can be deleted either using software, with strong magnetic fields or by physical destruction (shredding) of the storage media. However, it can be assumed that a certain percentage of hard disk drives are treated as a separate waste stream.

A significant point concerning the recovery of critical raw materials from hard disk drives is that the fractions of importance for raw materials (incl. PCBs and magnets) are difficult to separate from the other material (incl. stainless steel and aluminum). This is mainly due to the very compact design and the use of a wide variety of different screws. In addition, as well as the screw connections, the cover on the hard disk drive (usually made from stainless steel) is firmly glued to the aluminum housing. The consequence of this is that it is very labor intensive to manually open the hard disks and separate the components containing important raw materials into different types, and the process can only be mechanized to a certain extent. The PCBs are the easiest to remove as in most cases these are screwed onto the underside of the hard disk drive from outside and can therefore be dismantled without opening the cover.

Possible stages which could be mechanized include the following measures:

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[27] Losses occur primarily at the interface between the pre-treatment and the refining processes. If raw material fractions of importance such as fragments of assembled PCBs are sorted into other fractions (e.g. aluminum or steel), then the precious or special metals in them are lost by dissipation in the downstream refining process.

- Use of drills to drill out the screw connections
- Heating the PCBs to release the adhesive bonding (Scrap 2011)

This is the reason why hard disk drives are fed into a mechanical shredder and sorter along with other components by most waste disposal companies, resulting in the bulk of the critical raw materials which they contain being subject to dissipative loss in the subsequent processing. Whilst losses of precious metals can be estimated at more than 70% (see remarks on previous page), the losses of rare earths reach 100%, because the magnets attach to steel parts during sorting and therefore all end up in the steel fraction.

3.10 Potential for optimization in the recycling chain

To protect resources it is recommended that notebooks should be manually disassembled to the greatest extent possible. Besides the legally stipulated detoxification (removal of the display and batteries), the assembled motherboard and potentially the PCBs for the drive and hard disks should be removed and fed into a suitable recycling process (see Section 6.1).

Recycling the hard disk drives is of particular importance for reasons of resource conservation. According to Kara et al. (2010), over 30% of the neodymium used in 2008 was destined for hard disk magnets. The proportion was around 35% in 2003. This means that hard disks represent an important potential secondary source of raw materials for neodymium (and to a certain extent also praseodymium and dysprosium). The reason for this importance is that other applications containing neodymium, such as wind turbines and hybrid and electric vehicles have not currently reached the end-of-life stage in any quantity.

It is therefore generally recommended to send hard disks – as far as economically feasible – to a manual disassembly process (see Section 3.9). Besides removing the magnets, this measure would also lead to a noticeable increase in the quality of the aluminum, stainless steel and PCB fractions. It should be borne in mind that large-sized hard disk drives have considerably larger quantities of important raw materials than do notebook hard disk drives. Manual disassembly should therefore focus primarily on 3.5 inch hard disks (those from desktop PCs and computing centers)[28].

As the material recycling of rare earths from magnets is not yet established on an industrial scale (see Section 6.3), the magnets obtained in this process should be put into temporary storage.

[28] While 2.5 inch hard disk drives have an average weight of 109 g, 3.5 inch hard disk drives weigh 529 g (Oeko-Institut measurements on five 2.5 inch and ten 3.5 inch hard disk drives).

4 Smartphones

Over the last three years, smartphones have rapidly replaced the traditional mobile phone many times over. Many publications on critical metals like to cite mobile phones as an example as they contain numerous metals, including many critical metals, even if mostly in very small absolute quantities (UNEP 2009). This also applies to smartphones which, in contrast to traditional mobile phones, provide the user with numerous additional new applications (apps) – and all this with a comparatively low weight and volume. High performance in electronic equipment often entails a relatively high content of special and precious metals. The following metals and metal groups from the list of 14 EC metals have been identified as of relevance for smartphones by a project which is still ongoing (prosuite 2011):

- Cobalt,
- Gallium,
- Indium,
- Niobium,
- Tantalum,
- Tungsten,
- Platinum group metals and
- Rare earths.

Metals such as copper, nickel, lead, bismuth, lithium (batteries) and, of course, the important precious metals silver and gold, should be added to this list. Of the critical metals, rare earths can be linked to the permanent magnets, cobalt to the battery, indium to the LCD display and tantalum, gallium and the precious metals to the assembled PCB (prosuite 2011). Quantitative data for the amounts of critical metals in smartphones could not be determined, despite thorough investigation. However, the future growing demand for gallium for the increasingly powerful processors (GaAs or GaN) for smartphones must be pointed out (Achzet 2001).

Typical figures for mobile phones are therefore used as a basis for some important precious metals. Recycling experts, however, assume that the relative amounts in smartphones will tend to be higher (Umicore 2011), i.e. the following data for the content of precious metals should be seen as on the conservative side. Thanks to the high value of precious metals and the relatively high amounts, they are an important driving force for the recycling of mobile phones and hence also for the future recycling of smartphones.

4.1 Precious metals

Based on analysis values from Umicore for mobile phones, Hagelüken und Buchert (2008) give the following amounts of precious metals[29] per device:

- Silver: 250 mg
- Gold 24 mg
- Palladium 9 mg

Assuming a mean weight for a mobile phone (without battery) of 90 g and a mean weight of a smartphone of 110 g (also without battery), then a linear extrapolation can be made of the minimum content of precious metals in smartphones:

- Silver: 305 mg
- Gold 30 mg
- Palladium 11 mg

These quantities of precious metal per unit may appear small. However, it can be pointed out using the example of palladium that, at 100 ppm, the content of palladium in mobile phones/ smartphones is at least 10 times greater than in the natural ore which is used for the exploitation of platinum group metals. Furthermore, recycling smartphones provides synergies from the potential recovery of other metals such as copper, lead, nickel, bismuth, etc.

4.2 Indium, gallium, tantalum

There are no quantitative data available for the content of these critical metals in smartphones. There is a basic need for research on this in order to determine the future importance in smartphones and the potential options for the recycling industry.

4.3 Cobalt

Batteries in standard mobile phones weigh around 20 g of which approx. 3.8 g consists of cobalt (Hagelüken & Buchert 2008). The Oeko-Institut's own tests have recorded a battery weight of 33 g for a smartphone. This results in an estimate of around 6.3 g of cobalt in the batteries per smartphone.

[29] Although traces of platinum are also found in mobile phones, these concentrations are negligible compared to the silver, gold and palladium.

4.4 Rare earths

There are also no quantitative data available for the amount of rare earths in smartphones. It is known that mobile phones and smartphones also contain small loudspeakers with neodymium iron boron magnets. The Oeko-Institut measured a permanent magnet from a mobile phone with a weight of 190 mg. Assuming a composition similar to that in notebook loudspeakers (rare earth percentage of 31%), this gives a quantity of rare earths per smartphone of 60 mg with a ratio of neodymium to praseodymium of approx. 5 to 1.

4.5 Summary of critical metals in smartphones

No quantitative data could be found for a whole range of critical metals such as gallium, indium and tantalum, despite analyzing data from mobile phones. Data can be estimated for smartphones for the following critical metals:

Table 25: Content of important critical metals in smartphones (Oeko-Institut e.V. estimates)

Metal	Metal per smartphone in g	Components
Cobalt	6.300 g	Battery
Silver	0.305 g	PCB
Gold	0.030 g	PCB
Palladium	0.011 g	PCB
Neodymium	0.050 g	Loudspeaker magnet
Praseodymium	0.010 g	Loudspeaker magnet

4.6 Market data for smartphones

Smartphones , like tablet PCs, are currently conquering the market, especially amongst the important younger consumer group. In 2010 around 7,702,000 smartphones were sold in Germany alone, with growth up 161.4% compared to 2009 (GfK, gfu 2011). For 2010, this gives a potential for the following critical metals from smartphones sold in Germany:

Table 26: Potential quantities of important critical metals in smartphones in 2010

Metal	Metal per smartphone in g	Metal potential from smartphones sold in Germany in 2010 in kg	Components
Cobalt	6.300 g	48,500	Battery
Silver	0.305 g	2,350	PCB
Gold	0.030 g	230	PCB
Palladium	0.011 g	85	PCB
Neodymium	0.050 g	385	Loudspeaker magnet
Praseodymium	0.010 g	77	Loudspeaker magnet

As can be seen in the table above, the potential for cobalt (batteries) from smartphones sold in Germany in 2010 is over 48 tons. There are also 2 tons of silver and over two hundred kilograms of gold. As mentioned frequently, smartphones also contain other interesting metals, in particular large quantities of copper. The precious metals silver, gold and palladium are already being recovered from old mobile phones during copper recycling. It is likely that this will be extended to smartphones in the future. A relatively short actual service life of three to four years at the most can be assumed for electronic products such as smartphones, largely driven by the acquisition of higher-performance and newer generations of devices. This means that the massive increase in the last three years in the number of smartphones in the use phase will soon reach the end-of-life stage and therefore the recycling industry in Germany.

4.7 Collection rates for smartphones

According to calculations by Chancerel (2010), in 2007 2,273 t of mobile phones became obsolete, of which only 110 t were collected by official return and collection systems. This means that in Germany only approx. 5% of all mobile phones are sent to controlled recycling facilities. It can basically be assumed that this value also applies to smartphones. As with flat screens and notebooks, the whereabouts of the remaining devices cannot be stated with certainty. However, in general it can be assumed that a large proportion of the mobile phones which are not collected are stored by the users over longer periods of time, so that a delayed end-of-life management can be expected. In addition, the ease with which small devices can be binned plays a role in the improper disposal via domestic waste.

4.8 Status of recycling technology for smartphones

The recycling of smartphones – although as a relatively new product group they have not yet reached the end-of-life stage in any great quantity – can be compared to the recycling of mobile phones and is just as easy. It is important to remove the cobalt-containing lithium-ion batteries in order to send these separately to suitable battery recycling plants (see Section 6). Mobile phones are normally fed into pyro-metallurgical plants such as e.g. Umicore's facility in Belgium, without any further disassembly. This processing primarily recovers high yields of metals such as copper, lead, nickel and tin and precious metals such as gold, silver and palladium.

4.9 Potential for optimization in the recycling chain

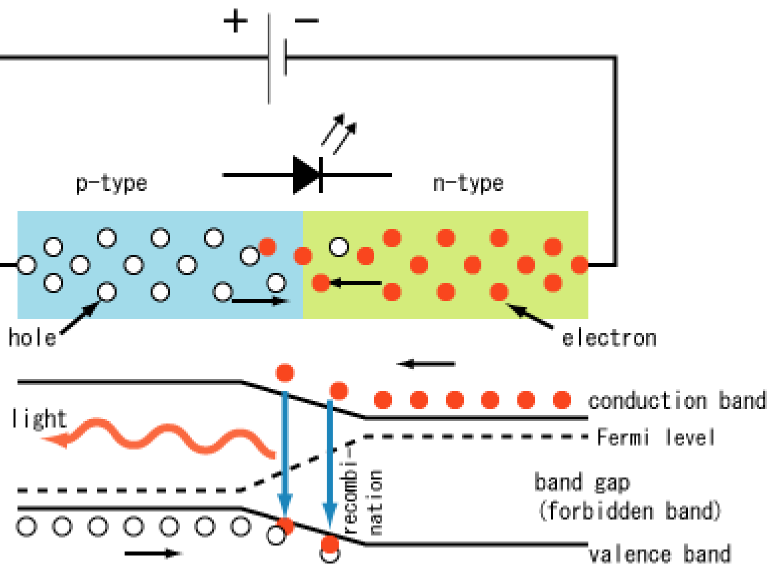
The most important measure for increasing the optimization potentials in the recycling chain for smartphones is clearly to raise the currently very low collection rate. Furthermore, the importance of removing the cobalt-containing batteries must be stressed. Recycling using the proven copper bus bar enables the recovery of not only copper but the precious metals silver, gold and palladium at recovery rates of 95%. There are now equally efficient processes for recovering cobalt from the lithium-ion batteries. For the other critical metals such as tantalum, gallium, indium, neodymium and praseodymium, there is a need for basic research on the quantities involved and on the issue of whether these metals can be recovered at reasonable expense despite the probably low absolute quantities.

5 LED lights

In recent years white LEDs have increasingly been used for lighting. These new lights have many benefits. For instance they currently provide very energy-saving lighting due to a high luminous efficacy of 50-80 lm/W. Their light is of high quality with a color rendering index of 80-90 and a continuous spectrum. They have a long service life of up to 50,000 hours, good switching stability and start-up time (period between the beginning of the current flow through the LED and reaching their maximum light intensity) and are very shockproof and vibration-resistant. In addition, their small design permits new design solutions. This enables a wide range of applications, such as in the automotive industry. With constantly rising values for luminous efficacy due to technological advances and the ability to produce LEDs with white light, they are also of interest for room lighting.

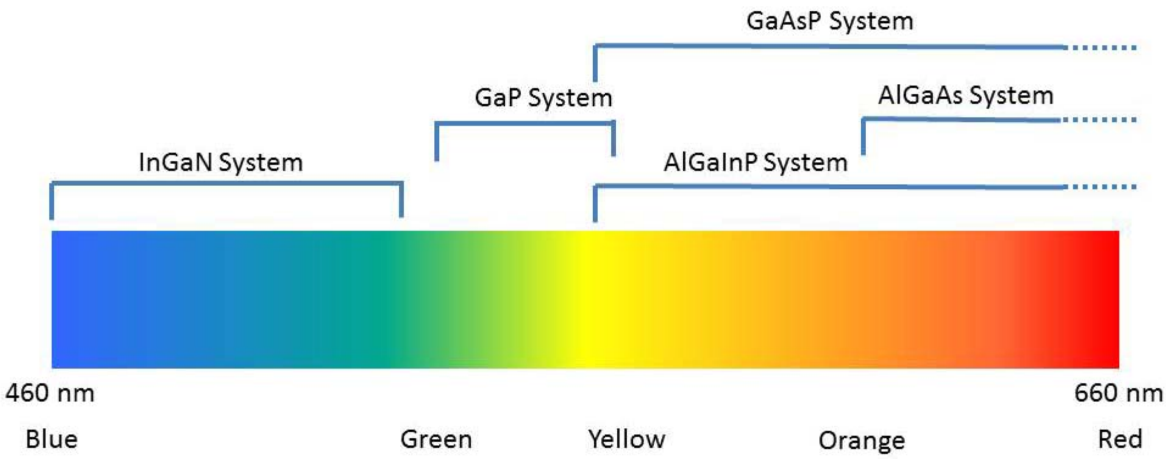
The basic design of an LED is similar to that of a semiconductor diode. Diodes are electronic components which only allow electrical current to pass in one direction. In a semiconductor diode the diode chip contains adjacent layers of an n- and p-doped semiconductor. An n-doped semiconductor can be imagined as a substance in which individual electrons can function as charge carriers. In contrast, in a p-doped semiconductor this is the missing electrons ("holes").

Figure 17: Operating principle of a semiconductor diode (Wikipedia, 05.12.2011, source: Use:S-kei)



If the semiconductor diode is now switched into the conducting direction, electrons flow from the n-doped side to the p-doped side (see Figure 17). This transition releases energy whose quantity is dependent on the crystal properties of the semiconductor used. In contrast to the simple semiconductor diodes where this energy is released in the form of lattice vibrations (= heat), in LEDs what is known as radiant transition takes place in which electromagnetic radiation is emitted. This can be in the form of infrared, visible or ultraviolet light, depending on the semiconductor band gap (see Figure 18).

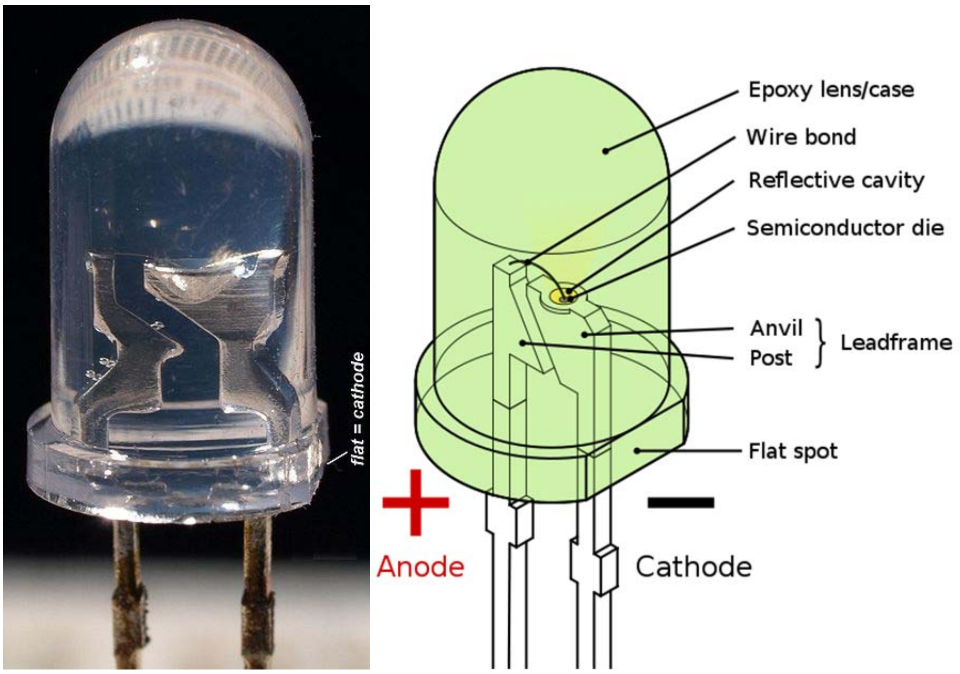
Figure 18: Effect of the semiconductor material used on the color of the LED light (diagrammatic)



The larger the band gap, the shorter is the wavelength of the radiation emitted. However, radiant transitions only take place for specific values of some lattice parameters of the semiconductor used. These parameters are mainly produced by what are known as III-V semiconductors which are composed of elements from the 3rd and 5th main groups of the periodic table. The basis of this compound is often gallium linked to arsenic, phosphorous or nitrogen. The light of an LED is initially mostly monochromatic. There are basically two ways of creating a white light for use in room lighting. The light of several colored LEDs can be superimposed, mixing them into white light. This has the benefit of achieving a relatively good luminous efficacy (this is usually larger for LEDs in the visible spectrum compared to LEDs in the near IR or near UV spectra). It also permits the color temperature to be set very precisely.

Colored LEDs are therefore mainly used in applications where this characteristic is important and the disadvantage of the high price is not a deciding factor, such as for lighting for TV recordings, stage lighting etc. The second type of white LEDs is more common for general use. This is based on a blue LED whose light, in a similar way to fluorescent tubes, undergoes a shift towards longer wavelengths through a coating of luminescent material. The composition of the coating of luminescent material and its thickness largely determine the color temperature of the resulting white light (cold white/similar to daylight: 5,500-6,000 K, warm white: 2,700-3,000 K). Different luminescent substances are usually combined to provide better color reproduction. The semiconductor normally used for this is gallium nitride (GaN). One disadvantage of this way of producing white light is the loss in luminous efficacy.

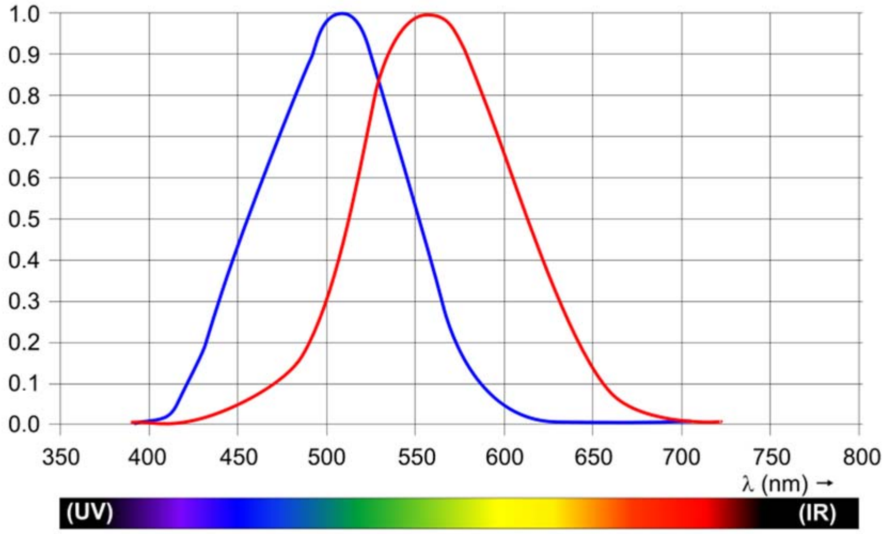
Figure 19: Photo and diagram of an LED (Wikipedia, Wikipedia, 05.12.2011, source Grapetonix; Inductiveload)



The semiconductor chip and luminescent material in an industrial LED are usually placed in a metal cup which bundles the light emitted in different directions and also serves to dissipate the heat produced. For practical applications these components are usually sealed in epoxy resin and mechanically fixed to a circuit board by means of the feed wires (anode and cathode) (see also Figure 19). A recent development is the SMD LED (surface mounted device LED) in which the LED is mounted directly on the circuit board. These enable a compact design and are only manufactured industrially.

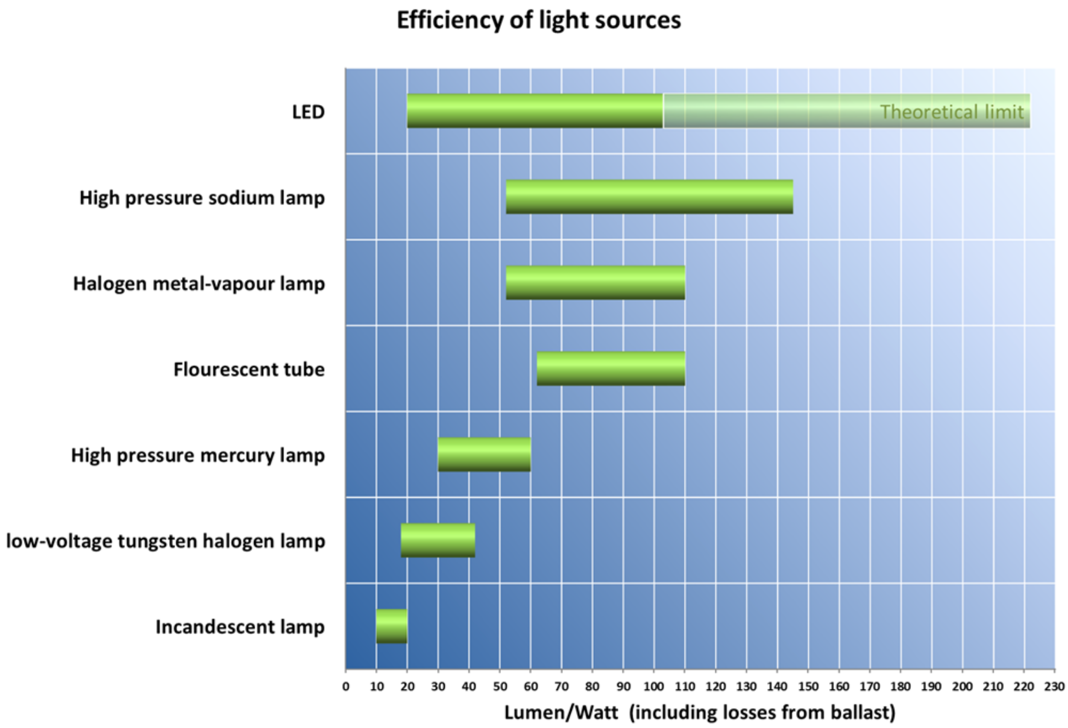
In order to quantify the subjective brightness of a light source, what is known as its luminous flux, measured in lumen (lm) is defined. The luminous flux is determined from the weighting of the spectral radiant flux of the light source (the electromagnetic energy radiated per unit of time) by the sensitivity curve of the human eye. This reaches its maximum in the green spectrum (see Figure 20).

Figure 20: Light sensitivity curve of the human eye, day vision (red), night vision (blue) (Wikipedia, 05.12.2011; source: Hhahn)



If a light source shines in this part of the spectrum (green light), then the eye perceives this as brighter than from a light source of the same power but of a different color temperature. What is known as the luminous efficacy of a light source defines the ratio of the luminous flux and power consumption of the light source and is given in the units [lm/W]. Therefore, the greater the luminous efficacy, the brighter the light source appears for the same power consumption. Conversely, if the same brightness is required, then a light source with a higher luminous efficacy can be operated at lower power and therefore saves electrical energy. The luminous efficacy of different common light sources naturally varies depending on the operating principle of the lights (see Figure 21).

Figure 21: Luminous efficacy of different light sources (source: Stadtwerke Düsseldorf, 05.12.2011)



Whilst a conventional light bulb has a luminous efficacy of a maximum of 20 lm/W, fluorescent tubes and energy saving lamps achieve values of over 100 lm/W. Although a typical high pressure sodium lamp has a very high luminous efficacy of up to 140 lm/W, it is not used in the home because of its almost monochromatic emission spectrum in the yellow range. Under laboratory conditions white LEDs have already demonstrated that luminous efficacies in the range of 200-250 lm/W are technically possible (Cree 2010, Nichia 2010, Cree 2011), a value already approaching the maximum physically possible luminous efficacy of 350 lm/W for cold white light (color temperature 6700 K). LED lights with a luminous efficacy of over 100 lm/W are already available commercially.

A significant variable for estimating the quantity of critical metals in WLEDs is the size (and therefore the weight) of the actual semiconductor chip. This largely depends on the design and varies from one manufacturer to the next. The product range of a single manufacturer also contains differing chip dimensions, depending on the requirements. In general, larger LED chips enable a lower current density and hence a somewhat higher luminous efficacy. However, the size of the chip has an upper limit as larger semiconductor crystals have a higher probability of lattice defects which impair the functional performance of the LED.

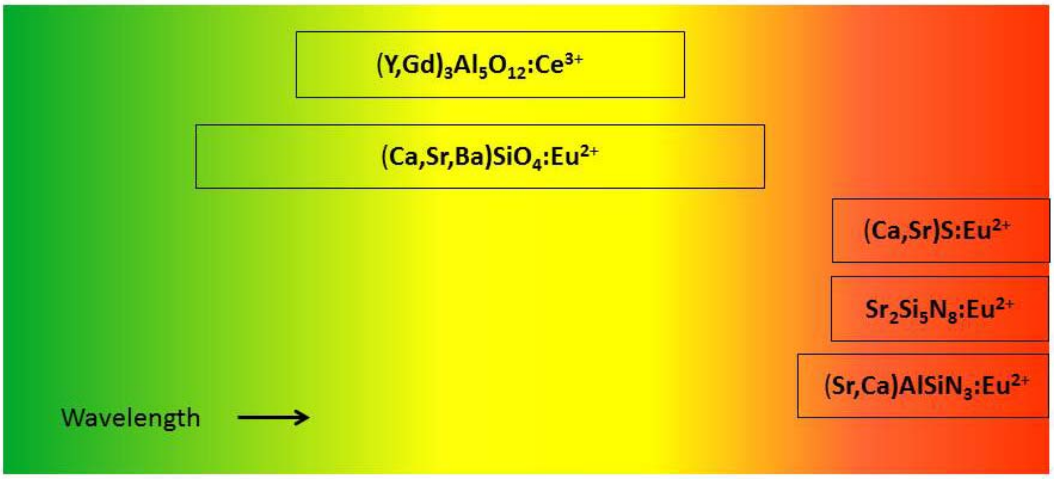
As lights using LED luminous material have only been on the market in large quantities for a short time, there is little data on which to base a realistic estimate of the typical service life of a light. In the laboratory environment the lifespan of a single white LED has been determined to be around 50,000 hours. LEDs become less bright with time (i.e. the luminous efficacy declines slowly) in contrast to incandescent lamps whose end of life is exactly defined when the filament breaks. In practice other factors also determine the actual lifespan of LED lights. It is reduced if the LED semiconductor chip is at too high a temperature, for example if there is inadequate heat dissipation through the lamp housing. The lifespan is also limited if the current densities in the LED are too high. The ballast required for current stabilization in LED lights is also a limiting factor. Depending on its design and quality it can sometimes have a shorter lifespan than the actual LED. As there is an increasing trend to combine the LED and ballast in a single module, when the ballast fails the LEDs in a light also have to be disposed of.

5.1 Rare earths, gallium and indium

Amongst the materials used in an average LED (see Figure 23) are also a range of critical metals. Rare earths in LEDs are mainly used in the luminescent substance which converts the high-frequency blue or near UV light from the actual LED chip into a continuous spectrum in the visible wavelength range. The composition of the luminescent material is critical for the performance of a WLED. Manufacturers' specifications on the exact composition of the luminescent substances they use are not usually published and are therefore almost impossible to obtain. The data which follow in this section are based on empirical values from professional experience

Cold white LEDs usually contain only a yellow luminescent substance whilst a red luminescent substance is added to warm white LEDs. The basis of the yellow luminescent substance in white LEDs is mainly Ce^{3+}-doped yttrium aluminum garnet (YAG) or gadolinium aluminum garnet (Y,Gd) AG:Ce^{3+}. The luminescent substance added in warm white LEDs obtains its red color spectrum from the activator ion Eu^{2+} as a doping. However, depending on the carrier medium, this can also emit in the yellow-orange spectral range (see Figure 22).

Figure 22: Spectral ranges of different carrier media and doping substances in the luminescent material of white LEDs.



Normally 0.1 mg of the yellow luminescent substance is used for cold white LEDs. Table 27 shows the proportion of the individual elements in a yellow luminescent substance for the chemical compound $(Y_{0.77}Gd_{0.2}Ce_{0.03})_3Al_5O_{12}$.

Table 27: Composition of a typical yellow luminescent material in a WLED.

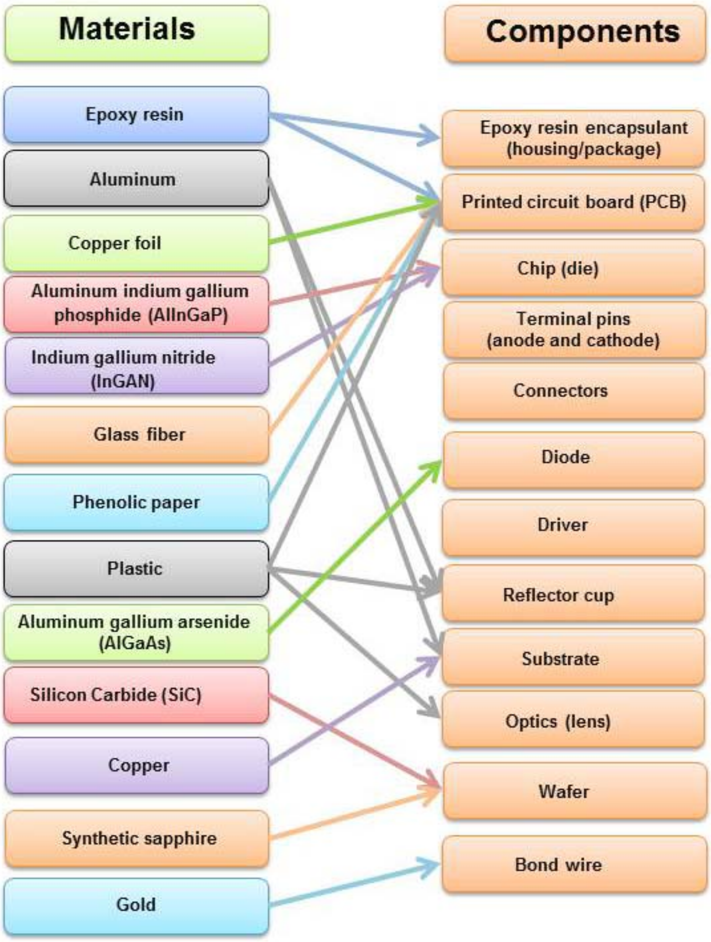
Element	**Y**	**Gd**	**Ce**	**Al**	**O**	**$(Y_{0.77}Gd_{0.2}Ce_{0.03})_3Al_5O_{12}$**
Molar mass (g/mol)	88.91	157.25	140.12	26.98	16.00	639.24
Coefficient	2.31	0.6	0.09	5	12	1
Percentage (rounded)	32%	15%	2%	21%	30%	100%
Weight per LED [µg]	32	15	2	21	30	100

In warm white LEDs, approx. 10 µg of the reddish, europium-containing luminescent material are added to the 100 µg of yellow luminescent material. If doping with 5 mol% europium (M = 151.96 g/mol) is assumed, then this gives quantities of 0.4 µg to 0.9 µg europium in a WLED (see Table 28).

Table 28: Composition of a typical red luminescent material in a WLED.

Luminescent substance	**Molar mass (g/mol)**	**Coefficient for Eu^{2+}**	**Percentage weight of Eu^{2+}**	**Weight of Eu^{2+} per LED [µg]**
$Ca_{0.5}Sr_{0.45}Eu_{0.05}S$	99.14	0.05	8%	0.9
$(Sr_{0.95}Eu_{0.05})_2Si_5N_8$	434.12	0.10	4%	0.4
$Ca_{0.5}Sr_{0.45}Eu_{0.05}AlSiN_3$	168.14	0.05	5%	0.6

Figure 23: LED components and the materials used in them (from CGGC)



Gallium is one of the important components of the actual LED chip. In an LED, the semiconductors gallium nitride (GaN) and indium gallium nitride (InGaN) emit light in the blue-green to ultra violet spectral region which is converted to white light by a luminescent substance applied to the chip. In white LEDs indium gallium nitride is mainly used in the chemical formula $In_xGa_{1-x}N$, where the size of the band gap and hence the wavelength of the light emitted varies linearly with the mixing parameter x. The indium:gallium mixing ratio is 40:60 mol% for the most frequently used LED chips which emit light with a wavelength of 450 nm (see also Zukauskas 2002). Varying figures are given for the dimensions of a typical LED semiconductor chip. Based on the professional experience of an expert, chip type A has a thickness of 10 µm for a base area of 1 mm. For chip type B, in contrast, this height is 250 µm (ISI 2009, citing Dagar 2008). The density of the $In_xGa_{1-x}N$ semiconductor can be taken to be 6.5 g/cm^3. This produces the values given in Table 29 for the LED chips of the two different types A and B.

Table 29: Composition of a $In_xGa_{1-x}N$ semiconductor chip LED, types A and B (see text)

Element	In	Ga	N
Molar mass (g/mol)	114.82	69.72	14.01
Coefficient	0.4 1.0	0.6 1.0	1.0 1.0
Percentage (rounded)	45% 58%	41% 35%	14% 7%
Weight per LED [mg]	0.029 0.170	0.0325 0.5300	

Chips of design A contain significantly less indium and gallium due to their smaller height. The data on the composition of LED chips and luminescent substances and on the absolute quantities of critical metals are very limited, mainly due to their classification as a trade secret. These data and all the projections and deductions arising from them must be taken purely as a general indication. Using the quantities of gallium and indium from chips of type A in the calculations should lead to rather conservative estimates of the demand for rare metals.

A demand forecast for 2030 can be estimated based on the material composition of type A which is summarized again in Table 30 and assuming future growth rates for the LED producing industries (ISI 2009):

Table 30: Typical content of critical metals in a white LED (used for projection of future demand)

Element	In	Ga	Ce	Eu	Gd	Y
Weight per LED [µg]	29.0	32.5	2.0	0.6	15.0	32.0

Indications of the future demand for gallium from the manufacture of LEDs can be derived from estimates of the growth of the LED market as a whole. This market, which covers both white and colored LEDs, is assumed to have a growth of 37% from 2006-2011, corresponding to an annual growth rate of 6.5% (ISI 2009 citing Steele 2007). It is assumed that the proportion of white LEDs increases from around 48% in 2006 to 60% in 2011, corresponding to approx. 4.6% p.a. Using these assumptions, 21 billion white LEDs are manufactured in 2009 and 25 billion in 2011, giving an annual growth rate of around 11% (see Table 31). Two scenarios with different dynamics are considered for the period after 2011 (ISI 2001). Scenario A has rather conservative dynamics, being based on growth of the total market of a fixed 6.5% p.a. and a constant proportion of white LEDs of 60%. This results in an annual growth of the market for white LEDs of 6%. The more dynamic scenario B envisages a growth in the total market of 15% p.a. from 2011-2020, followed by only 10% from 2020-2030 due to increasing market saturation. The proportion of white LEDs increases from 60% to 70% between 2011-2030. This corresponds to market growth for white LEDs of

16% in the period 2011-2020 and 11% in the period 2020-2030. According to the conservative scenario around 84 billion LEDs would be manufactured in 2030, in the more dynamic market development scenario around 271 billion.

Table 31: Number (billion LEDs) of WLEDs produced and projections for the three scenarios A, B and C

Projection	Number 2006	Number 2009	Number 2011	Number 2020	Number 2025	Number 2030
A (ISI 2009)	15	21	25	45	62	84
B (ISI 2009)	15	21	25	97	162	271
C (Young 2011)	-	24	71	164	164	165

In order to test the validity of these calculations, another market study (Young 2011) containing an estimate of the number of GaN chips produced can be referred to. As the main application of these chips is in white LEDs, it is assumed that these estimates can be applied directly to the number of white LEDs manufactured. This estimate assumes a growth of around 95% for 2009 compared to 2008 which declines roughly exponentially in subsequent years and in 2015 is only 9% compared to the previous year. This scenario C is therefore even more dynamic than scenario B described above in the initial phase of the forecast, but then becomes saturated more quickly. Starting from around 24 billion WLEDs in 2009, this then gives 71 billion WLEDs produced in 2011 (see Table 31). If this development is extrapolated (reduction of the annual growth rate by 50% by 2015), it produces around 164 billion WLEDs manufactured in 2020, and around 165 billion WLEDs in 2030. This means that in the long term scenario C lies between the two scenarios A and B (ISI 2009) and therefore lends support to the order of magnitude of their estimates.

Figure 24: Projections of the future development of annual production figures for white LEDs (worldwide)

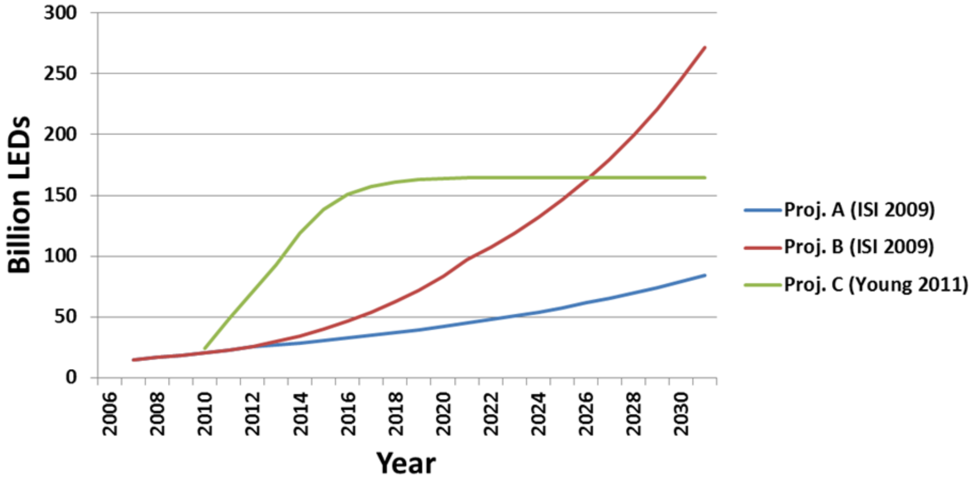


Table 32: Estimate of the future demand for gallium for the manufacture of white LEDs

Raw material	World production 2010[30] [t]	Use in WLEDs [t]				
		2010	2015	2020	2025	2030
Gallium	161	0.75-1.56	1.07-4.90	1.46-5.34	2.00-5.35	2.74-5.35

Indium is used in semiconductor chips in LEDs, mainly in the form of indium nitride in combination with gallium nitride. The mixing ratio for this is variable and primarily determines the width of the semiconductor band gap which in turn directly determines the color of the light emitted. An estimate of the future demand for indium resulting from the manufacture of WLEDs produces the consumption figures for the three future scenarios A, B (each according to ISI 2009) and C (according to Young 2011) given in Table 33.

Table 33: Estimate of the future demand for indium for the manufacture of white LEDs

Raw material	World production of In 2010[31] [t]	Consumption of In for WLEDs [t]				
		2010	2015	2020	2025	2030
Indium	574	0.67-1.38	0.95-4.37	1.30-4.76	1.78-4.78	2.45-4.78

[30] USGS Ga 2011; USGS In 2011

[31] USGS Ga 2011

Rare earths are mainly used in the luminescent material in white LEDs. The global demand for some important rare earths, derived from the above projection, is shown in Table 34.

Table 34: Estimate of the future demand for rare earths for the manufacture of white LEDs

Raw material	World production 2010[32] [t]	Use in WLEDs [kg]				
		2010	2015	2020	2025	2030
Cerium	40,000	46-96	66-301	90	123-329	169-329
Europium	400	14-29	20	27-99	37-99	50-99
Gadolinium	4,000	347-720	492-2,260	674-2,470	923-2,470	1,260
Yttrium	8,900	739-1.540	1,050-4,820	1,440-5,260	1,970-5,270	2,700-5,270

5.2 Summary of critical metals in LED lights

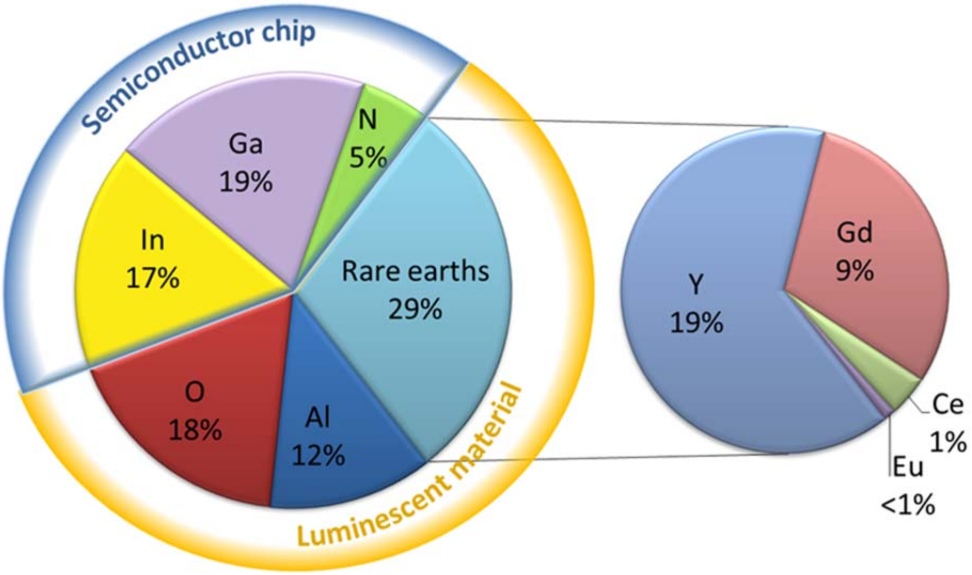
The quantity of critical metals used in a typical white LED (the rare earths used in white LEDs are indium and gallium) are listed in Table 35. Figure 25 depicts the percent by weight of the individual elements. It should be noted that the values shown here are provided as an indication only. As white LEDs constitute a new technology with a rapidly changing development status, individual cases which deviate from the values given here may well occur.

Table 35: Typical content of critical metals in a white LED

Element		Weight per LED [µg]	Occurrence
Indium	In	29	Semiconductor chip (100%)
Gallium	Ga	33	Semiconductor chip (100%)
Cerium	Ce	2	Luminescent substance doping (100%)
Europium	Eu	0.4 – 0.9	Luminescent substance doping (100%)
Gadolinium	Gd	15	Luminescent substance carrier medium (100%)
Yttrium	Y	32	Luminescent substance carrier medium (100%)

32 BGR 2011, Schüler et al. 2011,

Figure 25: Percent by weight of critical metals in a white LED (semiconductor chip and luminescent material)



5.3 Market data for LED lights

The use of lighting based on white LEDs is a relatively new phenomenon in the private sector. It was only the technological advances in the development of high-performance white LEDs with a high luminous efficacy along with good and reliable operating characteristics which enabled these lights to be manufactured on a large scale. The price reductions accompanying this increased their attractiveness, not just in the business-to-business area such as the automotive industry, but also for private consumers. The market responded by developing LED lights with a retrofit design which, instead of conventional incandescent lamps, CFL lights or halogen plug-in lamps, can be used in lamp housings with E27 or E16 connectors. In addition, complete light modules have recently been developed in which the LED, ballast and housing are one integrated unit and exchanging the LED light to reuse the housing is not intended.

This latter development has a number of reasons. First, an LED lifespan of up to 50,000 hours is generally significantly longer than the ballast integrated in the housing. Second, by integrating the LED firmly in the housing, the good heat dissipation required for operating the LED can be implemented significantly better as the housing also performs the function of the heat sink. This is not possible to the required extent in a retrofit lamp. This is why the total power of the lights in retrofit models is limited and at the same time the necessary heat sink increases the weight and size of the light, thus limiting the application possibilities. However, if the LEDs are integrated in the lamp housing, this poses new challenges for the future recycling of the luminescent material, especially for the collection and pre-treatment stages.

One new development is the *organic light emitting diode*, OLED, which differs in being made of thin-film mechanically moldable organic semiconductor layers instead of the LED made from single inorganic semiconductor crystals. The current density and therefore luminance is lower than for LEDs. As OLEDs can be manufactured in larger surfaces they are best suited for screens and displays (e.g. in smartphones). This application in screens makes best use of their advantages, such as high contrast, low waste heat, small cubic capacity and weight, very low reaction times and a large side viewing angle. The energy efficiency is also improved in comparison with LCD screens with LED background illumination, as the image pixels themselves emit light (in a similar way to a plasma screen) instead of filtering white light through a colored filter with a loss in brightness. A decrease in the production costs can also be expected in the future due to the rapid development of this technology.

The disadvantages of the OLEDs currently produced are the relatively low life expectancy, a poor color stability, the necessity for expensive control for large monitors, the risk of burn-in and an increased sensitivity to humidity and UV radiation. In addition, the power consumption depends on the brightness of the image: very bright images require significantly more power than do dark ones.

Because of their flat design, OLEDs in principle have the potential of being used as light sources for room illumination in the future. The first commercial models have already been developed by some companies such as OSRAM (Model *ORBEOS CDW-031*), Philips (Model *Lumiblade*) and Novaled (Model *Victory*). However, the use of these light modules is expected to be limited to display and small-scale lighting in the meantime, since their luminous efficacy of around 25 lm/W still falls short of that of energy saving bulbs or LED lights. It can be anticipated that this recent technology will quickly develop further over the coming years and that OLEDs will be able to be used for room illumination to a greater extent.

For estimating the future demand for luminescent materials based on white LEDs in the private living sector it is assumed that the average quantity of luminous flux installed in a private household is a fairly constant quantity over time. This installed quantity of luminous flux has been estimated at around 40,500 lm per household for Germany in 2005 (Smil 2007). This order of magnitude appears to be a relatively credible value, at least for industrialized countries (see Table 36). An installed quantity of luminous flux of approx. 50,4000 lm per household is therefore estimated initially for the USA (Smil 2007). A comparable value of 51,180 for the USA can be derived from figures for North America (Young 2011). In comparison with Germany, an important factor is the larger surface area requiring illumination in an average home in the USA (160 m² in the USA, 90 m² in Germany).

Table 36: Lighting in private households in Germany, the USA and Japan (2005) (from Smil 2007)

	Germany	USA	Japan
Lights / household	30	43	17
Mean luminous efficacy [lm/W]	27	18	64
Mean power rating [W]	50	65	45
Mean area / household	90	160	95
Installed luminous flux / household area [lm/m²]	450	315	515
Total installed luminous flux / household	40,500	50,400	48,925

Under these conditions and assuming that the average household area does not change significantly, future developments point to an increasing percentage of LED lights in the total installed quantity of luminous flux over time. The estimate of the number of white LEDs which would be installed in the course of a complete or partial replacement of traditional lighting in an average household is inevitably surrounded by uncertainty due to the current rapid technological advances in the realm of LED development. The increases in the luminous efficacy of individual LEDs in particular, i.e. the ratio of the target luminous flux and the electrical power consumption (in lm/W) lead to the hope that in future significantly higher luminous fluxes can be anticipated for the same use of materials in the LED chip (see discussion in the introduction to Section 5). Nevertheless it must be remembered that laboratory values for the luminous efficacy are not the only factors affecting overall utilization but that other components in the light such as the heat sink for dissipating the waste heat (a technical necessity for LED lights) can place an upper limit on the luminous efficacy. In addition, the luminous efficacy of an LED has an upper limit of approx. 350 lm/W for theoretical reasons and, taking the ballast into account, of around 220 lm/W. Current models available on the market have a luminous efficacy of approx. 50-90 lm/W. Although a future increase in the luminous efficacy of LED lights can be anticipated, this will be limited to an approximate doubling of the luminous efficacy compared to current models.

Another point of relevance for these calculations is the number of LED chips installed in an LED light with a specified total flux. This number is subject to a certain range of variation caused by the different technologies of the LEDs used. In our calculations we have therefore concentrated on the model example of a retrofit LED light which, with a luminous flux of 800 lm, roughly corresponds to a traditional 75 W light bulb (900 lm) and can be used in a similar way thanks to the E27 socket, plus a comparable ceiling spot with a high luminous flux.

Although these are currently about the highest performance models available and therefore relatively expensive, they are the ones most likely to be used for the illumination of living areas. It is likely that the market will adapt to these requirements over the next few years and that LED lights with this quantity of luminous flux will occupy a larger share of the supply. Three LED lights were used for the estimate: the BIOLEDEX® NUMO 10 W, the Koeppen LED light 800 lm and the LOBS.LED "DUO" mounted ceiling warm white LED spot (see

Table 37 for specifications and illustrations of the LED lights). The very different number of LEDs used in the two lamps therefore reflects the large variation of LED lights on the market in this respect.

Table 37: Specifications for the three examples of LED lamps

Manufacturer	Product name	Luminous flux [lm]	Power rating [W]	Luminous efficacy lm/W	Number of LEDs	Color temperature [K]
BIOLEDEX	NUMO 10 W E27	800	10	80.0	132	2,700
Koeppen	LED light E27 800 lm CORN	800	11	72.7	72	4,000
LOBS.LED	"DUO" mounted ceiling warm white LED spot	960	18	53.3	12	3,000

Assuming 40 million households in Germany, an estimated luminous flux demand of 41,000 lumen per household and the stated numbers of LEDs per luminescent substance given in Table 37, a calculation of the quantities of critical raw materials which would be installed in private households in Germany due to a complete or partial replacement of the traditional lighting by LED lights can be made. This makes the assumption that a white LED on average contains the quantities of critical metals given in Table 30. The projected values are given in Table 38 for different levels of replacement of traditional lighting: a replacement of 70% of incandescent lamps, all incandescent lamps, all lights with screw fitting (incandescent lamps and CFL) and all lights. This assumes that around 58% of the installed luminous flux in Germany at present is produced by incandescent lamps and 16% by energy-saving lamps (CFL) (see Figure 26; these are values for North America according to Smil, 2007, which are used as a basis for the calculation).

Figure 26: Calculation basis for the composition of the luminous flux installed in a private household in Germany (2005)

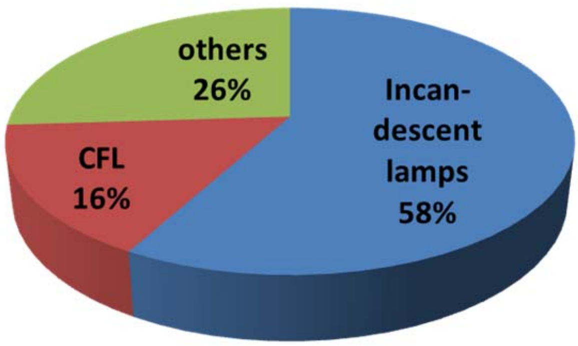
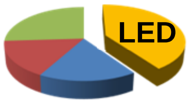
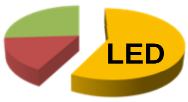
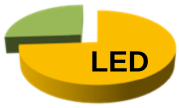
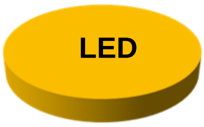


Table 38: Spectrum of demand for the critical metals gallium, indium, cerium and europium for partial or complete replacement of lights by LED lights of various types in households in Germany.

Proportion of LEDs in household lights		Weight Ga [t]	Weight In [t]	Weight Ce [t]	Weight Eu [t]	Weight Gd [t]	Weight Y [t]
	70% of all light bulbs replaced	3.63 1.98 0.27	3.24 1.77 0.25	0.22 0.12 0.02	0.067 0.037 0.005	1.67 0.91 0.13	3.57 1.95 0.27
	All light bulbs replaced	5.18 2.83 0.39	3.24 1.77 0.25	0.32 0.17 0.02	0.096 0.052 0.007	2.39 1.30 0.18	5.10 2.78 0.39
	All light bulbs + CFL replaced	6.58 3.59 0.50	4.62 2.52 0.35	0.41 0.22 0.03	0.122 0.066 0.009	3.04 1.66 0.23	6.48 3.54 0.49
	All lights replaced	8.96 4.89 0.68	5.87 3.20 0.44	0.55 0.30 0.04	0.107 0.090 0.013	4.14 2.26 0.31	8.83 4.81 0.67

According to these figures, several t of gallium, gadolinium and yttrium will be required for the extensive use of LED lights in private households within Germany. Quantities of the rare earths cerium and europium also occur in the order of a few hundred kilograms. It should be noted in relation to this that in the course of technological advances, LEDs in future will probably be fitted with somewhat smaller LED chips for the same luminous efficacy and will therefore tend towards being more resource-efficient. However, it must be remembered that LED lighting also lends itself for illumination outside the private sphere (street lighting, storage halls, office buildings), as the technology required is basically the same as for private use. Usage in these areas would increase the necessary quantities of critical metals for producing the WLEDs. In addition, the nominal lifespan of a white LED of 50,000 hours, although high in comparison to other forms of lighting, refers as a rule to a laboratory value which is often not achieved in practice. The lifespan of the complete LED module is determined by such things as the ballast which often has a lifespan shorter than the LED itself. This is another reason that potentially larger quantities of critical metals will be in circulation due to the use of WLEDs for lighting.

5.4 Collection rates for LED lights

LEDs are a relatively new product group so that there are currently no available specific values for the end-of-life collection. Assuming that in future collection rates for LEDs will be similar to those for other forms of lighting, then a collection rate of only 30% can be estimated, in line with the data for gas discharge lamps in Germany and the general EU data (BMU 2009, Huisman et al. 2007)[33].

5.5 Status of recycling technology for LED lights

As LED lights are a product group which has only been developed in recent years, there are still no special developments for a specific recycling method. Nevertheless, LED lights are included in the guidelines issued by the Zentralverband Elektrotechnik- und Elektronik-industrie e.V. (ZVEI 2009):

The disposal of lights in the technical sphere (b2b) includes all lights (...) e.g. lights with integrated LEDs (...). This also applies to fitted LED modules (...). LED lights and LED tubes (...) are subject to mandatory waste disposal irrespective of the regulations governing the disposal of lights and must (...) be disposed of using the relevant lamp disposal routes e.g. recycling depots or manufacturers' take-back systems. The German Electrical and Electronic Equipment Act expressly excludes (...) lights used in private households from the disposal obligation and this also applies to lights from fitted LED modules.

5.6 Potential for optimization in the recycling chain

It is not currently possible to derive reliable statements and recommendations on this topic for LED lights. In terms of the recovery of luminescent material, advances in recycling rare earths from waste energy-saving lamps should be followed up over the next year or two. Evidence is required in future as to whether the low concentrations and quantities of rare earths and of indium and gallium in LED lights allow recycling of these metals.

6 Refining processes for electronic waste fractions containing important resources

The successful recovery of critical metals from post-consumer products like those in the product groups flat screens, smartphones, notebooks and LED lights studied in this project depends not only on good collection and pre-treatment of the post-consumer products and electronic waste fractions, but advanced refining methods and adequate plant capacities. As shown in the following subsections, the current situation for the refining technologies for the different critical metals which were identified in this project as of importance for the four product groups appears very variable. This confirms previous research by the Oeko-Institut (UNEP 2009). However, over the last 2-3 years changes have been noticed and further advances can be expected (see detailed information on this in the following subsections).

[33] The values on which this is based do not contain any delays due to the use phase of the devices. They are purely estimates of the actual collection rates.

6.1 Precious metals

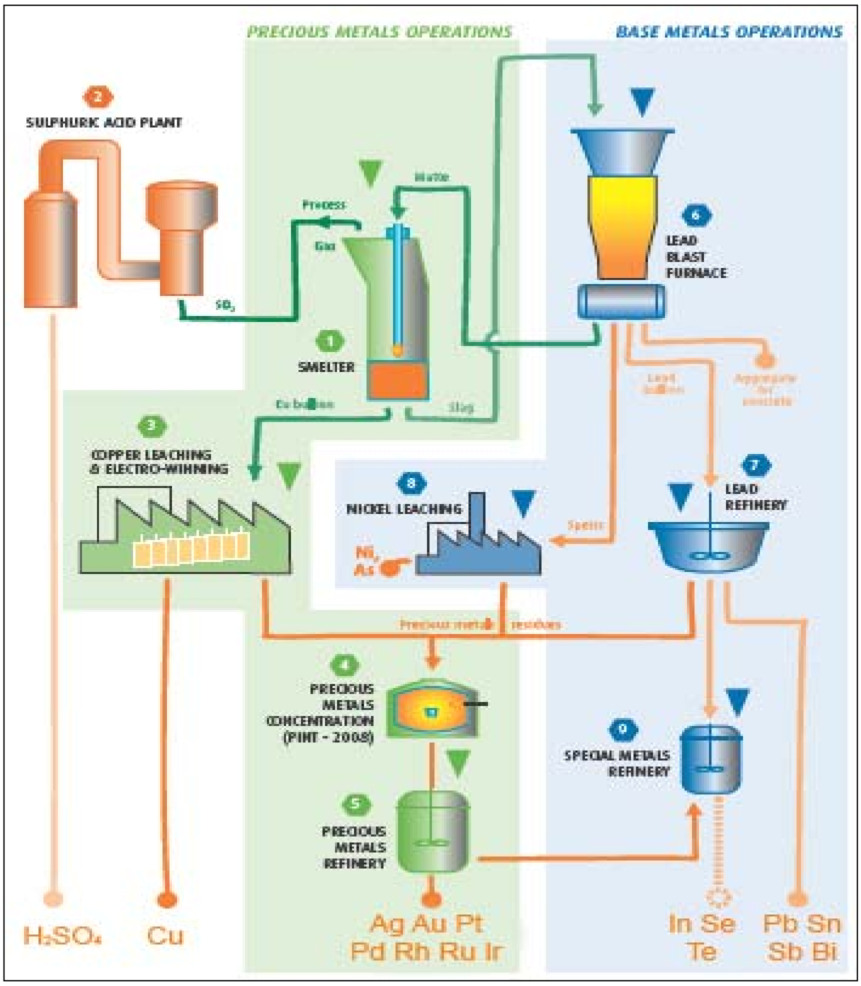
Advanced refining methods have existed for a long time for the recovery of high purity precious metals such as gold, silver, palladium and platinum from various secondary materials such as old jewelry, industrial catalysts, automotive catalytic converters, dental products and, of course, electronic waste (see GFMS 2005, UNEP 2009). Precious metals from the waste electronic equipment sector are normally recovered as an extremely valuable by-product from secondary copper production. Suitable components such as PCBs (e.g. from notebooks) which contain both appreciable amounts of copper as well as smaller amounts of precious metals are usually subjected to a melting process (pyro-metallurgy). The copper functions as what is known as a collecting agent for the precious metals, i.e. the precious metals are very successfully bound in the developing fluid copper phase. The plastic fraction from the electronic waste is used as an energy carrier for the processes. Non-precious components (e.g. glass, aluminum) are bound in the slag. After tapping the copper phase, this is followed by a further processing stage (electrolysis of the raw copper) for purifying the copper. The precious metals (gold, silver, platinum and palladium) accumulate in significantly increased concentration in what is known as the anode sludge. Special processes, which differ in detail in the individual companies, are used to recover the precious metals with a high degree of purity at very high recovery rates (sometimes significantly more than 90% cf. GFMS 2005).

Europe is home to leading companies which recover the secondary copper and precious metals mentioned above in state-of-the-art plants. Due to the fast-growing quantities of electronic waste, considerable expansion of the processing capacities is taking place. In 2011 the German copper group Aurubis expanded its total recycling capacity at the Lünen site in North Rhine-Westphalia. The throughput in the existing KRS bath smelting furnace in Lünen rose from 275,000 tons to 350,000 tons per year (EUWID 2011a). According to information from the company, the plant is particularly suited to the treatment of complex recycling materials such as metal-containing industrial wastes, copper-rich shredded material and electrical and electronic waste. Further capacity for recycling electronic wastes is located at Aurubis' works in Hamburg.

In Scandinavia, the Swedish mining and metals group Boliden also own copper smelters which recover secondary copper and precious metals from electronic waste. The group's recycling capacities for electronic waste are currently undergoing considerable expansion: from 45,000 to 120,000 tons per year (EUWID 2011b).

In Belgium (in Hoboken near Antwerp) the company Umicore processes a wide range of secondary materials. Each year high yields of valuable metals are recovered (see Figure) from over 350,000 t of raw material (catalytic converters, PCBs, mobile phones, industrial intermediate products and residues, slag, fly ash, etc.) using a complex pyro-metallurgical process.

Figure 27: Process flow diagram for Umicore's integrated precious metal smelting works in Hoboken near Antwerp (source: Umicore)



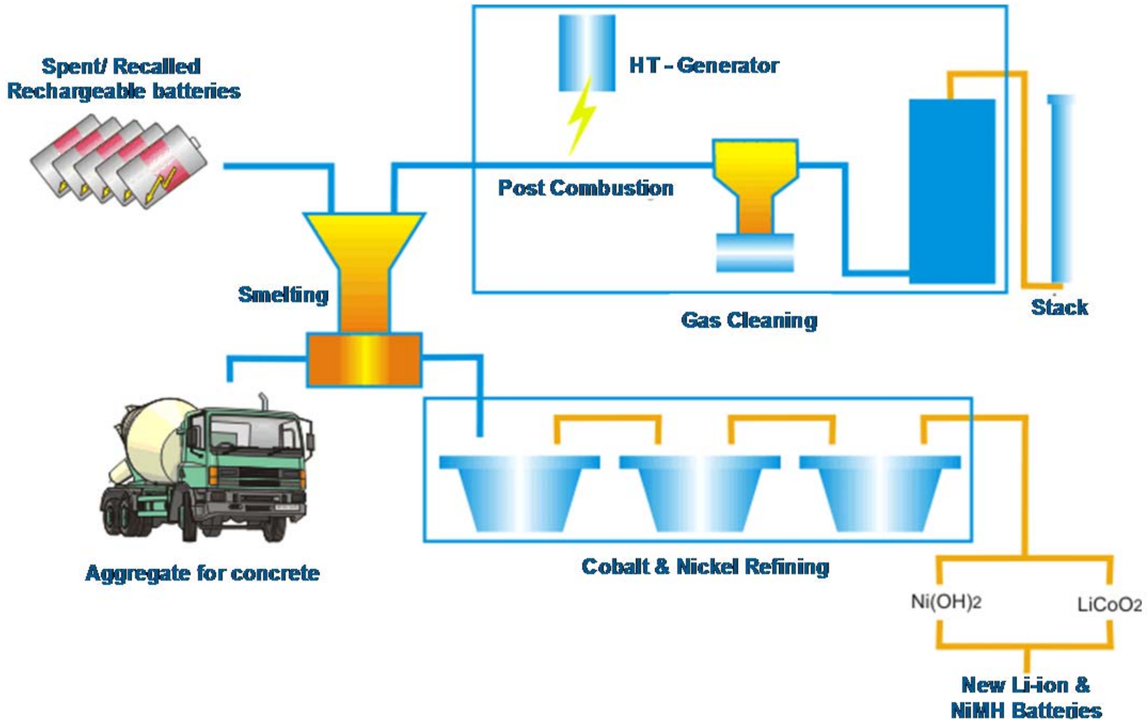
The process management was originally optimized for the precious metals (in this case gold, silver, platinum, palladium, rhodium, ruthenium and iridium) so that long cycle times and high precious metal yields were and are achieved. The throughput quotas can also be increased by the combined processing of a large range of complex materials containing precious metals. This also increases flexibility and the robustness towards contaminants. The copper contained in the melt binds the precious metals and is pelletized immediately after tapping and fed to a downstream electrolysis process where the precious metals are finally separated from the copper. The primary slag, on the other hand, undergoes a further blast furnace treatment in which lead and other base metals are separated and the remaining precious metal fraction recovered. This also produces side stream material which is likewise reintroduced into the process cycle and can then undergo further processing. The pre-enriched concentrates are fed into special hydrometallurgical processes until the individual elements are recovered in a highly purified form. This enables a range of special metals (e.g. tellurium) to be recycled nowadays besides the precious metals.

Overall it can be said that, for refining precious metals, Germany and Europe are using advanced technologies with very good recovery rates for the secondary recovery of these valuable metals. Considerable plant capacity is available which is currently being significantly expanded. Weak points in the recycling chain for precious metals still exist in places in the areas of collection of the electronic devices and components and the pre-treatment stages (see relevant subsections in Sections 2-5).

6.2 Cobalt

As explained in Sections 3 and 4, the batteries from notebooks and smartphones are of importance for cobalt. In contrast to other critical metals, there are already established recycling processes for cobalt from a range of applications. This applies particularly to cobalt alloys and cobalt-containing super-alloys but also to cobalt catalysts (UNEP 2009) from the industrial sector and recently from the rechargeable battery sector (Meskers et al. 2009). Between 2009 and 2011 the German Federal Environment Ministry funded two parallel projects which looked into the research and development of recycling of lithium-ion batteries from the automotive sector (e-mobility) (Kwade et al., Treffer et al.). In the summer of 2011 the Belgian material and recycling company Umicore officially opened a pyro-metallurgical plant at the Hoboken site near Antwerp with an input capacity of 7,000 tons of lithium-ion batteries and nickel metal hydride batteries per year (Umicore 2011b). The new plant is fed with a mixed input of these cobalt and nickel-containing batteries. At present it mainly handles batteries from notebooks, mobile phones and power tools. However, the plant is also intended for processing battery cells from the automotive sector.

Figure 28: Process flow diagram for Umicore's battery recycling in Belgium (source: Umicore)



The main product obtained from the smelting process at high temperatures is a cobalt/nickel/copper alloy. Carbon-containing components (plastics, graphite, electrolyte) are used as an energy carrier and contaminants in the waste gas stream reduced as far as possible using advanced waste gas purification. An important by-product is a slag which is used in the construction materials industry (aggregate for cement production). The alloy obtained from the process is purified of contaminants such as iron and manganese in a separate cobalt/nickel refining plant in Olen in Belgium. The main products are pure nickel and cobalt salts (e.g. sulphates) which can be reused for the production of cathode material for batteries. What is known as copper cement is produced as an important by-product and then undergoes further processing into pure copper in Antwerp.

There are therefore existing recycling technologies and capacities for the cobalt-containing lithium-ion batteries from notebooks, mobile phones and now smartphones. These batteries present an attractive end-of-life product on account of their high cobalt content. The greatest challenges for the recycling industry are once more better collection and systematic separation of the batteries in preparation for the refining processes described.

6.3 Rare earths

Due to the very low prices for rare earths such as neodymium, praseodymium, etc., until a few years ago there was little incentive for recycling these metals and their compounds.

Added to this are their unfavorable chemical characteristics for pyro-metallurgical treatment. As a result of their base character, the rare earth metals are not absorbed with high yields in a copper phase, unlike the precious metals, but end up diluted in the form of their oxides in slags and have therefore not been available for recycling to date (UNEP 2009, Schüler et al. 2011). Furthermore, in the common pre-treatment processes for electronic waste (e.g. with magnetic separation) the rare earth metals neodymium, praseodymium, dysprosium and terbium which are contained in neodymium permanent magnets in e.g. notebooks, end up as fine particles attached to the larger steel waste streams in the steel recycling (the neodymium permanent magnets are brittle and are therefore easily pulverized under mechanical stress) and are therefore lost from any recovery process. Overall, the end-of-life recycling rates (EOL RR) which represent the recovery rates over all stages of the recycling process (collection, preparation, refining) from the post-consumer sector are currently less than one percent to zero for all rare earths (Graedel et al. 2011).

Due to the dramatic deterioration in the supply of rare earths to the western industrialized nations, 97% of which are currently mined and processed in the People's Republic of China, the issue of recycling rare earths has suddenly moved to center stage (Buchert et al. 2011). The Oeko-Institut has recommended the development and establishment of a European competence network focused on recycling of rare earths in order to combine existing competences in science and industry, create synergies and thus achieve measureable progress in the recycling of rare earths as soon as possible (Schüler et al. 2011).

For example, in 2011 the joint project MORE was launched under the supervision of Siemens in order to study the recycling of components, magnetic alloys and rare earths from the electro mobility field of application (electric motors with neodymium permanent magnets) (Bast et al. 2011). Especially worthy of mention is the announcement by the French company Rhodia which has considerable experience in the chemistry of rare earths including the manufacture of luminescent substances and catalytic converters (cerium for automotive exhaust gas converters) that, in the first quarter of 2012, it plans to begin post-consumer recycling of rare earths from waste energy-saving lamps in two of its own plants. It should be pointed out here that, under the terms of the WEEE Directive, in the EU these lights must be collected separately and sent for suitable treatment (mercury removal and collection). Up until now the luminescent materials and rare earths contained in these e.g. yttrium, europium, terbium, were sent to landfill. The completion and commissioning of these plants in France (La Rochelle und Saint-Fons) will be the first time that post-consumer recycling of rare earths will have been carried out anywhere in the world.

6.4 Gallium, indium

Similarly to the situation with rare earths, the EOL RR for gallium and indium is currently less than 1% to zero worldwide (Graedel et al. 2011). The reason for this is the very low quantities used anywhere in the world (in the case of gallium primary production is just over

100 t/a and in the case of indium, around 600 t/a, UNEP 2009) and the generally dissipative applications i.e. relatively small quantities of these metals are contained per product unit. This places very high demands on recycling systems and technologies. Nevertheless, the recycling of gallium and indium from processing residues is established in e.g. Japan but also in Germany (UNEP 2009, PPM 2011). The recycling of gallium and indium from waste electronic fractions studied in this project is currently not possible as the relevant technologies are lacking. However, suitable research and development projects are likely in the near future.

6.5 Tantalum

Tantalum is also one of the large group of metals which still exhibit end-of-life recycling rates of <1%. Apart from applications for particular alloys (aircraft construction) and industrial cutting tools (tantalum carbide), tantalum is contained in special capacitors which are used for PCBs. Tantalum is therefore important primarily for the notebook device group studied. Similar to the rare earths, in the standard pyro-metallurgical processes for refining PCB waste, tantalum is converted to the resulting slags as tantalum oxide, due to its base character. The concentrations of tantalum there are much too low to carry out large-scale recovery. It should be mentioned in connection with tantalum that the company H.C. Starck, the world market leader in the processing of tantalum compounds, is based in Germany, providing a high degree of expertise in the relevant process technology. H.C. Starck is principally open to and interested in taking back tantalum residues for recycling (H.C. Starck 2011). However, recycling tantalum from the capacitors in PCBs would require a mechanical separation of these capacitors from the PCBs, something that has not been done so far.

7 Summary and recommendations for action

In this section the detailed results of the study, i.e.

- The life cycle inventory analysis for the metals and equipment studied,
- A description of the market situation and its development,
- Presentation of the current recycling situation and
- Developments in recycling

which are presented in detail in Sections 1 to 6 are summarized and recommendations for action drawn from these.

Life cycle inventory analysis

As part of the life cycle inventory analysis, the potential quantities of metal for subsequent recycling are summarized using the recorded amounts of the selected metals per device and the number of flat screens, notebooks and smartphones (only the private market excluding business customers) marketed in Germany in 2010. Due to a lack of accurate sales figures for the fourth group of devices investigated, LED lights, (only those for home use were included here) a 70% replacement of all incandescent lamps i.e. all lamps in private households was applied for this sub-segment to reach an estimate of their importance. The results of the life cycle inventory analysis are summarized in the following table. The individual values which are taken from Sections 2 to 5 are rounded off in the table. Significant amounts in terms of recycling potential are highlighted in bold red.

Table 39: Overview of the life cycle inventory analysis results for the product groups flat screens, notebooks, smartphones and LED lights (private households in Germany)

Metal		Content in all flat screens sold in Germany in 2010 [kg]	Content in all notebooks sold in Germany in 2010 [kg]	Content in all smartphones sold in Germany in 2010 [kg]	Estimate for LED: replacement of 70% of light bulbs	Estimate for LED: replacement of all lamps [kg]	Occurrence
Cerium	Ce	30	1		120	300	Luminescent substance
Dysprosium	Dy		430				Voice coil accelerator
Europium	Eu	50	<1		40	90	Luminescent substance
Gadolinium	Gd	10	5		910	2.260	Luminescent substance
Gallium	Ga	15	10		1.980	4.890	Semiconductor chip
Gold	Au	1.645	740	230			Printed circuit boards, contacts
Indium	In	2.365	290		1.800	3.200	Internal coating on display; Semiconductor chips
Cobalt	Co		461.000	48.500			Lithium-ion batteries
Lanthanum	La	40	<1				CCFL background illumination
Neodymium	Nd		15.160	385			Permanent magnets
Palladium	Pd	465	280	85			Printed circuit boards, contacts
Platinum	Pt		30				Hard disks
Praseodymium	Pr	<1	1.950	80			Voice coil accelerator, loudspeaker; CCFL background illumination
Silver	Ag	6.090	3.100	2.350			Printed circuit boards, contacts
Tantalum	Ta		12.065				Capacitors
Terbium	Tb	14	<1				CCFL background illumination
Yttrium	Y	680	12		1.950	4.810	Luminescent substance

The following results from the life cycle inventory analysis are worth noting for the metals or metal groups under study:

- **Rare earths (luminescent material):** europium, gadolinium and yttrium are of importance in LED lights and therefore have a recycling potential for the future; this also applies to yttrium in flat screens,
- **Rare earths (permanent magnets)**: neodymium and praseodymium are of importance in notebooks,
- **Precious metals**: the results for gold, silver and palladium show a noteworthy potential in the flat screen, notebook and smartphone groups of devices,
- **Gallium**: gallium has a potential in the LED lights group of devices (semiconductor chips),
- **Indium**: indium shows a significant result primarily in flat screens and LED lights (semiconductor chips),
- **Cobalt**: cobalt shows a considerable potential in notebooks and smartphones (from lithium-ion batteries),
- **Tantalum**: a potential for tantalum is evident in the notebooks device group.

It is important to note that an individual weighting must be applied (in relation to world production which can vary greatly, the price per kilogram, the global supply situation, etc.) when estimating the importance as regards the amounts of the individual metals. In addition, when setting the priorities in the overview, factors such as potential recycling opportunities for the specific types of device or the specific components are also taken into account. As a result of the life cycle inventory analysis, the areas highlighted in bold red in the above table suggest a suitable prioritization for the present or future recycling efforts for the selected metals.

Market situation and development

For the four groups of devices studied, the market situation and its future development can be summarized as follows:

In the TV segment, **LCD flat screens** displayed renewed strong growth in sales figures in Germany (8.3 million appliances in 2010, up 9.3% compared with 2009). The number of flat screen TV sets in private households is currently estimated at around 50 million, of which by far the largest proportion are LCD televisions. Significant technical trends for this group of appliances are an increasing proportion of appliances with LEDs (2011: 40%) for the background illumination and a clear tendency to have ever larger screen sizes. Sales figures for the **PC monitor** segment showed a steep downward trend of minus 21% (2010: 2.6 million devices sold). A corresponding marked trend towards notebooks and tablet PCs was apparent.

Notebooks have become the driving force on the German computer market. Sales of mobile computers for the private sector have increased by a factor of 3-4 since 2005. A total of 7,097,000 notebooks (including tablet PCs) were sold in the private sector in Germany in 2010. Tablet PCs are likely to have a market share of up to 30% in 2013. In 2010 the percentage of LEDs for background illumination was already 92% worldwide. The trend towards tablet PCs promotes the use of higher numbers of LEDs (in comparison to notebooks) in order to ensure brighter background illumination.

Smartphones, like tablet PCs, are currently conquering the market, especially amongst the important younger consumer group. In 2010 around 7,702,000 smartphones were sold in Germany alone, with growth up 161.4% compared to 2009. A relatively short actual service life of three to four years at the most can be assumed for electronic products such as smartphones, largely driven by the acquisition of higher-performance and newer generations of devices. This means that the massive increase in the last three years in the number of smartphones in the use phase will soon reach the end-of-life stage and therefore the recycling industry in Germany.

LED lights (use of lamps based on white LEDs) in the private sector are a very new trend. There are no figures for this segment as relevant studies generally record all white LEDs, i.e. without distinguishing the application. It is estimated that 21 billion white LEDs were manufactured in 2009 worldwide (a growth rate of approx. 11% per year). Continuing high growth rates are expected over the coming years (up to 2020 or 2030). The future market penetration of LED lights for the important private household area of application will depend principally on technical (luminous efficacy etc.) and cost factors. Irrespective of these variables, high growth rates for LED lights are expected in Germany for the private household field of application over the next few years.

The current recycling situation

The study has clearly shown that, notwithstanding what are often highly developed and established recycling processes for refining a range of metals from waste electronic equipment (principally copper and precious metals), there are still serious shortcomings in the collection and pre-treatment of the appliance groups studied. Due to their recent appearance on the market, smartphones and LED lights currently do not play a part in the recycling industry in any noteworthy quantities, although this will change in the near future. A significant cause of large losses of critical metals in the initial stages of the recycling chain (disassembly and pre-treatment) is also due to an undesirable misallocation resulting from statutory guidelines such as quantity-based recycling quotas which run counter to selective disassembly compared with the use of shredder technologies.

The following table shows the total potential for critical raw materials for Germany and the potential loss when using current collection, pre-treatment and refining processes for the important notebook product group. These figures are based on the general assumption that the devices sold in 2010 (which will on average reach the end-of-life stage after around 6.6 years) will be handled according to the collection, recycling and disposal systems which are standard in Germany at present[34]. The table shows that up until now only a fraction of the critical metals contained in notebooks have been fed back into the industrial cycle.

[34] The following assumptions were made: Cobalt: 80% of the batteries were removed and recycled separately; the final treatment achieved a recovery rate of 96%. Tantalum: The final treatment achieved a recycling rate of 95%. Indium: 80% of notebook displays are fed into a separate recycling process. Yttrium, gallium, gadolinium, cerium, europium, lanthanum, terbium: For 40% of notebooks the background illumination is fed into a separate recycling process (lamp recycling). Platinum on the hard disk drive platters is completely lost in the light shredder fraction or the aluminum fraction.

Table 40: Critical raw material potentials in notebooks and losses from the collection and treatment systems currently used in Germany.

Metal		Content in all notebooks sold in Germany in 2010 [t]	Losses during collection	Losses during pre-treatment	Losses during final treatment	Recovery in Germany [t]
Cobalt	Co	461.31	50%	20%	4%	177
Neodymium	Nd	15.16		100%	100%	0
Tantalum	Ta	12.06		100%	5%	0
Silver	Ag	3.11		70%	5%	0.443
Praseodymium	Pr	1.94		100%	100%	0
Gold	Au	0.74		70%	5%	0.105
Dysprosium	Dy	0.43		100%	100%	0
Indium	In	0.29		20%	100%	0
Palladium	Pd	0.28		70%	5%	0.040
Platinum	Pt	0.028		100%	5%	0
Yttrium	Y	0.012		40%	100%	0
Gallium	Ga	0.010		40%	100%	0
Gadolinium	Gd	0.0048		40%	100%	0
Cerium	Ce	0.00069		40%	100%	0
Europium	Eu	0.00028		40%	100%	0
Lanthanum	La	0.00008		40%	100%	0
Terbium	Tb	0.00003		40%	100%	0

The low collection rate for notebooks of around only 50% is caused by the drain of materials from the numerous illegal exports to e.g. Africa or Asia. Often simple but important manual disassembly steps are not carried out, such as removing the batteries containing cobalt which is required for the subsequent special treatment and recovery of the battery metals. Following the collection losses, these shortcomings in pre-treatment lead to further total losses of secondary metals. The manual processes are not currently carried out everywhere in Germany for the following reasons:

- At low and average raw material prices, the higher wage costs associated with manual removal are not fully compensated by the increased income;

- Many of the loads delivered are not adequately sorted, so that devices of importance for raw materials first have to undergo costly separation from other devices with less importance for raw materials (e.g. irons, toasters).

These factors along with the statutory stipulated recycling quotas in the WEEE Directive and the corresponding German law as well as competition on the open market for the most cost-effective disposal create an incentive system which mainly leads to mechanized processing and a focus on bulk raw materials.

The collection rates for mobile phones (more or less the predecessors of smartphones) are currently very low (5%). This is a problem as mobile phones, like smartphones, can be recycled directly in pyro-metallurgical plants without any intermediate steps (apart from the important prior removal of the batteries). Copper and the precious metals silver, gold and palladium in particular can be returned to the economic cycle in this way with very good recovery rates (around 95%).

Of all the product groups studied, the current situation is best as regards the collection rates for televisions (85%) and the flat screens associated with these. There are as yet no empirical values for LED lights as this product group is still in its infancy and has not yet reached the recycling industry to any extent worth mentioning.

Developments in recycling

With regard to the recovery of **rare earths** from the magnets contained in notebooks, this requires pilot projects on removing and separating them manually. The removal quota for the background illumination in notebooks must also be raised considerably above the currently adopted 40%. The lack of a final treatment option for rare earths could be remedied in the case of luminescent substances in the near future through the commissioning of appropriate new plants (see Section 6). A series of comprehensive research projects has also been started on the recovery of rare earths from neodymium permanent magnets, so that solutions can also definitely be expected for this in the future. Overall, by implementing these measures a significantly higher proportion of the potential critical metals contained in notebooks can be recovered and made available to the markets again.

With regard to the recycling of lithium-ion batteries which contain the important metal **cobalt** amongst other things, research and development efforts have recently produced solutions and plant capacity has been created. The successful recovery of cobalt from this segment therefore depends all the more on increasing future collection and separation rates of lithium-ion batteries from notebooks, smartphones, etc.

Recycling **gallium**, **indium** and **tantalum** from waste electronic equipment has not yet been implemented. Besides systematic separation of the relevant components, recycling in future also requires a great deal of effort to be given to their concentration in the secondary material flows and lastly their final recovery in an adequate degree of purity. There is a high probability that research and development efforts for indium in particular will be increased in the near future.

Recommendations for action

Based on this study, the following recommendations can therefore be made:

- In terms of optimizing the recycling rates, a **significant increase in the collection rates** should be aimed at for all product groups. This can be achieved by an improved collection infrastructure on the one hand and by targeted information and return campaigns on the other. There is a particular need for optimization for small devices such as smartphones, of which in Germany only about 5% are currently sent to controlled recycling facilities. Consideration should be given especially to extending the existing collection infrastructure for used batteries in small devices such as mobile phones, smartphones, MP3 players and cameras. In principle an improved collection system like this should also be developed for lamps, as both gas discharge lamps and LEDs present a considerable raw material potential. When designing a suitable collection infrastructure, measures must be put in place to guard against the potential mercury emissions from damaged gas discharge lamps.
- In order to increase the collection rate the **illegal exports of waste equipment** to Eastern Europe, Africa and Asia must be controlled. Although recent studies show that a part of the exports is intended for reuse as second-hand goods and is therefore not necessarily to be classified as illegal, many exports primarily serve the purpose of cheap disposal and should therefore be judged negatively from a sustainability point of view in many respects. Improved export controls could bring about a significant reduction of these problems and retain raw material potentials within the EU. This assumes that the implementing authorities will be given clear and practicable means (device functionality, suitable transport packaging, etc.) for distinguishing old devices which can no longer be used (illegal export) and reusable used devices (legal export.).
- When it comes to **optimizing the recycling chain** it should be remembered that one-sided regulations and quotas based purely on quantity can produce negative incentives for the recovery of critical raw materials. Article 7 of the European WEEE Directive, for instance, gives quantitative targets for the recycling of waste equipment. As these quotas are not formulated specifically in terms of material or components, but relate to the weight percent of the complete devices, while they do create a regulatory incentive for recycling bulk raw materials such as steel, copper, glass, etc. this is not so for critical raw materials which normally only comprise a very minor proportion of the weight of the devices. For the revision of the **WEEE Directive and the corresponding German law** the recycling quotas should therefore be critically questioned and supplemented by alternative objectives such as efficiency rates

(targets set for the end-of-life recycling rates for important critical metals and product groups).

- Currently the greatest need for improvement for the **technical optimization of recycling** is improved manual disassembly during the pre-treatment stage. Various recent studies show that the generally standard practice in Germany of shredding whole devices leads to considerable losses of critical metals – in particular precious metals – which cannot be compensated by the downstream sorting and refining processes. To improve the recovery of precious metals and cobalt it is essential to manually remove the components containing important raw materials such as PCBs and batteries and feed these separately to recycling facilities. In the last few years various small and medium-sized businesses which manually disassemble the devices with important raw materials in the collection groups 3 (IT and telecommunication equipment) and 4 (consumer electronics products) have been able to maintain a position on the market and therefore enable significantly better recovery rates for critical raw materials. These companies often work as social enterprises with a large proportion of employees in the second labour market. The North Rhine-Westphalia region has the opportunity of targeting support to enterprises of this kind. In addition, discarded office equipment from public bodies can be disposed of by being given to such businesses.
- As the study has shown, there are still no appropriate refining processes for many critical raw materials. This situation can change significantly for some scrap fractions and metals. It is anticipated that the recovery of rare earths from luminescent substances will become established on the recycling market over the next few months or years. There are also numerous research and development projects on the recovery of rare earths from magnets and of indium from flat screens. It is recommended to pursue this **advance in recycling methods** promptly in order to introduce the necessary optimization into the recycling chains without delay.
- With the anticipated technical advances in recycling, a **temporary storage site** needs to be considered for various raw material fractions. This applies in particular to the luminescent substances containing rare earths. These are already extracted from gas discharge lamps and cathode ray tubes for the purpose of managing harmful substances (including mercury, but also cadmium) and stored at a cost in hazardous waste sites. In order to be able to make use of this raw material potential in the future, these luminescent substances should be deposited in such a way that they can be salvaged at a future date without significant cost and fed into recycling processes. A similar approach needs to be looked into for LCD modules from screens (indium) and LEDs (indium, gallium, rare earths) and, last but not least, for magnets containing rare earths (from notebooks and desktops).

- Research is also needed into how to remove tantalum capacitors from the relevant devices (notebooks etc.) or components (PCBs). Appropriate **research projects** are needed to investigate which applications and device generations are suitable for a procedure of this kind and what conditions are required for an economic recovery process.
- Besides optimization of the established disassembly and refining processes, the **structure and design of the devices** is of crucial importance for recycling. A suitably optimized device design can assist manual disassembly and therefore the recovery of critical raw materials. Especially worthy of mention in this context is a current design trend for integrated lithium-ion batteries in mobile electronic devices (including smartphones, tablet PCs and netbooks). This type of design means that high costs are incurred in removing the cobalt-containing lithium-ion batteries before feeding them into a separate recycling process. Apart from the corresponding losses, especially for cobalt recycling, incorrect handling of lithium-ion batteries causes fire and explosion hazards in recycling plants.

  To avoid these kind of design problems and support a recirculation of raw materials with recycling-friendly product design, regulatory options should be assessed for their suitability for **implementing design for recycling strategies**. Besides the WEEE Directive, the current implementation process for the Ecodesign Directive (2009/125/EC) is of relevance here. Although the current process deals with energy-related aspects for specific products and implements these in the form of binding minimum standards, the directive also offers the opportunity to integrate other relevant environmental topics.

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