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Accelerate SSL Innovation for Europe

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Author:	Sander Gielen, TNO (sander.gielen@tnol.nl) Andrius Plepys, LU (andrius.plepys@iiiee.lu.se) Reine Karlsson, LU (reine.karlsson@luopen.lu.se) Jessica Richter, LU (jessica.luth_richter@iiiee.lu.se)
Co-authors:	Thomas Lindhqvist, LU Jos Kunen, TNO

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1 Summary

The ambition of the SSL-erate Green Business Development is to accelerate the deployment of solid-state lighting (SSL), which is considered to have great potential from a sustainable development point of view. Awareness of both positive sustainable development aspects as well as potential material scarcity issues in relation to SSL are needed to improve the overall customer and societal value.

Sustainability for electronics in general and SSL specifically is at present mostly driven by energy efficiency concerns, which is the dominant factor in the environmental LCA of lighting products. SSL products generally perform well in relation to other lighting products for a range of environmental indicators.

There are several materials of high sustainability interest in SSL products. Rare earth materials are used in the luminescence materials on LEDs for improved colour. Gallium and indium are critical materials used in LEDs in which the demand is expected to exceed availability. However, it should be noted that the amount of these materials per LED are small, which tend to make recycling and recovery more challenging. Further development of potential alternative materials as well as recycling is important.

A range of both voluntary and mandatory policy measures exist that are relevant to SSL to encourage waste reduction, increased collection, proper disposal, and better design of the products. The collection of disused electronic equipment (WEEE) is increasing in Europe, however, still a large portion is exported. Collection rates of lighting products in general is about 30% in the EU and this, as well as the small amounts of material per product means that profitable recycling is currently difficult. To improve overall effectiveness, EcoDesign methods can be applied in a number of ways, including designing for disassembly or designing the individual luminaires themselves for better materials recovery with easy connectors, less materials or fewer (or reusable) components. However, the focus should remain on design for optimal functionality.

Taking into account the value of materials currently used in SSL products, business models for the collection of SSL materials should also be considered and further explored. This could involve take-back schemes and/or combination with upgrading and maintenance services. The disposal systems for SSL products should be considered in relation to developments in EcoDesign and improved recycling procedures and processes. In addition, existing relationships and behaviours (e.g. the landlord tenant problem of the mismatch of interests and incentives that exist between the building owner, who pays the investment, and the user who pays the running costs) may affect the uptake of new SSL lighting systems and should be addressed.

Overall, realizing the potential of SSL requires understanding the entire life-cycle of the SSL materials and how to create green business models. Considering the range of interlinked aspects over the life-cycle promotes the design and production of intelligent lighting systems that make use of environmental considerations in the design process and aim to increase the overall functionality of the product. To achieve this, it should be ensured that sustainable development is integrated in the core of SSL design. SSL in itself is already an energy efficient technology, but further incorporating a wider view of sustainability provides opportunities to find solutions that, with more advanced guidance to development and selection of solutions, provide the right light, in the right place, at the right time, for everyone.

2 Introduction

2.1 Background

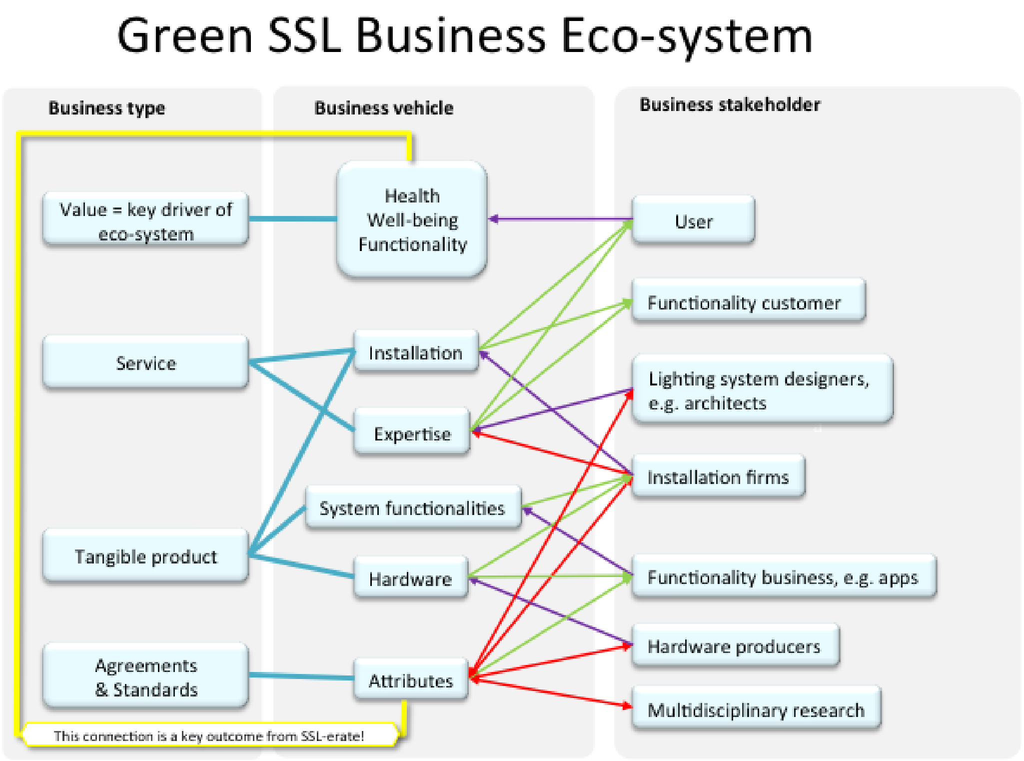
To be able to make use of the sustainable development knowledge of solid state lighting (SSL) presented in this report it is important to first introduce the SSL-erate project in general, clarify the assessed business system, the main business concerns and the development openings.

The ambition of the SSL-erate Green Business Development is to accelerate the deployment of SSL, which is considered to have great potential from sustainable development point of view. The energy-saving potential of SSL is already noted and Work Package 2 primarily aims to summarize the other important, but less noted, sustainability dimensions of smarter lighting systems. Now that it is, for example, known from circadian rhythm research that the quality of lighting is important for quality of life (which will be explored in WP3), it is apparent that it is a social responsibility to take actions so as to make use of this opportunity and create additional functional value through SSL. This social responsibility is analogous to corporate social responsibility (CSR) and consequently it is a sustainability and “green” development priority to take action. As a tool to trigger renewal oriented interest pre-commercial procurement, innovative purchasing and demonstration facilities, in collaboration are promoted in WP4. Achieving this will require highlighting how green and city actors can benefit from the new smart lighting opportunities. The sustainable development framing used in this project aims to incorporate a wider systemic view, for example the one highlighted in the Brundtland report, 1987, which combines social and economic progress as well as environmental improvements.

To achieve significant real life acceleration, SSL-erate aims to activate the Green Business priorities as integrated renewal oriented development drivers in the core of the SSL-related Business System. The key driver of any business eco-system is the customer, user and society appreciation of the added value. It is vital to create an “agreement”, of what it is that constitutes the basic attributes of the enhancement of the added value. The WP3 clarification of health and wellbeing values is one main aspect. To make it truly interesting to invest in SSL, it is vital that the “agreement” creates coherent engagement among a wide range of sustainable development and value chain actors. Consequently, it is important to make use of the Innovation Platform as a base for the dialogue about the continually evolving “agreement”. WP2 promotes Smart Lighting as a key tool for creation of Smart Cities and Smart Buildings.

SSL-erate aims to clarify the human value of better lighting and better functionalities. SSL in itself is already an energy efficient technology. Incorporating a wider view of sustainability provides opportunities to find solutions that provide the right light, in the right place, at the right time, for everyone. This means that it is possible to develop dynamic lighting systems that optimise the functionality and attractiveness for users. Moreover, focusing on the actual “usefulness” of each part of the light enables very large energy savings. One main aim of the SSL project is to promote solutions that have a positive social effect, e.g. by enabling better living environments in preschools, schools and for elderly people. Another main aim is to promote green investments, i.e. sustainability oriented investments and thereby green jobs.

New B2C and B2B models for green business development have the potential to accelerate the deployment of SSL solutions with additional customer value by integrating services and with product installations, fostering material stewardship, and encouraging life-cycle oriented investment patterns. Figure 1 focuses on the aim to create new value (and local jobs) from better, more appreciated, personalized solutions & services. Again, it is emphasised that clarification and articulation of the importance of high-quality products, solutions and services are important to be successful.



Colour coded to simplify reading of relationships:

- Significant axiom that need to be developed by the project for the business eco-system to be effective
- Uni-directional relationship indicating that the business stakeholder to the right of the arrow produces the Business vehicle to the left.
- Uni-directional relationship indicating that the Business vehicle to the left of the arrow is utilized by the Business stakeholder to the right.
- Bi-directional relationship indicating that both above-described uni-directional relationships are utilized in different situations.

Figure 1: Business system canvas for SSL related concerns.

A successful sustainable transition requires political, societal and technological efforts, to reduce the vulnerability for supply disruption and in parallel create new relevant business opportunities to connect industry and end-users in new ways (Figure 2). To make things happen it is also important to find ways to engage the value chain actors between the customer value and the "agreement" about what it is that constitutes the user and society value. Platforms for realization are the Digital agenda, Sustainable cities and EcoDesign. SSL-erate aims to make these discourses truly interested in SSL, i.e. to trigger engagement and to trigger incentives.

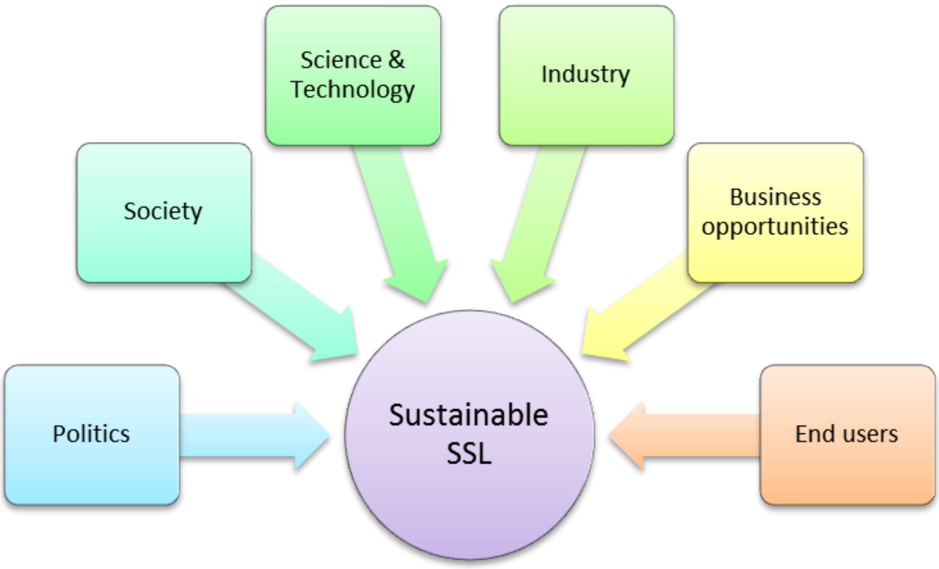


Figure 2: Actors in the SSL sustainability arena.

The main challenge for *creating value with green* is the multi-disciplinary and interlinked aspects: design and production of smart lighting systems, their use and disposal, new business models, political and industrial incentives, as well as logistics and regional situations interact. In all, these areas alignment over different parts of the life cycle and the entire value chain should be taken into account.

2.2 Overview of SSL sustainability aspects

Sustainability refers to the long-term maintenance of the well-being of humans and our environment without compromising the future generations. The notion of sustainability for electronics in general and solid state lighting (SSL) specifically is at present mostly driven by energy efficiency during the use phase, which from a perspective of life cycle assessment is indeed the dominant factor in the environmental impact of lighting products. However, limiting the use of hazardous substances, significant environmental footprints of rare earth elements used in electronics, depletion of resources, and environmental damage are rapidly growing in importance. This is not only based on the need for long-term environmental sustainability, but also due to shorter term issues like the supply risks and the availability of sufficient resources to enable the transition to less energy consuming technologies. This report therefore presents both an overview of technology aspects related to the materials, production, and use and recycling of SSL as well as information about political, legal, social, and business aspects that are relevant to sustainability in this context.

Electronics by their nature use relatively small amounts of material per device. However, the environmental footprints of many materials are significant. This is due to the efforts required to acquire rare metals and other elements as well as substantial environmental loadings due to high resource intensities and increasing material purity requirements demanded by the manufacturing processes (Plepys, et al., 2004). The total volume of the electronics and associated components leads to the significant and potential dissipative use of many scarce and valuable metals. Moreover, some materials, mainly rare metals, appear extremely diluted in waste streams and are not economically feasible to recycle if no precautions are taken. This results in the loss of strategic raw materials that are vital to the economy and continued reliance on virgin materials.

This means that for SSL, properly dealing with waste is in this respect crucial. However, unlike product manufacturing, dealing with waste in an optimal way involves many players at various stages of the value chain. From a technological perspective the composition and design of products and assemblies should be such that materials can be more easily separated, identified and recovered. From a business perspective the incentive should be distributed fairly among the various players. This will also involve governmental regulations and cooperation of users. Figure 3 gives an overview of various sustainability aspects related to the SSL lifecycle.

Figure 3: Overview of the SSL lifecycle and various aspects (adapted from Gielen, 2013).

3 Technology elements

3.1 Life cycle assessment

A life-cycle assessment (LCA), also known as life-cycle analysis, eco-balance, and cradle-to-grave analysis, is a technique to assess environmental impacts associated with all the stages of a product's life from-cradle-to-grave, i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. (U.S. Dept. of Energy, 2012a). LCAs can help avoid a narrow outlook on environmental concerns by:

- Inventorying of relevant energy and material inputs and environmental releases;
- Evaluating the potential impacts associated with identified inputs and releases;
- Interpreting the results to help make a more informed decision.

There is no single comprehensive LCA methodology and depending on the product and material streams under consideration, specific additions may be needed, for example to include recycling in more detail (Ligthart, et al., 2012). Still, a generic approach is shown in Figure 4. The US Dept. of Energy compared life-cycle energy consumption of an LED lamp to that of an incandescent lamp and a CFL based on a review of ten published studies and its own LCA study (U.S. Dept. of Energy, 2012a; U.S. Dept. of Energy, 2012b). It should be noted, that in the context of SSL, only very few studies exist with limited data.

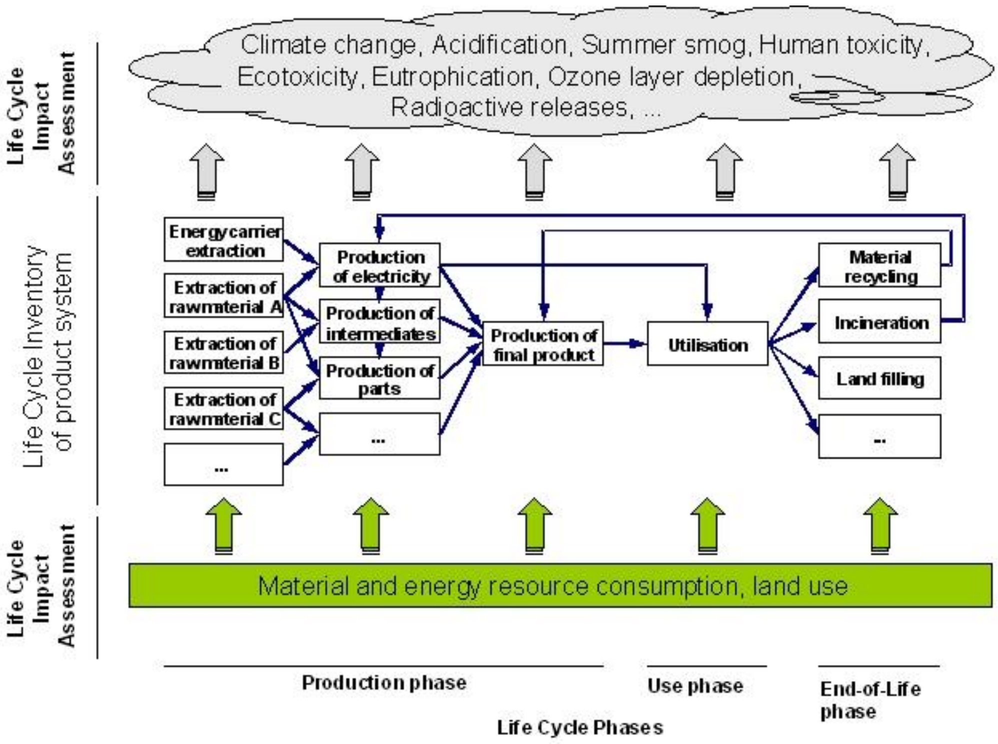


Figure 4: Scheme of a product's life cycle with data collection of product and waste flows (blue lines) and resources (green) and emissions (grey arrows) followed by the impact assessment of the emissions and resource consumption (European Commission, 2012).

The general procedure for conducting a life cycle assessment is defined by the International Organization for Standards (ISO) 14000 series. The main phases of an LCA according to ISO guidelines are goal, scope, and boundary definition; life cycle inventory (LCI); life cycle impact assessment; and interpretation.

One fundamental basis in LCA is that it should deal with the quotient

$$\frac{Environmental\ load}{Functional\ value}$$

Functional value in this sense is a measure of an amount and the quality of function delivered by a product or service system (also called functional unit), to which all environmental loadings are attributed.

In the context of further greening the SSL industry, the environmental load should be considered for the complete cradle-to-cradle loop, instead of the conventionally used cradle-to-grave lifespan. In the context of LCA the environmental loadings are measured using the so-called mid-point approach expressing bundles of environmental impacts through artificial measures of impact potentials. Although traditionally the environmental impact potentials have been expressed from natural science perspective, recent trends show increasing interest in social impact oriented measurement within the LCA framework (UNEP: Buchert, et al., 2009; Jørgensen, et al., 2008).

This is a basis in the LCA ISO standard. The application of the so-called “Factor Four” concept, i.e. the doubling wealth, halving resource use (Von Weizsacker, et al., 1997), has highlighted that it is equally important to clarify the functional value and how this can be improved as it is to analyse the total environmental load and how this can be reduced. Furthermore there is a fundamental difference between consumption, i.e. destruction of a material that is being used and only “borrowing” some material from the human pool of valuable material (Karlsson, 1998). The worst sustainability effect is to lose or destroy a quantity of valuable material, and in fact, at a rational level, this is equally important for primary produced materials and recycled material. It is equally bad from a resource point of view to lose 1 kg of gold, independently of whether it comes directly from primary production or if the same quantity has been used a number of times. This can be handled by means of proper LCA accounting of recycling. However, when looking at how LCA is actually being used, this aspect of the LCA methodology is still rather immature in its development.

3.2 Materials in SSL

The key component of SSL products is light emitting diode (LED) fabricated on a die. When building lighting systems the LED die is packaged. The LEDs are put into modules and built into luminaires (Figure 5). When disposing the luminaire, these materials could be regained through appropriate “de-manufacturing” approaches.

Figure 5: When building lighting systems, the packaged LED is built into the module, this in turn is built into the luminaire.

Table 1 shows an overview of materials involved in LED lighting products at the different levels of the product. The main functional materials in LED dies are semiconductor p-n junctions based on the die-level material in the first column in combination with the Phosphorous materials.

Table 1: Materials of high interest in LED die, package, module, and luminaire (Gielen, 2011).

Die Level	Package Level		Module Level	Luminaire Level
	Phosphors	Bonds, Solders, etc.		
Gallium	Yttrium	Gold	Copper	Iron
Indium	Cerium	Silver	Aluminium	Aluminium
Arsenic	Europium	Tin	Tin	Copper
Aluminium	Terbium	Copper	Silver	Plastics (housing)
Silicon	Erbium	Carbon	Indium	Clear Plastics
Magnesium		Silicon		
Zinc				
Tungsten				
Germanium				
Sapphire (Aluminium Oxide)				

The weight ratio of these materials is shown in Figure 6. For desired functional parameters, such as the colour (temperature) of light, different other luminescent materials are added into dies in different quantities, also shown in Figure 6. These materials are the most important ones in relation to the lighting function and, due to increasing demand and limits of supply, several of these elements are becoming scarce materials.

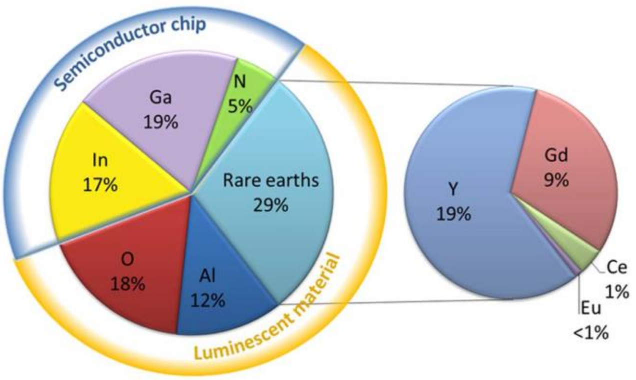


Figure 6. Percent by weight of critical metals in a white LED semiconductor chip and luminescent material (Buchert et al., 2012).

Among the other materials such as glass, plastic, bulk metals or resins, used in an average LED (Figure 7), there are some other rare and sometimes critical metals used (Buchert, et al., 2012). These are e.g. rare earths such as cerium, yttrium and gadolinium in Ce^{3+}-doped yttrium aluminium garnets (YAG) or gadolinium aluminium garnets (Y, Gd) AG:Ce^{3+} that are mainly used in the luminescent substance for converting blue or near UV light into the visible wavelength range. Data on the exact composition of the luminescent substances are rarely published by the manufacturers. These materials are also the materials that pose the biggest challenge to claim back from the waste streams. The issues associated with scarce materials in SSL are further discussed in 4.1.

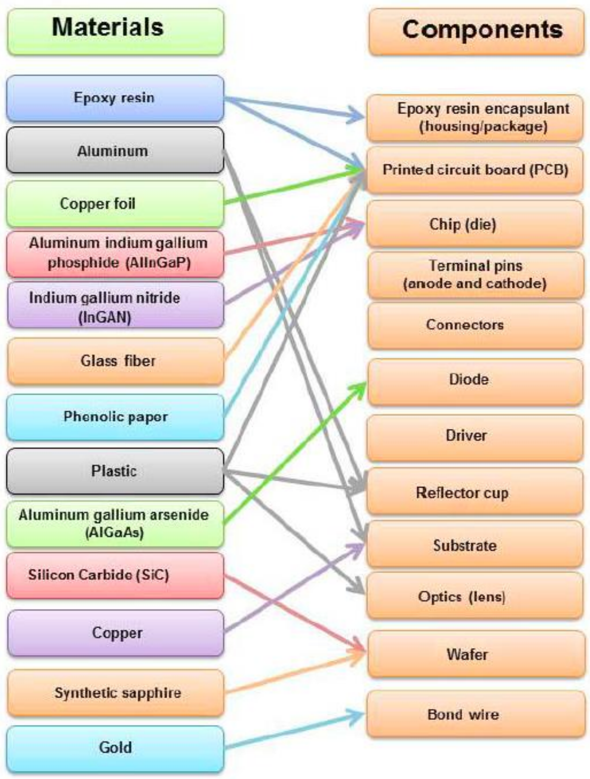


Figure 7: Other components and materials needed to build LED. Source: Buchert, et al., 2012.

3.3 Environmental impact of SSL production

In Figure 8 the material use, expressed in environmental impact indicators, is shown. The use was calculated per 20 million lumen hours for incandescent, CFL and LED lamps... It is clear that in certain material aspects the current LED lamp (green line) is not yet the winner but is expected to improve in the coming years (purple line). A detailed analysis is given in the full report (U.S. Dept. of Energy, 2012b).

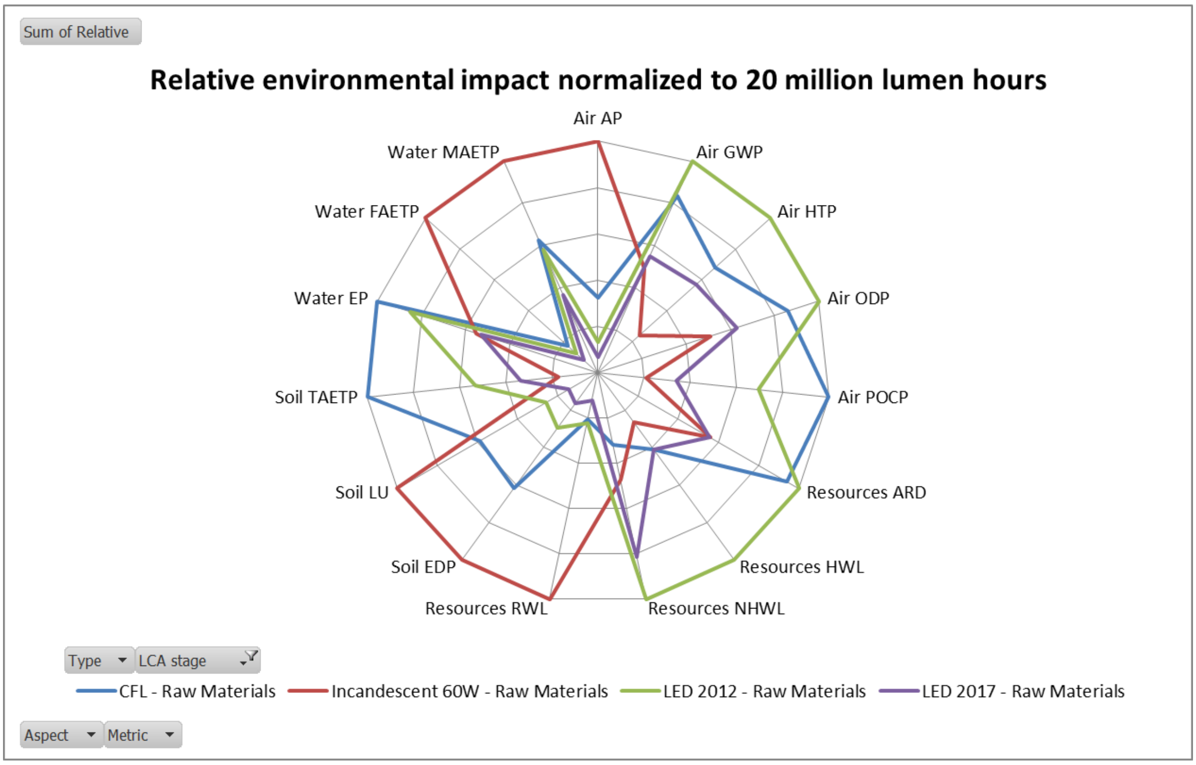


Figure 8: Relative environmental impact of different lighting products normalized to 20 million lumen hours and relative to the maximum impact value per category. All data used was obtained from (U.S. Dept. of Energy, 2012b) but reformatted to this figure. The abbreviations are explained in Table 2.

Table 2: Abbreviations for impact assessment indicators in Figure 8.

	Abbreviation	Name	Indicator
Air / climate	GWP	Global warming potential	Greenhouse gas emissions
	AP	Acidification potential	Air pollution
	POCP	Photochemical ozone creation potential	Air pollution
	ODP	Ozone depleting potential	Air pollution
	HTP	Human toxicity potential	Toxicity
Water	FAETP	Freshwater aquatic ecotoxicity potential	Water pollution
	MAETP	Marine aquatic ecotoxicity potential	Water pollution
	EP	Eutrophication potential	Water pollution
Soil	LU	Land use	Land use
	EDP	Ecosystem damage potential	Biodiversity impacts
	TAETP	Terrestrial ecotoxicity potential	Soil degradation and contamination
Resource	ARD	Abiotic resource depletion	Resource depletion
	NHWL	Non-hazardous waste landfilled	Non-hazardous waste
	RWL	Radioactive waste landfilled	Hazardous waste
	HWL	Hazardous waste landfilled	Hazardous waste

One way of greening products is by reducing the materials in the product. In particular (potentially) toxic and scarce materials will be the prime target for reduction. However, the reduction of materials introduces other risks. These risks include:

- If material amounts in the product fall below a certain level, in particular levels defined in directives and legislation, the concentration might get too low for efficient recovery.
- The processing needed to create small amounts of materials, in particular thin films, consumes additional energy, due to the need for increasingly pure materials, process chemicals and clean room environments, as shown in Figure 11. Therefore, the material reduction needs to be in balance with the methods needed to reduce the materials.
- In some cases the material may become unhealthy or even toxic due to the size of the particles and fibres under the circumstances they are free moving (i.e., not particles or thin-film fixed to another material). It is known, for example, that very small glass fibres may induce inflammatory reactions for people. This needs consideration as the phosphors for light conversion could be replaced by quantum dots, or nano-wires (e.g., ZnO nano-wires) with comparable light conversion properties.

Also helpful for lessening environmental impact is the expected efficiency increase of the LED that increases the overall lumen output characteristics in combination with extended lifetime, reducing the average environmental impact to about 60% of the current LED lamp value. Furthermore, the increased efficiency will also reduce the heat sink size, as less heat will be generated in future LED products.

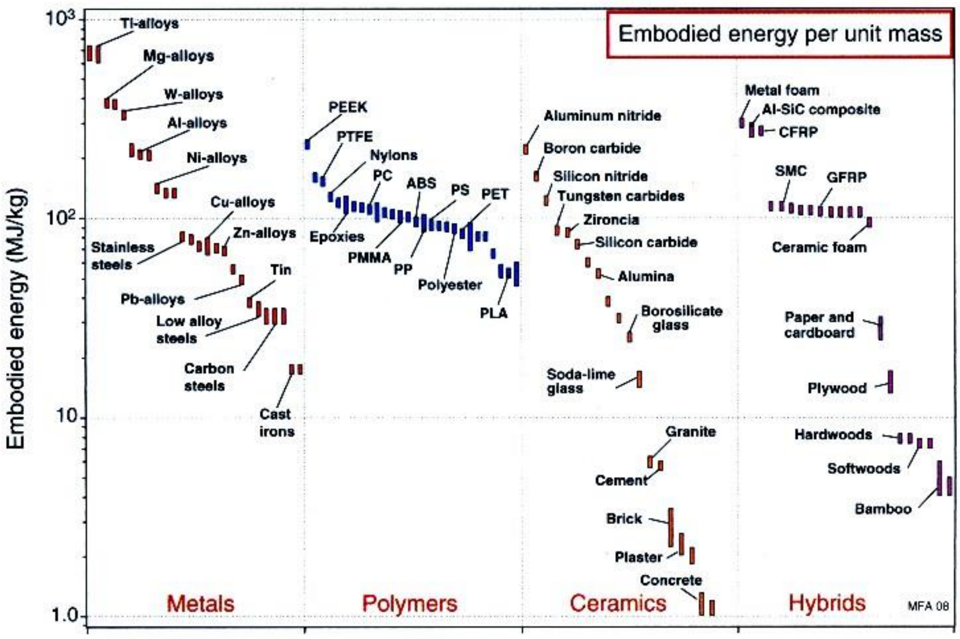


Figure 9: Energy embodied in bulk materials expressed per unit mass (Ashby, 2009)

In order to reduce the environmental footprint of the materials in LED products and supporting materials in the process represented in terms of energy embodied in the mass in Figure 9, one may want to choose more favourable materials. Furthermore, based on availability (scarcity), alternate materials that are readily available and that need less exotic refining processes may improve the green factor.

As shown in different studies (for example (U.S. Dept. of Energy, 2012a; U.S. Dept. of Energy, 2012b; OSRAM, 2009), there is still room for improvement in the SSL manufacturing chain. LED lamps are already superior to CFL lamps in terms of environmental performance (Figure 10) and further environmental impact reduction is expected. Like for the materials, this is mainly due to the increase efficiency and lifetime.

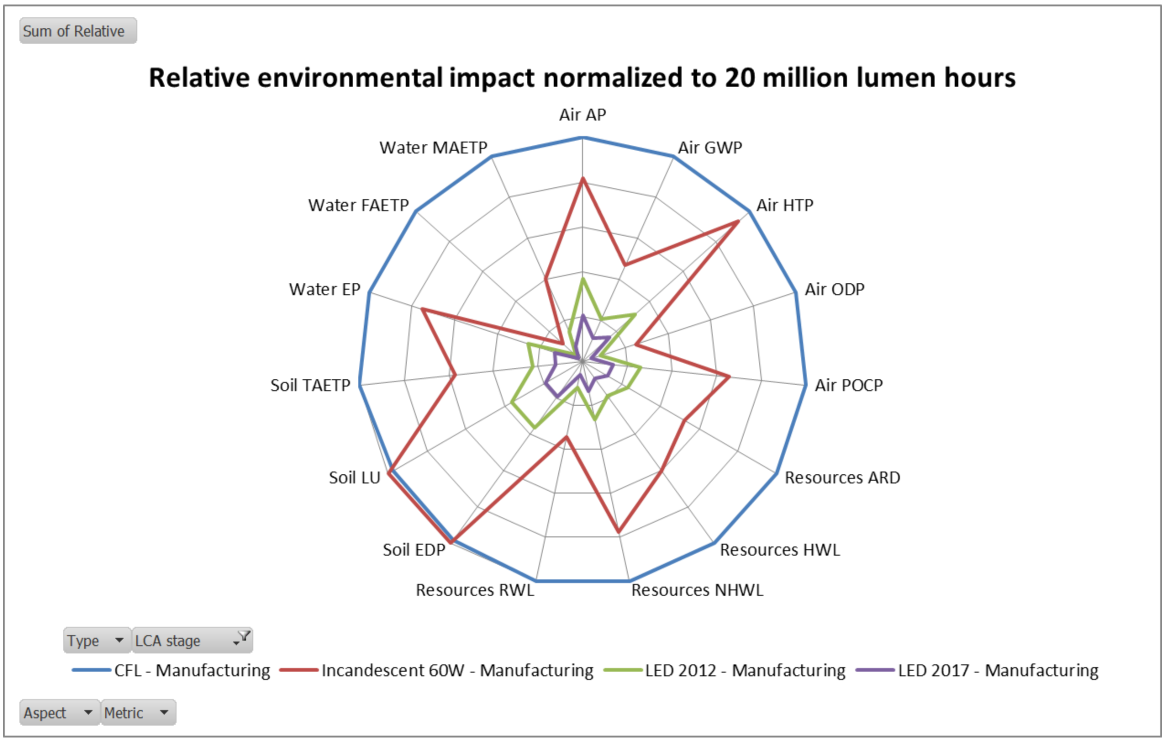


Figure 10: Relative environmental impact of different lighting products normalized to 20 million lumen hours and relative to the maximum impact value per category. All data was used was obtained from (U.S. Dept. of Energy, 2012b) but reformatted to this figure.

An important method to reduce the material use is using thin films and coatings. An important drawback however, is that generating the small amount will require more energy (Figure 11).

A comprehensive overview on the interaction of manufacturing with LCA, R&D, and legislation is described in (Gutowski, et al., 2005). An extension of this survey with China, Korea, and India would be very useful. Furthermore, the investigation could be made more specific for the SSL industry.

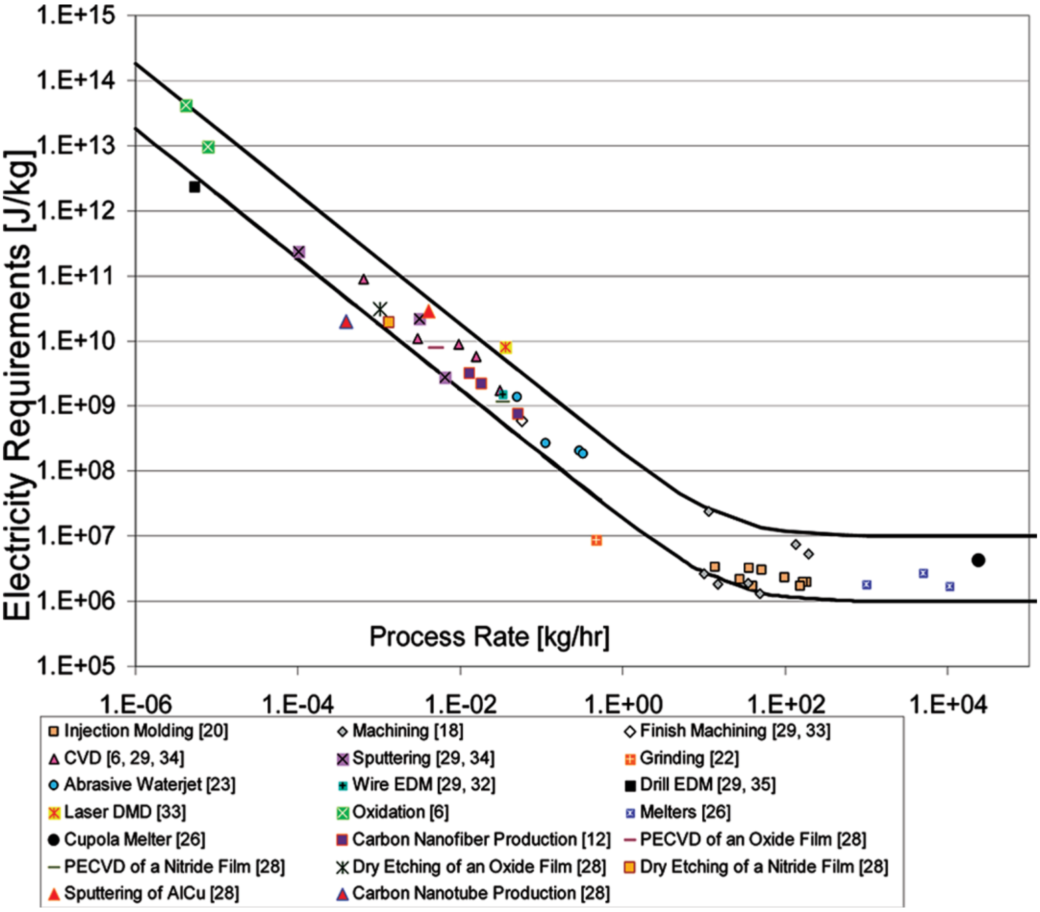


Figure 11: Electricity requirements for different production processes. The typical thin film processing technologies have low rate and high electricity requirements (Gutowski, et al., 2009).

3.4 Energy use in SSL

In terms of light output per unit of energy LEDs are efficient light sources compared to their predecessors (Figure 12). The average luminary efficacy of LEDs in working conditions in 2010 has reached around 50 lm/W, which is somewhere between the efficacy of the incandescent (15 lm/W) and standard fluorescent light source (100 lm/W). Nevertheless, the improvement rates of LED efficacies are very high and have followed the Haitz's law of improving by a factor of 20 every decade. In laboratory conditions LED efficacies have crossed 100 lm/W in 2010 and are expected to reach 200 lm/W by 2020. Commercially available LED light sources that are dominating the market today (2014) can reach on average up to 100 lm/W efficiency. The best generation LED light sources reach luminous efficiencies in the range of 200-250 lm/W for 2010-2011 generations of CREE and Nichia. This is near the maximum physically possible luminous efficacy of 350 lm/W for cold white light (6,700K colour temperature) (Buchert, et al., 2012).

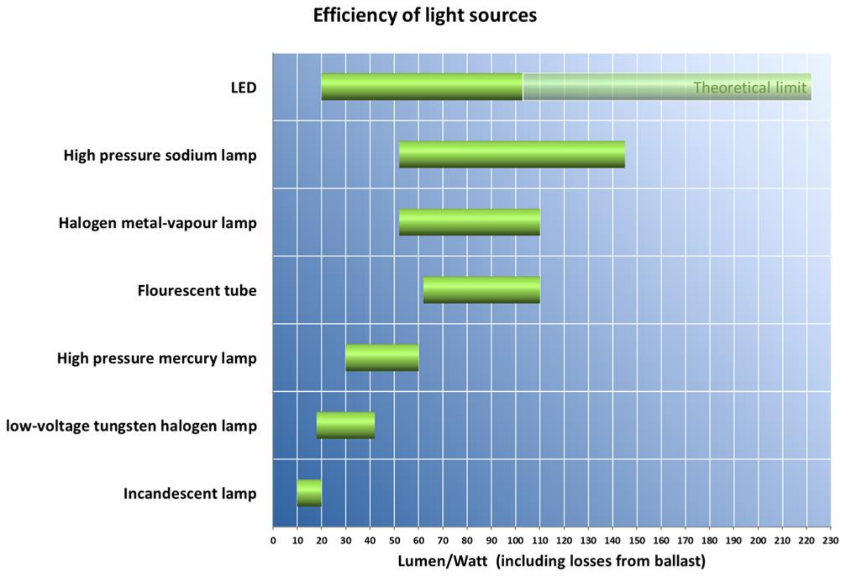


Figure 12. Luminous efficacy of different light sources. [Source: Stadtwerke Düsseldorf, in: Buchert, et al., 2012)].

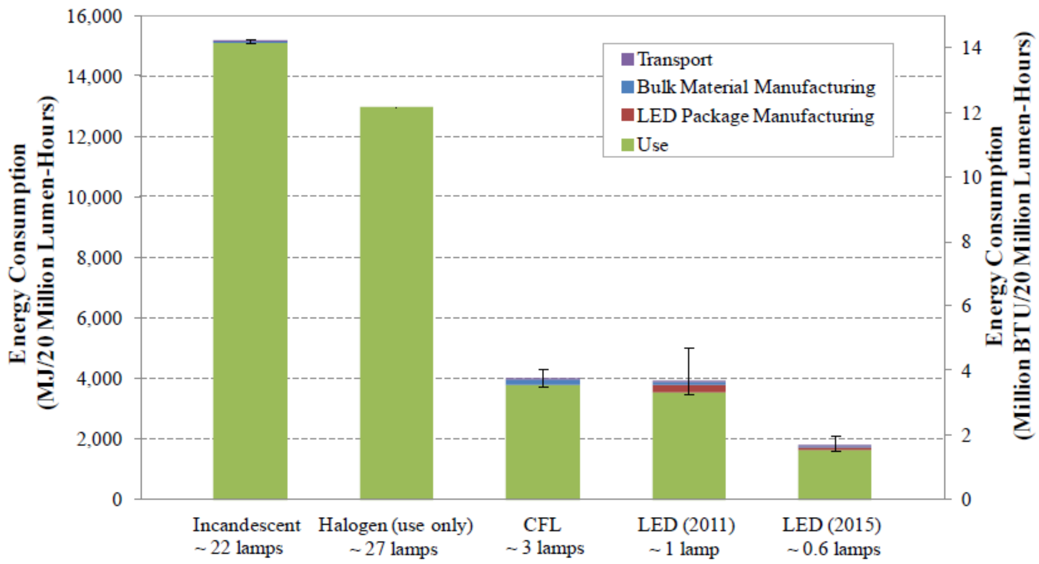


Figure 13: Energy consumption and energy needed for transport, material, and product manufacturing. (U.S. Dept. of Energy, 2012a).

Solid-state-lighting, in particular LED lighting, already has a very “green” image because of the energy saving that is realized due to the higher efficiency of the light source compared to traditional light sources (Figure 13 and Table 3). The energy saving can be further enhance by making the SSL light sources intelligent, such that lights are switched off when there is sufficient daylight or no people are present, and other smart applications that tailor the light generation to the actual need, see for example (Pandharipande, et al., 2011).

Table 3: Performance Parameters for Lamps in the analysis of (U.S. Dept. of Energy, 2012b).

Characteristics	Incandescent	CFL	LED lamp 2012	LED lamp 2017
Power (W)	60	15	12.5	6.1
Output (lm)	900	825	812	824
Efficacy (lm/W)	15	55	65	134
Lamp Lifetime (h)	1500	8000	25000	40000
Lifetime Light (M lm h)	1.35	6.6	20.3	33.0
Impact scalar	15.04	3.08	1.00	0.61

As LED light sources in general will exceed the lifetime of traditional light sources, the design of luminaires can be reconsidered. In a traditional luminaire it is required that the light source can be replaced as the luminaire lifetime is a multiple of the source lifetime. For LED the luminaire lifetime and source lifetime can be equal. This opens opportunities to design and produce different ways. This different ways should be greener as well and may reduce the relative high energy consumption of the materials and LED packaging for LED lights that can been seen in Figure 13.

In Figure 14 the environmental impact over lumen-lifetime of different lighting sources is shown. Both the current (2012) and the future (2017) LED light sources demonstrate superior environmental performance in comparison to their alternatives on the market.

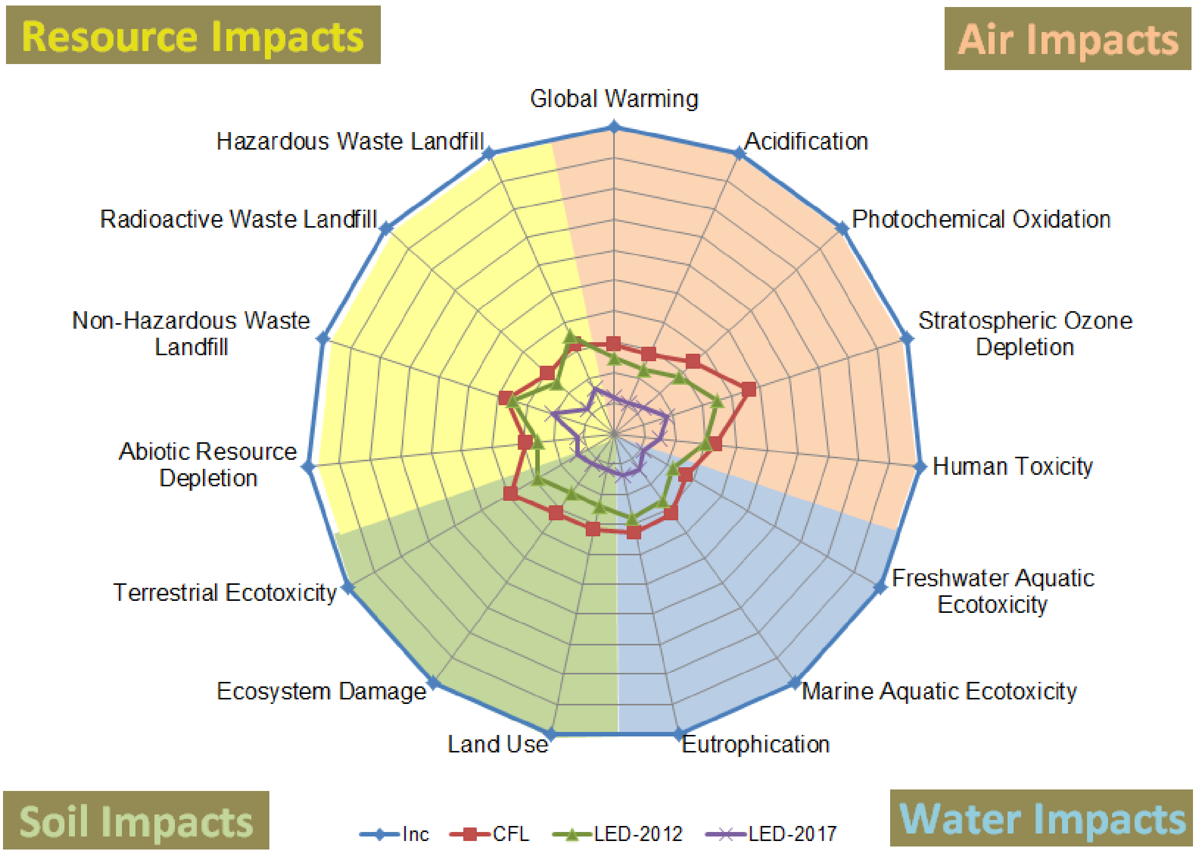


Figure 14: Comparison of environmental impact of different light sources normalized to the impact of the incandescent light sources (U.S. Dept. of Energy, 2012b).

3.5 Recycling of SSL

LED lighting is environmentally friendly during its lifespan and can be even more beneficial to the environment if recycled and manufacturing processes are further “greened”. The general expectation is that eventually over 95% of an LED lamp should be recyclable. For consumer LED lamps the current approach is that the harmful components are omitted or well encapsulated, that they can be disposed of and recycled in the same way as an ordinary light bulb and CFL lamps. Still, this does not ensure that recovery of materials is most successful or efficient in this manner. Similar statements hold for professional lighting.

Based on how and where the recycled material of the LED lamp is used again, the recycling process is called, closed loop, open loop or semi-closed loop recycling. The different recycling schemes are explained Figure 15.

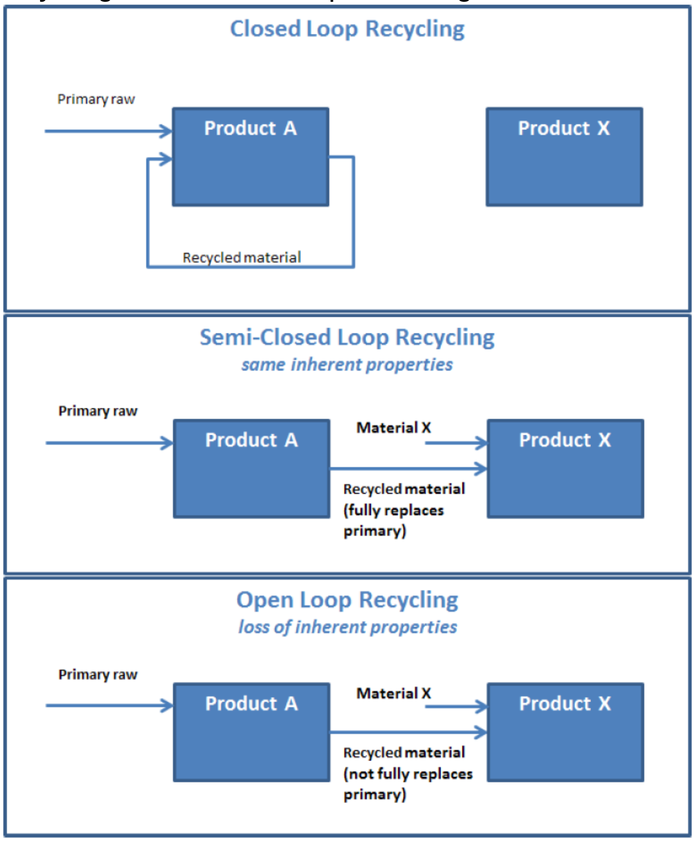


Figure 15: Closed loop, semi-closed loop and open loop recycling (Ligthart, et al., 2012).

A recycling process is called closed loop recycling when the materials of the discarded product are reused in the same product system. This in contrast to open loop recycling where the recycled materials is used in another system. Since this way of recycling often means a changing the material properties and therefore loss of quality, this type of recycling is also called down cycling. However if the recycled materials are used in another product system and there is no loss in quality of the material properties, one uses the term semi-closed loop recycling.

As LEDs do not contain significant amounts of any harmful components, they can be disposed of and recycled in the same way as an ordinary light bulb. The recycling process generally involves the LED bulbs being crushed and separated, using a bar screen, into constituent components. From here, the glass is passed through a magnetic field that can remove any ferrous metal present. To remove the aluminium and lead that is present in LED lights, a non-ferrous metal separator blasts airs at the crushed glass to direct the metal down a separate chute. The glass can then be used in other products, as can the aluminium. As glass does not degrade during recycling, it can be recycled many times over.

Reclaiming the metals used in SSL by means of recycling will lead to a small profit. However the recycling of plastics and glass still cost money, adding to this the transportation and process cost, and overall recycling of SSL will resolve in a negative money flow. For this reason the recycling rates of SSL relevant rare metals (Ga and In) is very low (below 1%) (Figure 16).

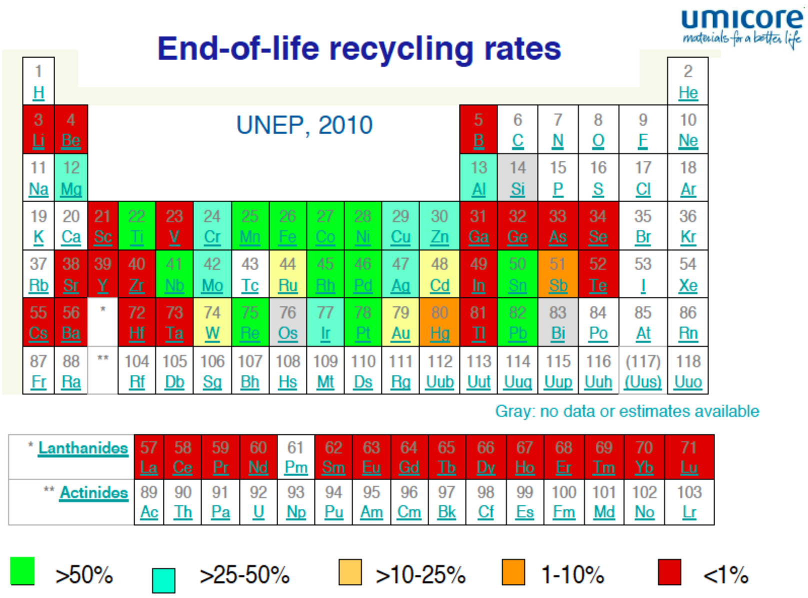


Figure 16. End-of-life recycling rate of different elements from the periodic table. Source: (Umicore: Mark Cafferey, 2012)

4 Political and legal aspects

4.1 Material scarcity and critical materials

The scarcity of certain materials makes them critical in terms of the security of supply. Material criticality can be determined by structural scarcity, physical scarcity, geographical-political and speculative scarcities as well as economic scarcity due to price inelasticity. The main attributes in materials criticality are typically their economic relevance and supply risks. In recent years the EU has placed greater attention to the fact that certain materials are more essential than others for the EU economy. In 2010 an ad-hoc group under the European Commission in close co-operation with Member States and other stakeholders identified 14 raw materials, mainly metals, which are of high importance for the EU economy and show a high supply risk. The European Commission has clearly stated that the security of supply of metals has become increasingly important for individual business and often to entire industrial sectors:

“Metals are […] essential to modern industrial activity as well as to the infrastructure and products used in daily-life. […] Modern cars, flat-screen televisions, mobile phones and countless other products rely on a range of materials, such as antimony, cobalt, lithium, tantalum, tungsten and molybdenum. The same group of high-tech metals are also fundamental to new environmentally friendly products, with electric cars requiring lithium and neodymium, car catalysts requiring platinum, solar panels (partly) requiring indium, gallium, selenium and tellurium, energy efficient high-speed trains requiring cobalt and samarium, and new fuel-efficient aircraft requiring rhenium alloys” (EC, 2010, 11).

4.1.1 The environmental significance of rare materials

From the lifecycle perspective the manufacture and the use phases of electronics are often responsible for the bulk of the life-cycle-wide environmental impacts of EEE (Koomey 2008, Koomey, Berard et al. 2009, OECD 2010). The ecological relevance of different electronic components differs between the diverse EEE, as does their mass distribution. Steel and plastics are the two dominant materials in terms of mass. However, in terms of the significance of environmental impacts due to resource intensity and the potential toxicity the other much smaller components may become important.

The environmental backpacks of some electronic components are indeed significant in terms of their environmental pressures. This is due to high resource intensity of raw material acquisition and purification (as well as purity requirements of fabrication processes) (Plepys and Schischke 2004, Krishnan, Williams et al. 2008, Williams, Krishnan et al. 2008, OECD 2010). For example, gold in mobile phones accounts for less than 1% of the device weight, but at the same time accounts for over 50% of the material flows induced by its production (resources extraction used and unused, in terms of *total material requirement*[1]) (Bakas, et al., 2012)). Likewise, the manufacturing of a 2-gram 32 MB DRAM chip requires 1,600g of fossil fuels and 72g of high purity chemicals (Williams, Ayres et al. 2002).

1 The *total material requirement* (TMR) is an indicator comprising both the used extraction and the unused extraction associated with the material extraction, the so-called ”hidden” material flows (i.e. the material rucksack).

Indeed, the rarer the material is, the more efforts it requires to acquire it, the higher is the price and the higher is its environmental loading too. For instance, a rough illustration of CO2 intensity of different materials is illustrated in Figure 17. Many precious, rare and scarce materials exhibit similarly highly environmental backpacks in terms of energy, water and pollution intensities.

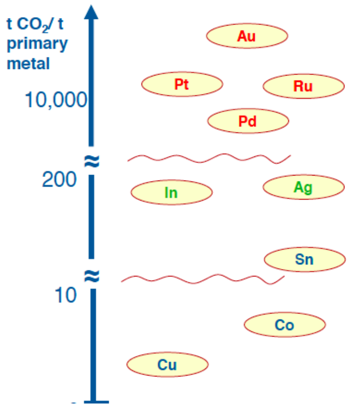


Figure 17. Indicative CO2 emission intensity of primary metal production. Source: ecoinvent 2.9, EMPA/ETH-Zurich, 2007 in (Umicore: Mark Cafferey, 2012)

4.1.2 The scarcity of rare materials

Critical metals are often not mined as main products, but rather as by-products when acquiring many bulk minerals. However, fluctuations of demand for the by-products induced by the dynamics in the electronics sector do not have strong influence on their supply side. This is because mining investments that are strongly correlated with the expected monetary rate of return are primarily related to the production of the main products, not one of the by-products (Bakas, et al., 2012). The same is almost true for the production of metals from secondary resources, as recycling activities are basically driven by the main products of the recycling processes.

Therefore, due to the missing incentives for mining investments for by-products, the supply-demand-relationship is partly not balanced and critical materials are often exposed to the risk of insufficient supply. Such scarcity is called structural or technical scarcity as the reasons are not caused by limited ore deposits, but rather by economic or technical boundary conditions for the mining and production of the critical metals (Bakas, et al., 2012).

Other types of scarcities include physical, political, speculative, economic (price) and temporary scarcities (time lag between demand and installation of production capacities). These can be caused by imbalanced reserve-to-production ratios, regional concentration of resources (e.g. in China) or lack of suitable recycling technologies and poor economies of scale.

4.1.3 The use of rare materials in electronics

The semiconductor sector in the EU today employs over 200,000 workers and generates around 10% of the European GDP. Equipment and materials suppliers contribute with €9bn and semiconductor device makers with €20bn to the EU economy. The semiconductor sector's value chain thus plays a significant role with regard to the national GDP of Austria, Belgium, France, Germany, Ireland, Italy, Malta, the Netherlands, and the UK. For instance, for Germany, about 80% of its exports depend in some way on ICT, and semiconductors enable the generation of 10% of its GDP (Bakas, et al., 2012).

Due to continuous innovations and modifications of function and design, electronics contains increasingly highly heterogeneous mix of materials. The palette of materials used in electronics is continuously growing – from about 12 main elemental components used in computer chips in the 1980s to more than 60 different elements used today (Figure 18). Many of these materials are used as compounds or alloys formed with other elements to form unique electrical, dielectric, or optical properties to electronic components.

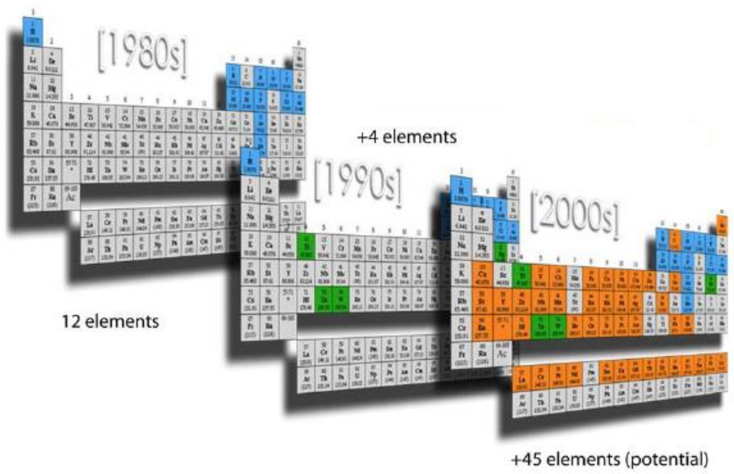


Figure 18: Development of number of materials used in IT products. Source: NRC (2008)

The limited availability of these metals can imply negative consequences for the possibilities of producing and using new technologies that can maintain a sustainable energy supply and achieve advancements in ICT.

4.1.4 Scarce materials relevant to SSL

Material scarcity always causes price increases whereas the increasing demand cannot be compensated by an increased supply. This is especially the case if certain metals are produced only as by-products of base metals (e.g. indium (In) or germanium (Ge) from zinc mines or gallium (Ga) from aluminium processing) and show a very low price elasticity of supply. Gallium is especially relevant for the production of solid state lighting (SSL) components, where rather few substitutes (with exception of selenium and indium) exist to date. The use of particular material in light emitting diodes (LEDs) is determined largely by the desired colour (Figure 19) and light intensity.

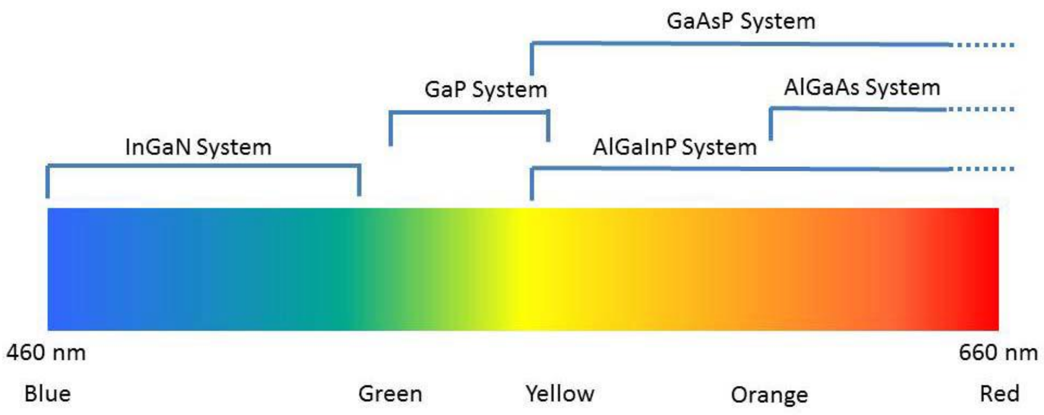


Figure 19. Effect of the semiconductor material used on the colour of the LED light (Buchert, et al., 2012).

Gallium is important element due to its good semiconductor and optoelectronic properties. For instance, in the US 74% of the present consumption of gallium is used in integrated circuits[2], especially in mobile phones, and 25 % in optoelectronic devices, from which laser diodes and LED account for 22 % and photo-detectors and solar cells for about 3 % (Jaskula, 2011). According to the U.S. Geological Survey, more than 99 % of gallium consumption included GaAs (gallium arsenide) used for the production of integrated circuits and optoelectronic devices or GaN (gallium nitride) for the manufacturing of LED and laser diodes (e.g. blue laser diodes used in Blu-ray disc devices (Vulcan, 2009; Jaskula, 2011).

China is the main producer (75%) of raw gallium, while in the EU there is also some production in Hungary and Slovakia. During the recent years South-Africa, China and Russia imposed or are imposing some trade restrictions related to gallium (EC 2010). Substitution of gallium is possible only in a few applications.

Most of ***indium*** used worldwide today is related to the EEE sector. This includes indium tin oxide (ITO) for thin-film coatings (84 %) mostly used for indium-based LED, devices for optical transmission of data and to a lesser extent for LED displays and ca. 5 %, for electrical components and semiconductors (Tolcin, 2008).

According to a recent study by the European Environmental Agency (Bakas, et al., 2012), indium is regarded as a scarce material. The main factors determining this is lack of poor reserve-to-production ratio, regional concentration of resources and rapid price development. Indium, is also regarded as critical material for the EU (EC 2010). More than 81% of the EU's imports of indium originate in China, Substitutes for indium are possible only in some applications and recycling possibilities are limited mainly to manufacturing residues.

Some of the functional additives to LEDs (e.g. germanium and tungsten) are also regarded critical metals by some studies (Bakas, et al., 2012). Structural scarcity plays a significant role as metals production is coupled to bulk metals and metal groups. For instance, the supply of indium is coupled to the production of bulk zinc (Zn), lead (Pb) and tin (Sn) and the production of gallium – to aluminium (Al) (Hagelüken, et al., 2009). Therefore, fluctuations in

[2] Due to a lack of European and worldwide data, information from USGS Mineral Yearbook 2009 is used to give an insight into main applications of Gallium.

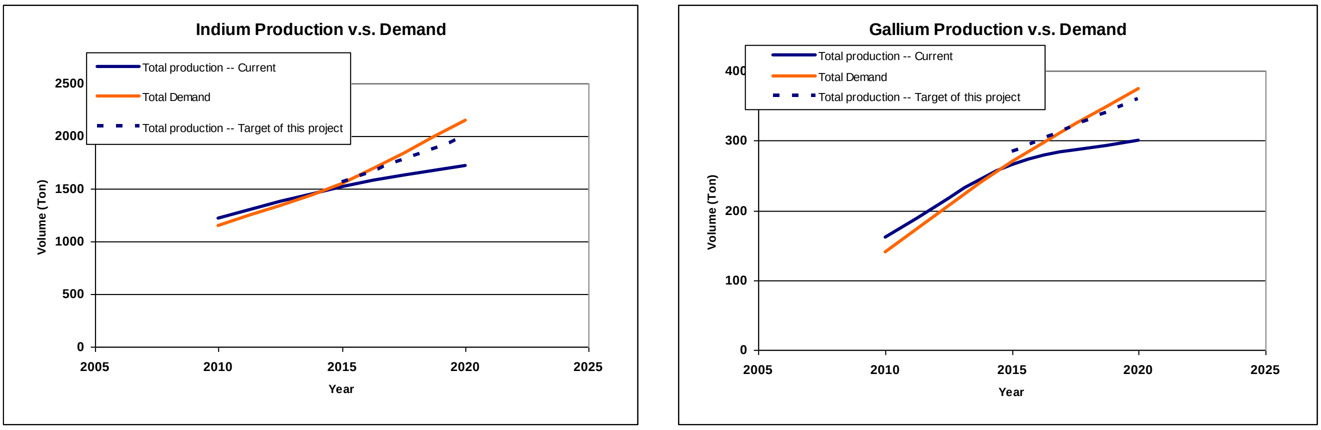
the production of bulk metals affect the production of rare materials too. This makes recycling an important source to address materials scarcity. Indeed, post-consumer electronic waste may appear a lucrative source for some metals. For instance while the average concentrations of gold (Au) and other platinum group metals (PGM) in primary ores are around 5g/t ore, the concentrations in waste are orders of magnitude higher, e.g. 200-250 g/t Au in PC circuit boards, 300-350 g/t Au in cell phones and 2,000 g/t PGM in car catalysts. (Umicore: Mark Cafferey, 2012).

Lastly, sapphire is also important for LEDs (for growing GaN LED substrates). One U.S. study estimated that more than 80 percent of LEDs are built on a sapphire substrate (Compound Semiconductor, 2011 in (U.S. Dept. of Energy, 2012b). A surge in demand for LEDs as the television industry converted to liquid crystal display (LCD) flat-screen technology with white-light LED, the market experienced an acute shortage in sapphire wafers (Yole, 2011 in U.S. Dept. of Energy, 2012b).

4.1.5 Amounts and demand of scarce SSL materials

Although the amounts of Gallium and Indium are small per LED, the use of the metals is not limited to SSL components (LEDs). Other product groups are competing for these scarce materials too, including mobile phones, PCs and notebooks, flat screen TVs and computer monitors, solar power converters and (partly) rechargeable batteries (Bakas, et al., 2012). Furthermore, Indium is a popular additive in solders. The potential shortage of the Gallium and Indium supplies worldwide is shown in Figure 20.

- Indium: Demand from electronic (especially flat display panel (FDP) and solder joints) and photovoltaic (PV) has also been foreseen. The Indium supply is projected to fall behind the Indium demand in year 2020. The price history of Indium did not represent the urgency due to growth of Indium recycling technology development.
- Gallium: Demand from electronics, SSL and photovoltaic has been foreseen. The Gallium supply is projected to fall behind demand in year 2020 resulting in a shortage.



(a) (b)

Figure 20: World-wide (a) Gallium and (b) Indium supply and demand.

A demand forecast for 2030 can be estimated based on the material composition of the most common types of small-scale LEDs, typically 10 µm thick and an area of 1 mm2, assuming future growth rates for the LED producing industries is summarized in Figure 21 (ISI 2009, in: Buchert, et al., 2012). Trends indicate that larger scale so-called high-power LEDs or the use of multiple low-power small-scale LEDs implies a larger demand for critical materials.

Future projections indicate that the market, which covers both white and colour 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, in: (Buchert, et al., 2012)). 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%. Several scenarios are quoted in different studies which project annual LED market growth rates in terms of number of devices between 5% and 15% during the period 2011-2020 and an average 10% annual growth rate for the periods after year 2020 (Buchert, et al., 2012).

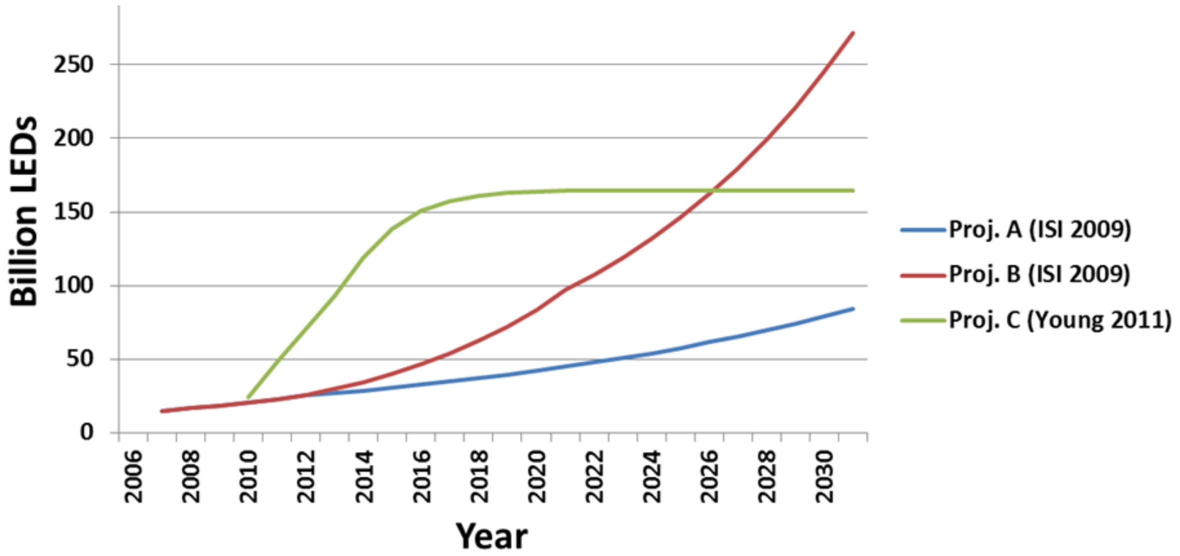


Figure 21: Projections of the future development of annual production figures for white LEDs (worldwide) (Buchert, et al., 2012).

In 2010 the annual global production of gallium and indium was 161 and 574 tons respectively (U.S. Geological Survey, 2011, in: Buchert, et al., 2012). The LED manufacturing sector demanded less than 1% of these materials, but the projected growth in demand is expected to increase this share if no parallel expansion of mining and production will take place (Table 4).
One has to realise, that the amount of these materials per LED product is quite small and that the cost of the LED dies is dominated by the processing costs rather than the raw material costs.

Table 4: Estimate of the future demand for gallium for the manufacture of white LEDs (based on the U.S. Geological Survey, 2011 data in: Buchert, et al., 2012)

Material	World production 2010, tons	LED industry demand (white LEDs), tons				
		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	574	0.67-1.38	0.95-4.37	1.30-4.76	1.78-4.78	2.45-4.78

This means that in the context of scarcity, the LED industry will find it easier to cope with increasing material prices, than for example the display industry, that uses vast amounts of indium and gallium, or the CIGS-solar industry, that uses vast amounts of gallium.

An example of the demand of SSL (LED) lighting devices and the corresponding demand of scarce materials in Germany depending on different assumptions of LED penetration rates in household sector is shown below. The amounts of material requirements in the future refer to only household sector and exclude the substantial demand of almost the same devices for the illumination of other public spaces such as streets, storage halls and office buildings. Even more materials will be demanded for LED applications in the commercial sectors.

Projections of the future material demand are uncertain due to several factors, such as:

- technology changes (smaller chips, thus different chip areas
- and thicknesses);changes in the lifespan of lighting devices (tendency to longer life);
- price developments and market conditions;
- and alternative technological breakthroughs.

Table 5: 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 (Buchert, et al., 2012).

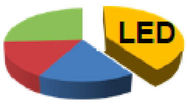
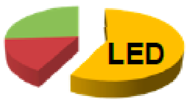
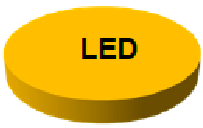
Proportion of LEDs in household lights		Weight Ga [t]	Weight In [t]	Weight Ce [t]	Weight Eu [t]	Weight Gd [t]	Weight Y [t]
	70% of all light bulbs replaced	3.63 1.98 0.27	3.24 1.77 0.25	0.22 0.12 0.02	0.067 0.037 0.005	1.67 0.91 0.13	3.57 1.95 0.27
	All light bulbs replaced	5.18 2.83 0.39	3.24 1.77 0.25	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

Table 6 below is using LCA inventory data that illustrates SSL related material quantities for most relevant product groups in the household sector in Germany, including such as LED based lighting systems as flat screen TVs, computer monitors and mobile phones, where the LEDs are used as back light of screens (Buchert, et al., 2012). Prospects for future material demands are estimated assuming different scenarios of SSL product replacement rates. The figures are covering only the domestic (household) sector. The demand of gallium and indium will increase significantly when high replacement rates of old products will be attained.

Table 6: Overview of the life cycle inventory analysis results for the product groups flat screens, notebooks, smartphones and LED lights (private households in Germany) (Buchert, et al., 2012).

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 smart-phones 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
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

4.1.6 Potential alternative materials for LEDs

One strategy to reduce material scarcity for SSL products is to look for material alternatives. Indeed, certain potential exists in reducing the dependence on indium and gallium.

Opportunities may be found in:

- Si wafers instead of sapphire wafers. The energy input required for the production of a Si-wafer is less than in a sapphire wafer. This is also (partly) reflected in the price of the wafers. Furthermore, with the larger sizes of the Si-wafers, in particular the MOCVD processes can be more efficient from a deposition area point of view.
- Creating LED sources that are not based on GaN but are based on ZnO, MgSe, and other semiconductor materials. Possible LED material compositions are given in Figure 22. An example of a ZnO nano-wire LED is shown in Figure 23.
- Replacing the critical Au wire bonds with Cu wire bonds as the availability of Cu is better than Au.
- Light (wavelength) conversion materials
  - More effective inorganic phosphors
  - Quantum dot phosphors
  - Organic phosphors

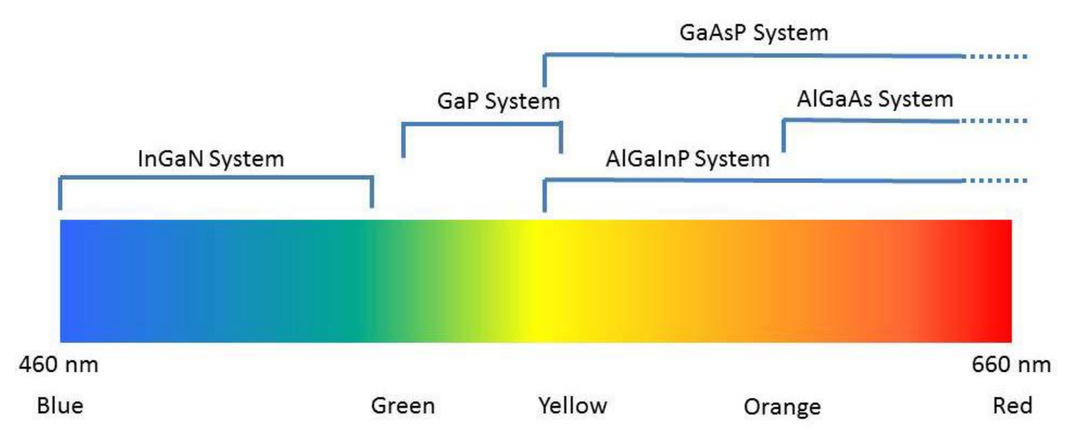
Alternate material systems	SiC, ZnS, ZnO, MgSe		AlP, ZnSe		AlAs		CdSe, InN
Currently used material systems							

Figure 22: The commonly used material systems for LEDs (bottom) and alternative material systems with potential to replace the existing formulations (top).

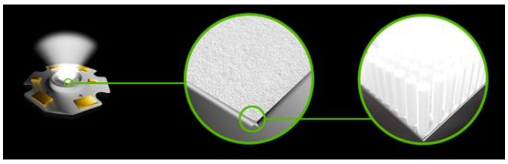


Figure 23: ZnO nano-wire LED (Ecosparke)

4.2 Collection and recycling of WEEE

Separately collected waste electric and electronic equipment (WEEE) in Europe are steadily increasing. In 2007, for instance, the total amount of WEEE reported as separately collected in the EU-27 was quite low compared with initial expectations when the WEEE Directive was originally implemented (Eurostat, 2011). 2.2 Mt was reported as separately collected in 2007 compared to an expected generated amount of over 7 Mt (United Nations University, 2007). In 2008, the total amount of reported separately collected WEEE increased to 3.1Mt, but was still lower than expected. Moreover, there is fair discrepancy between that is reported and what is really collected (est. at 2.6Mt for EU-27 in 2008). On the other hand, some sources claim that the true collection (and recycling) rate is much higher than the amount reported by Member States (Finland, 2011; Germany, 2011; Netherlands, 2012 and WRAP, 2011).

The latest available data form Eurostat show the amounts of electric and electronic equipment (EEE) that has been put on the market, and WEEE collected in total from private households and reused and recycled in the EU in 2010. Only a handful of countries (e.g. Sweden, Denmark, Norway) exhibit somewhat higher (50% and above) collection rates (Figure 24), while per capita collection volumes in Finland, Belgium, Luxemburg, Germany and Ireland are high too (Figure 25).

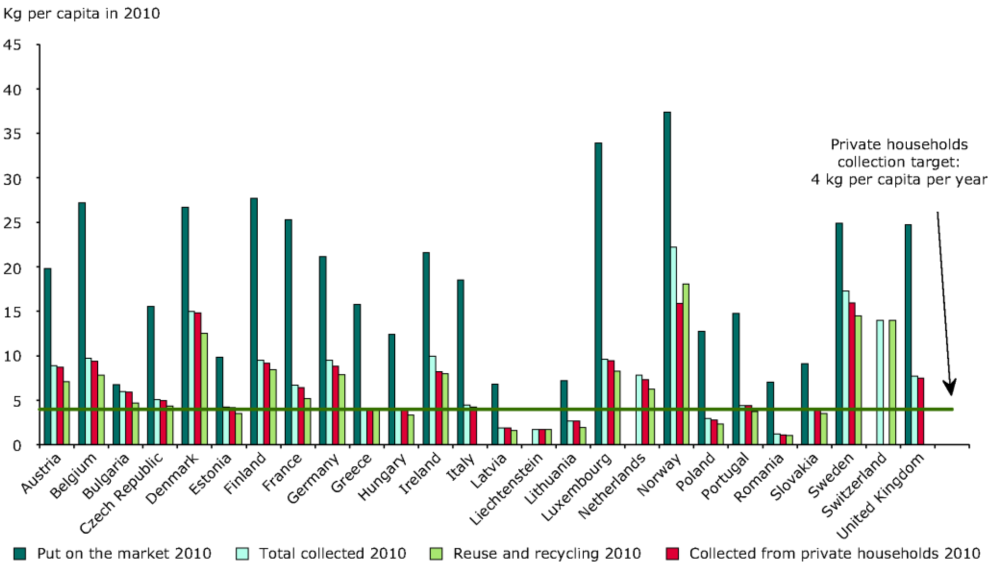


Figure 24. Amounts of EEE put of the market and amounts of WEEE collected, reused and recycled. *Source: Eurostat, 2014.*[3]

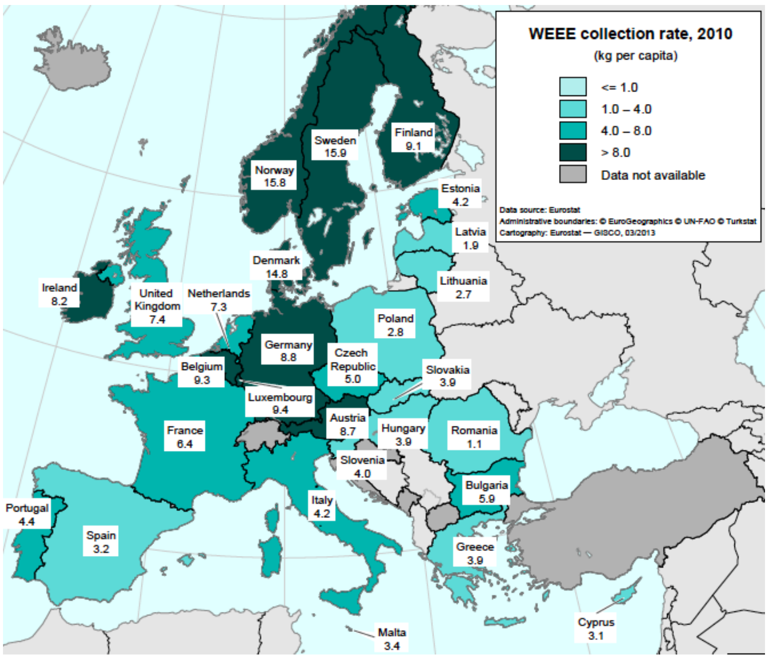


Figure 25. Per capita collection volumes of EEE in the EU member states. Source: (Eurostat, 2014)

Only part of separately collected WEEE is recycled, whereas the recycling concentrates mainly on the recovery of bulk materials such as bulk metals and plastics. The recycling rates of active components (semiconductors) are extremely low with most of it shredded and subjected to thermal treatment. So far the recycling industry is mainly focusing on precious metals especially those present in larger quantities in certain components such as connectors and junctions.

[3] URL: http://www.eea.europa.eu/data-and-maps/figures/weee-put-on-the-market-2

The existing recycling policy and infrastructure - the current forms of collection and recycling techniques - have not yet focused on this problem, meaning that the recovery of many critical metals is minimal. There are multiple reasons for this induced by economic, organizational and policy related limitations.

First, is the insufficient collection rate of WEEE and its availability in large volumes in one location to exploit the economy of scale making recycling profitable (Bakas, et al., 2012). Currently, a significant proportion of WEEE continues to be disposed of with mixed waste because, for example, householders do not always choose to use the WEEE take-back systems available to them. The recycling of rare metals is further complicated due to their dissipative use. Trends in miniaturization and performance increase in electronic products imply diminishing concentrations of rare materials, while the exponential increase is demand for electrical and electronic equipment (EEE) implies significant growth in volumes of rare (and potentially toxic) materials circulating in our society (Hagelüken, 2008).

Second, the additional costs of recycling have led to unregulated recycling of electronic waste, resulting in a negative environmental influence. Oftentimes this illegal trade dumps e-waste and toxic materials from the developed world in poorer countries in regions like Asia and Africa where exporting is easy, labour laws are flexible, and communities are poor. In general, export of WEEE to non-OECD countries is prohibited, whereas for example the export of used but fully functional equipment to non-OECD countries is permitted (see 4.4 for more information about relevant legislation). According to the European Environment Agency (EEA) the amount of notified shipments of WEEE in 2007 was around 104,000 tonnes. Surprisingly, this figure constitutes only a small amount of the generated and collected WEEE. One explanation for this is that some WEEE leaves the EU registered as used products rather than WEEE (ETC/SCP, 2010). Another estimate, based on studies undertaken by the German and the Danish Environment Agencies, suggests that the amount of used electrical and electronic products or WEEE illegally shipped from the EU to non-OECD countries is at least 300,000-500,000 tonnes per year (EEA, 2012).

Unfortunately, still rather large portion of WEEE are exported (legally and illegally) from the EU as used products. However, the recent recast of the WEEE Directive will lead to higher collection and recycling targets, the removal of the distinction between household and non-household WEEE and further measures to combat illegal exports. The situation with LEDs is most likely to be different as third country export will play a lesser role, with instead the role of inappropriate collection and disposal being much more significant. The inappropriate route of LED containing waste is likely to be either together with construction and demolition waste, or in mixed waste streams destined to landfills or incineration. The most likely appropriate route of LED waste is in the stream of separately collected WEEE, which is still rarely subjected to dismantling for material recycling and instead undergoes shredding and incineration or landfill disposal (or storage in rarer cases). This is largely due to poor economics of simple but labour-intensive manual dismantling operations.

Third, specific to critical metals, the recovery rate from end-processing of WEEE is insufficient for some of the metals as the recycling process (dismantling, pre-processing, end-processing) focuses and is tailored on extracting bulk materials, and satisfying end-processing technologies are missing. This is partly reasoned by the fact that thermodynamics limit the technical recyclability of certain metals if jointly contained in complex mixes with other elements (Gößling-Reisemann, 2008). Besides systematic separation of the relevant components, the recycling of these materials requires a significant effort in their concentration in the secondary material flows and their final recovery in an adequate degree of purity.

While there are sufficient metallurgical methods for material recovery and refining known today for many metals from WEEE, they are still mainly focused on copper and precious metals. The main barriers for other metals relate to economic feasibility and the costs of virgin alternatives that in today's conditions often outcompete material recycling options.

There is also a significant loss of critical metals in the initial stages of the recycling chain, namely - disassembly and pre-treatment (Bakas, Fischer et al. 2012). This is not only due to technical and logistical reasons, but 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 (Buchert, et al., 2012).

Structural and technology related losses are taking place in different waste processing steps, which even at relatively good yields in individual processes ultimately results in rather low recovery rates. For instance the process chain of the recovery of gold features rather high performance factors, though in the end results in much lower recovery rate (Figure 26. Example of gold recycling and losses in different recovery stages. Source: (Umicore: Mark Cafferey, 2012) The performance factors in the recycling of SSL related metals such as gallium and indium are much lower resulting in less than 1% recovery rate. This is why improvements in collection rates as well as the efficiency of dismantling and pre-processing are crucial to secure higher end-of-process yields.

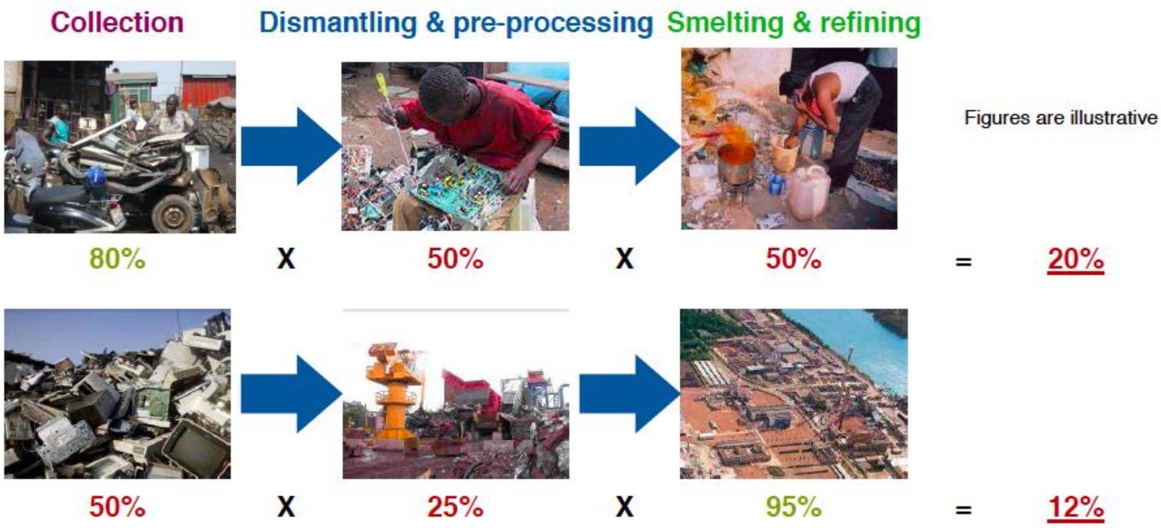


Figure 26. Example of gold recycling and losses in different recovery stages. Source: (Umicore: Mark Cafferey, 2012)

Table 7 illustrates the total potential for critical raw materials in Germany and their loss in current collection, pre-treatment and refining processes for notebooks. The data is based on the assumption that the products sold in 2010 have the lifespan of 6.6 years and will be handled according to the collection, recycling and disposal systems, which at present are standard in Germany. Only a fraction of the critical metals contained in notebooks have been fed back into the industrial cycle (Buchert, et al., 2012). The collection rate of notebooks is only around 50% owing to numerous legal or illegal exports to e.g. Africa and Asia.

Table 7. Critical raw material potentials in notebooks and losses from the collection and treatment systems currently used in Germany (Buchert, et al., 2012).

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

As of now, there only a handful of recycling facilities in Europe that attempt rare metal recycling on a large scale (e.g. Umicore in Belgium and partly Boliden in Sweden). Better recycling of WEEE would not only be an important part of a strategy to secure the EU's supply of critical materials, but also have positive environmental and socio-economic impacts such as reduced environmental impact from material extraction and end-of-life management, more jobs and higher economic turnover. In this way, recycling of WEEE and the associated recovery of critical metals could contribute to a greener economy (Bakas, et al., 2012).

The generic recommendations for securing better recovery of scarce materials proposed by the EU ad-hoc working group on critical metals (EU Commission, 2010) included several priorities for policy actions:

- mobilising EoL products with critical raw materials for proper collection instead of stockpiling them in households (hibernating) or discarding them into landfill or incineration;
- improving overall organisation, logistics and efficiency of recycling chains by focusing on interfaces and system approach;
- preventing illegal exports of EoL products containing critical raw materials and increasing transparency in flow;
- promoting research on system optimisation and recycling of technically- challenging products and substances

4.2.1 Collection rates of LED lights

LEDs are a relatively new product group so that there are currently no available specific pan-European data for the end-of-life collection volumes and rates. Somewhat more reliable data may exist in some countries (or regions) but at this moment it can serve only as an indication.

One study estimates, that assuming the future collection rates for LEDs will be similar to those of the other forms of lighting, then, in line with the data for gas discharge lamps in Germany and the general EU data, a collection rate of only 30% can be estimated (BMU 2009, Huisman et al. 2012, in: (Buchert, et al., 2012)). The values on which this is based on do not contain any delays due to the use phase of the devices and are purely estimates of the actual collection rates. The actual collection rates of SSL products are likely to be considerable higher in countries with high WEEE collection rates (e.g. Sweden, Denmark, Germany, and Netherlands). To secure high collection rates there is a decisive role for the way waste management systems are organised on the municipal level and how extended producer responsibility (EPR) systems are implemented on the national level.

4.2.2 Recycling of rare materials present in LEDs

Consistent with the situation for rare materials presented earlier, the recycling rate of gallium and indium today are very low – far less than 1%, (Graedel et al. 2011, cited in: (Buchert, et al., 2012)). The main reason for this low rate is that their applications are dissipative, i.e. very small quantities of material per unit product, which in turns hurts the economic feasibility of recycling in comparison to virgin material prices. (Johansson, et al., 2013)

Despite the challenges, recycling of gallium and indium from processing residues has been established, for example, in Japan, Belgium and Germany, for the processing of industrial and partly post-consumer waste. However, there remain significant bottlenecks for the recycling of these scarce metals. The main shortcomings are in the collection and pre-treatment of separate product groups (incl. LED equipment). LED based lighting devices are still relatively new on the market and do not play a part in the recycling industry in any noteworthy quantities.

4.3 Legislation and Regional Effects

Governments worldwide strive to reduce the use of energy, reduce the use of toxic matter, and encourage recycling, as summarized in the ISA Strategic Research Agenda on Green and Sustainability (Gielen, 2011). Recycling can enhance resource efficiency by reducing the use of virgin materials, while also reducing the environmental impacts related to the extraction and processing of virgin materials.

The European Commission in 2005 formulated a vision for the EU as a recycling society within its thematic strategy for waste prevention and recycling[4]. In order to increase recycling, the EU has introduced a variety of recycling policies over the past 15 years, including specific recycling targets for different end-of-life products including waste electrical and electronic equipment (WEEE), end of life vehicles, packaging, and batteries. These

[4] EU-Commission, 2005: Communication from the Commission on the Thematic Strategy on the Prevention and Recycling of Waste

initiatives focus on reaching minimum quantitative recycling targets by a given year in terms of a minimum percentage of the particular waste stream that has to be recycled.

A range of both voluntary and mandatory policy measures exist that are relevant to SSL. The main instruments include: Eco-design, Energy labelling, Eco-labelling, the Low-Voltage Directive / General Product Safety Directive, the Directives on the Restriction of Hazardous Substances (RoHS) and Waste Electrical and Electronic Equipment (WEEE), Green Public Procurement (GPP) and the New Legislative Framework.

Directive 2009/125/EC[5] of the European Parliament establishes a framework for the setting of EcoDesign requirements for energy-related products. This directive defines the legal framework for setting EcoDesign requirements on energy-related products, including lighting products. EcoDesign requirements are minimum requirements that the products need to fulfil if they are to display the CE marking, which is a requirement before placing the product on the EU market. EcoDesign aims to reduce the environmental impact of products, including the energy consumption throughout their entire life cycle. Since 2012, there is compulsory legislation on both directional and non-directional LEDs.

Energy Labelling[6] sets the framework for developing product-specific energy labelling measures to allow end-users to choose more efficient products through standard product information on energy consumption. LEDs are currently designated in the high B (for lower performing LEDs though the A+ category

Ecolabel[7] is a voluntary scheme which promotes products having high-level environmental performance. Revised Ecolabel criteria for light sources in order to include specifically LEDs are currently under consideration for development.

SSL products and lighting systems are also covered by EU Directives. The Low Voltage Directive[8] covers the safety of electric products operating under more than 50 volts and ensures that only safe electrical equipment is placed on the market. For products operating below 50 volts the safety issues are covered by the General Product Safety Directive.[9]

The Waste Electrical and Electronic Equipment Directive 2002/96/EC (WEEE Directive)[10] originally did not specifically name LED lamps in the scope or exclusions, leading to some confusion. The most recent recast of the Directive (Directive 2012/19/EU) specifically names and defines LEDs in the scope.

Restriction of Hazardous Substances (RoHS) Directive 2002/95/EC[11] restricts the use of six hazardous materials in the manufacture of certain types of electronic and electrical equipment, RoHS does not apply to LEDs sold individually (which are considered as components rather than an electrical product and therefore are not within the scope of RoHS). However, when being used as part of electrical equipment (this includes LED lamps), LEDs do fall within scope and therefore should be compliant with the legislation.

[5] Ecodesign: http://ec.europa.eu/energy/efficiency/ecodesign/eco_design_en.htm
[6]Energy labelling: (http://www.lightingeurope.org/uploads/files/LightingEurope_Guide_-_Regulation_874_2012_ENERGY_LABELLING__Version_1_23_May_2013.pdf)
[7] Ecolabel: http://ec.europa.eu/environment/ecolabel/
[8] The Low Voltage Directive (http://ec.europa.eu/enterprise/sectors/electrical/lvd/
[9] General Product Safety Directive: http://ec.europa.eu/consumers/safety/prod_legis/index_en.htm
[10] WEEE: http://ec.europa.eu/environment/waste/weee/
[11] RoHS: http://ec.europa.eu/environment/waste/rohs_eee/

These restrictions prevent the sale of equipment containing harmful levels of mercury, lead, cadmium, PBB, PBDE and hexavalent chromium. Due to this compliance, LEDs can be disposed of and recycled in the same way as an ordinary light bulb.

Additionally, the EU Waste Shipment Regulation (EU Regulation 1013/2006)[12] requires that the authorities have to be notified before WEEE is allowed to be shipped out of the EU. The EU Member States must report the shipments to the Basel Convention Secretariat and to the European Commission. Used, but working products do not require notification before shipment and can legitimately be shipped to Asia and Africa

To reduce the movements of hazardous waste between nations, The Basel Convention on the Control of Trans-boundary Movements of Hazardous Wastes and Their Disposal was designed in 1989[13]. The Basel Convention, is an international treaty that was specifically designed to prevent transfer of hazardous waste from developed to less developed countries. In addition to the Basel Convention, the Bamako Convention on the ban on the Import into Africa and the Control of Trans-boundary Movement and Management of Hazardous Wastes within Africa negotiated a treaty among African nations prohibiting the import of any hazardous waste (African Union, 1991). The Bamako Convention similar to the Basel Convention, but is much stronger in prohibiting all imports of hazardous waste.

Green Public Procurement (GPP)[14] is a voluntary scheme at EU level whereby public authorities seek to procure goods, services and works with a reduced environmental impact throughout their life cycle. In 2011, the new EU Green Public Procurement (GPP) criteria for "indoor lighting" was adopted and the existing criteria for "street lighting & traffic signals" was updated.

Since 2010, the enforcement of performance and safety requirements contained in most of the above instruments can rely on the New Legislative Framework (NLF)[15]. Since 2010, the NLF regulation sets out a stronger framework for market surveillance of electrical equipment as well as the powers and duties of national authorities. The NLF decision contains model provisions on obligations to which product harmonisation legislation should be aligned.

[12] See EU Waste shipment legislation: http://ec.europa.eu/environment/waste/shipments/legis.htm
[13] Basel Convention: http://www.basel.int/TheConvention/Overview/tabid/1271/Default.aspx
[14] GPP: http://ec.europa.eu/environment/gpp/index_en.htm
[15] New Legislative Framework: http://ec.europa.eu/enterprise/policies/single-market-goods/regulatory-policies-common-rules-for-products/new-legislative-framework/

5 Moving forward with SSL

This section explores methods for design and models for business that consider the full life cycle of product and promote the design, deployment, maintenance, disposal of products as well as potential barriers.

5.1 Eco-design

Full life-cycle sustainability of products requires that the design of products starts with consideration of the environmental information (such as that presented already in this report) and to then make "green" material choices, "green" manufacturing methods, and "green" disposal. The methodologies and tools that are developed endeavour to satisfy or express the so called "Ten Golden Rules", as described by (Luttropp, et al., 2006). In short these rules are:

1. Do not use toxic substances and utilize closed loops for necessary but toxic ones.
2. Minimize energy and resource consumption in the production phase and transport through improved housekeeping.
3. Use structural features and high quality materials to minimize weight in products if such choices do not interfere with necessary flexibility, impact strength or other functional priorities.
4. Minimize energy and resource consumption in the usage phase, especially for products with the most significant aspects in the usage phase.
5. Promote repair and upgrading, especially for system-dependent products. (e.g. cell phones, computers, CD players, and possibly SSL products).
6. Promote long life, especially for products with significant environmental aspects outside of the usage phase.
7. Invest in better materials, surface treatments or structural arrangements to protect products from dirt, corrosion and wear, thereby ensuring reduced maintenance and longer product life.
8. Prearrange upgrading, repair and recycling through access ability, labelling, modules, breaking points and manuals.
9. Promote upgrading, repair and recycling by using few, simple, recycled, not blended materials and no alloys.
10. Use as few joining elements as possible and use screws, adhesives, welding, snap fits, geometric locking, etc. according to the life cycle scenario.

The reason why we start by mentioning the ten golden rules is that this report aims to make Ecodesign understandable to a wider audience that is not normally working with life cycle assessments. In relation to SSL, these green design rules can be applied in a number of ways, including designing for disassembly, which can include removal from architectural structures but also designing the individual luminaires themselves for better materials recovery with easy connectors, less materials or fewer (or reusable) components. Standards can help increase modularity as well (Hendrickson, et al., 2010).

Traditionally, the focus of EcoDesign has been to improve product development methods to reduce environmental burdens. However, it should be noted that the foundation is design, i.e. to make products with an appreciated functionality. In a similar way as the quality work gradually has become integrated in design and production, it is also relevant to integrate the environmental considerations in the centre of the design process, and in fact this is going on. In this way, EcoDesign aims to enable enhanced human satisfaction together with positive developments in sustainable development (Karlsson, et al., 2006).

One renowned early publication on this subject is (Porter and Van der Linde 1995) where the case is made that environmental policies can stimulate innovation and that improving environmental performance can also improve economic performance and stimulate positive systemic change. Companies that have been successful in making sustainable core to their business have an organizational structure that encourages the application of environmental knowledge into the development processes, often through a "Design for Environment" champion. Including sustainability considerations as a mandatory dimension of project and company management also encourages a core perspective (Karlsson, et al., 2006).

EcoDesign also includes a more open ambition to use inspiration from a wider field of positive examples of smart products and methods, effective system solutions and attractive designs. In addition to being useful to product design, EcoDesign can also be a tool for the rethinking of process and systems that is needed to continually advance in the journey towards sustainability (Karlsson et.al 2006).

5.2 Business models for maintenance and upgrade

As indicated in the beginning of this report, a big progress in lighting products is expected in the coming year, in particular in efficacy and lifetime. This means that for light intensive places it can be useful to change the light sources to improved ones even before the lifetime of the current light source is consumed (see Figure 27). Furthermore, lighting companies are busy making the lighting systems more intelligent, to further save energy and enhance the user experience. These kind of aspect can give input to new maintenance and upgrade approaches, and thus new business opportunities.

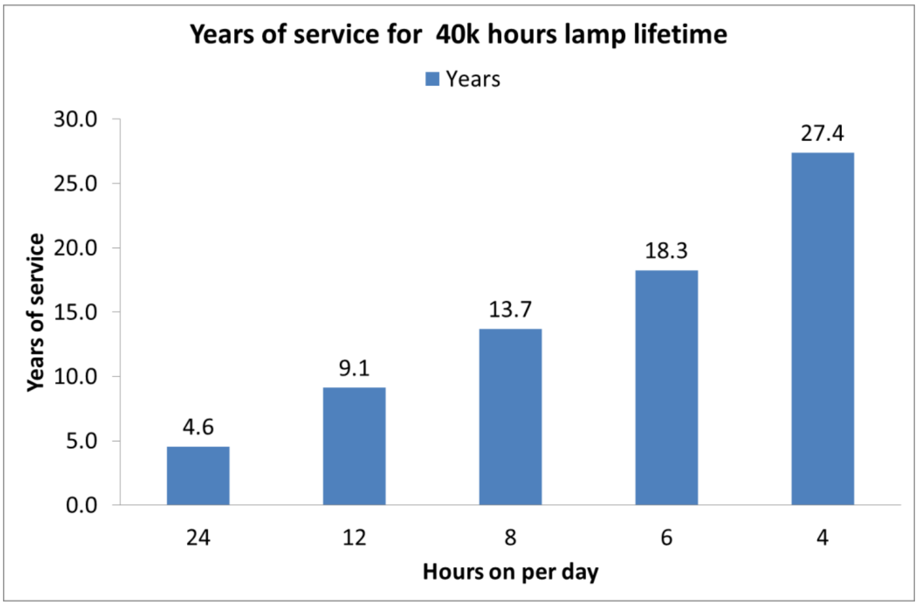


Figure 27: Service lifetime in years as a function of hours on per day for a 40k hour's lifetime.

5.3 Business models for disposal

As the recycling of products with valuable materials, and LED products belong to that category, there is value in the disposal of these products. In particular in the professional market, this can lead to new business opportunities. End of life management of SSL products may also involve a product take-back scheme. This can be designed on a few ways, including direct return to the manufacturer, central collection at existing recycling facilities, or through municipality led collection (Hendrickson, et al., 2010). Companies may consider combining the upgrade and maintenance services with targeted disposal and possibly re-use constructs. The attractiveness will depend on the developments in the field of disposal as well as the ease of disposal and recycling.
In the disposal phase there are several aspects that need to be considered:

- How are products disposed of? For professional lighting this will happen in a different way than for consumer products. In professional lighting, in particular installation companies are also active in disposing old lighting systems. For consumer products, large differences will exist in the world, depending on the urbanization, and the level of organization of the collection of lamp waste.
- What are the option for recollection of the materials? This depends on the measures that have been taken in the design of the products (see section EcoDesign) as well as the options to “demanufacture” the LED lamps. An overview for electronic products is given by (Williams, 2006) and the effect of product recovery is described by (White, et al., 2003).
- What new methods will come available in the waste stream treatment to enrich the waste streams to value sources of materials. This requires separation systems (see (Wolf, et al., 2010).

The disposal must also be considered in conjunction with the recycling processes that are discussed in sections 3.5 and 4.2.

5.4 Landlord tenant problem

A potential barrier to uptake of SSL technology that needs to be considered is the landlord tenant problem. The landlord tenant problem refers to the mismatch of interests and incentives that exist between the building owner, who pays the initial price of the lighting (and is likely to base decisions about lighting based on up-front costs rather than long term benefits), and the user who usually pays the running costs (and thus would be more interested in the longer term benefits but is usually not involved in the decision about what type of light to install). For example, when comparing today's LEDs with fluorescent lamps, their total cost of ownership is less after 5-6 years of usage (EU Commission, 2011) and their lifetime costs compare even more favourably with incandescent lamps. A landlord tenant situation inhibits the adoption and energy saving opportunities afforded by the energy efficient lighting because of the "split incentives" between investors and energy end-users, also known as the "principle agent" problem.

A 2007 study by the International Energy Agency found significant evidence that while the affected energy use on an individual basis for a landlord tenant situation was often small, when aggregated the problem was found to be significant. The report also suggested that such problems are pervasive, disbursed and complex, requiring the design of well-targeted policy packages to address specific contexts (International Energy Agency (IEA), 2007).

Such policy packages could include policies to address the contract design to ensure end-users face energy prices, for example by creating third party lighting service provider that would sign contracts to provide the up-front investment to install the LEDs, but also maintain the LED fixtures and charge occupants for light. This would remove the purchasing decision from the builders and allow pricing for the total cost of ownership (Vogler, et al., 2011). The tenant landlord problem was also one focus of the consultation for the European Commission's Green Paper for accelerating the deployment of innovative lighting technologies (EU Commission, 2012b).
Respondents to the consultation suggested different strategies for dealing with the issue including:

- Creating new opportunities for lease or elaborate new savings/leasing models with EC support
- Fixing the energy cost for tenants and allow the investing landlords to receive paybacks;
- Rewarding tenants aiming to realize energy saving works using the SSL technologies and incentives for tenants to buy SSL lamps/luminaires;
- Examining how the conflict is addressed in different EU member states in order to identify 'best-case examples' and promote those 'best-cases' in order to create awareness how the conflict can be overcome;
- Introduce LED interoperability and compatibility with the installed base of existing electrical installations in order to reduce the needed investment and operating costs (since there will be no need to change mechanical or electronic switch or luminaires decreasing the initial upfront investment costs and lessening the scope of this problem).

In addition, regulation of the level of energy efficiency in appliances and buildings is also important, as is improving access to information about sustainability factors for consumers (IEA, 2007). However, at present the landlord tenant problem remains a possible barrier to uptake of LEDs.

6 Conclusion

SSL technology has the potential to enable dynamic system solutions that provide the right light, in the right place, at the right time.

To reach this goal it is important to enhance the understanding of how the technical systems and the business systems work. Comprehensive systems analyses, e.g. LCA, will yield valuable guidance for the needed developments.

In relation to SSL, material scarcity (particularly of Gallium and Indium) is particularly relevant. Recycling is therefore important and business models for the disposal of SSL should be considered and further explored. The existing legislation and market surveillance also have an important role in the deployment and disposal of SSL to ensure that those lighting solutions that provide the best customer value are encouraged and realized. Lastly, the interlinkage of life-cycle aspects promotes the design and production of intelligent lighting systems that use knowledge about environmental considerations as an integrated aspect of the design process and aim to increase the overall functionality of the product. To achieve this, it should be ensured that sustainable development is integrated in the core of SSL design, deployment, and disposal.

7 Bibliography

African Union. 1991. *Bamako Convention on the ban on the Import into Africa and the Control of Transboundary Movement and Management of Hazardous Wastes.* 1991.
Ashby, Michael F. 2009. *Materials and the Environment: Eco-informed Material Choice.* 2009.
Bakas, I., et al. 2012. *Present and potential future recycling of critical metals in WEEE.* Copenhagen : European Topic Centre on Sustainable Consumption and Production, 2012. ETC/SCP 2012.
Buchert, M., et al. 2012. *Recycling critical raw materials from waste electronic equipment.* s.l. : North Rhine-Westphalia State Agency for Nature, Environment and Consumer Protection, 2012.
de Almeida, Aníbal, et al. 2011. Characterization of the house hold electricity consumption in the EU, potential energy savings and specific policy recommendations. *Energy and Buildings.* 2011.
Ecosparke. ZnO nanowire LED-chip. *Ecospark.* [Online] [Cited: October 17, 2012.] http://ecospark.se/products/product-1.
EEA, 2012. Trans-boundary shipments of waste in the European Union. Forthcoming report from the European Environment Agency
ETC/SCP, 2010. Trans-boundary Shipments of Waste in the European Union – Availability of data, methodologies and information on their drivers and environmental impacts
http://scp.eionet.europa.eu/publications/Transbound%20data%20report
EU Commission. 2010. *Critical raw materials for the EU. Report of the Ad-hoc Working Group on defining critical raw materials.* Brussels : European Commission, Enterprise and Industry, 2010. 85.
—. 2012b. *Green Paper Lighting the Future: accelerating the deployment of innovative lighting technologies. Results of the Public Consultation.* Brussels : EU Commission, 2012b.
—. 2011. *Lighting the Future. Accelerating the deployment of innovative lighting technologies.* Brussels : EU Commission, 2011. COM(2011) 889.
European Commission. 2012. LCA tools, services and data. *European Commision - Joint Research Centre.* [Online] 2012. [Cited: October 12, 2012.]
http://lca.jrc.ec.europa.eu/lcainfohub/introduction.vm.
Eurostat, 2011. WEEE Collection data. Addressed August 2011.
Eurostat, 2014. Key Waste Streams: WEEE. [Online] 2014.
http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/key_waste_streams/waste_electrical_electronic_equipment_weee.
Finland, 2011. Waste Flows in Finnish Producer Responsibility System– Case WEEE and Portable Batteries and Accumulators, September 2011 JYVÄSKYLÄ UNIVERSITY SCHOOL OF BUSINESS AND ECONOMICS
Germany, 2011. Ökopol. 2011.WEEE FLOWS IN GERMANY, Short analysis for HEWLETT PACKARD COMPANY
Gielen, Alexander. 2011. *Strategic Research Agenda Green and Sustainable Solid-state-lighting.* s.l. : International Solid-state-lighting Alliance, 2011.
Gielen, Alexander W.J. 2013. SSL products full life-cycle green manufacturing and recycling. *Global Strategic Outlook - 1.* s.l. : International Solid-state-lighting Alliance, 2013.
Gößling-Reisemann, S. 2008. Entropy analysis of metal production and recycling. In: Management of environmental quality
Gutowski, T., et al. 2005. Environmentally bening manufacturing: Observations from Japan, Europe and the United States. *Journal of Cleaner Production.* 2005, Vol. 13, pp. 1-17.
Gutowski, Timothy G., et al. 2009. Thermodyanmic Analysis of Resources Used in Manufacturing Processes. *Environmental Science and Technology.* 2009, Vol. 43, 5, pp. 1584-1590.
Hagelüken, C. and Meskers, C.E.M. 2009. *Technology challenges to recover precious and special metals from complex products.* Davos, Switzerland : Twin World Congress and World Resources Forum, 2009.
Hagelüken, C. 2008. *Opportunities & challenges to recover scarce and valuable metals from electronic devices.* Paris : OECD-UNEP Conference on Resource Efficiency, 2008. 24.04.2008..
Hendrickson, C. T., et al. 2010. *Reducing environmental burdens of solid-state lighting through end of life design.* s.l. : Environmental Research Letters, 2010.
Huisman, J., van der Maesen, M. and Eijsbouts, R.J.J. 2012. *The Dutch WEEE flows.* Bonn, Germany : United Nations University, ISP – SCYCLE, 2012.
International Energy Agency (IEA). 2007. *Mind the Gap.* Paris : IEA, 2007.

Jaskula, B. W., 2011. Gallium. Mineral commodity Yearbook 2011. United States Geological Survey, 703: 58-59.
Johansson, I., et al. 2013. *Kritiska metaller i svenska avfallsaskor .* Borås : Waste Refinery, 2013.
Jørgensen, A., et al. 2008. Methodologies for Social Life Cycle Assessment. 2008, Vol. 13, 2, pp. 96-103.
Karlsson, R. and Luttropp, C. 2006. *EcoDesign: what's happening? An overview on the subject area of EcoDesign.* s.l. : Journal of Cleaner Production, 2006. 14.
Karlsson, R. 1998. *Life cycle considerations in sustainable business development .* Gothenburg : Chalmers University of Technology, 1998. Doctoral dissertation.
Krishnan, N., E. D. Williams and S. B. Boyd, 2008. Case studies in energy use to realize ultra-high purities in semiconductor manufacturing. 2008 IEEE International Symposium on Electronics and the Environment, Proceedings of, San Francisco, CA, The Institute of Electrical and Electronics Engineers, Inc. (IEEE)
Koomey J. 2008. Worldwide Electricity Used in Data Centers. Environmental Resource Letters (IOP Publishing Ltd.): 1-9.
Koomey J.G., Berard S., Sanchez M. and Wong H. 2009. Assessing Trends in the Electrical Efficiency of Computation over Time, Lawrence Berkeley National Laboratory and Stanford University; Microsoft Corporation; Intel Corporation: 1-47.
Ligthart, Tom N and Ansems, Antoon M M. 2012. Modelling of recycling in LCA. [book auth.] Enri Damanhuri. *Post-Consumer Waste Recycling and Optimal Production.* s.l. : InTech, 2012.
Luttropp, Conrad and Lagerstredt, Jessica. 2006. EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of Cleaner Production.* 2006, Vol. 14, pp. 1396-1408.
Netherlands, 2012. The Dutch WEEE Flows. Study carried out by Huisman, J., van der Maesen, M., Eijsbouts, R.J.J., Wang., F., Baldé, C.P., Wielenga, C.A., 2012.
http://www.wecycle.nl/uploads/futureflows/Press/Report_Dutch_WEEE_Flows.pdf
NRC, 2008. Minerals, Critical Minerals and the U.S. Economy. National Research Council, Washington D.C., The National Academies Press.
Nyamwange, M. 1996. Public perception of strategies for increasing participation in recycling programs. *Journal of Environmental Education.* 1996, Vol. 27, pp. 19-22.
OECD Environment Directorate, 2010a. Materials Case Study 1: Critical Metals and Mobile Devices. OECD Global Forum on Environment focusing on Sustainable materials Management, 25-27 October 2010, Mechelen, Belgium
OECD Environment Directorate, 2010b. Materials Case Study 1: Critical Metals and Mobile Devices, Annexes. OECD Global Forum on Environment focusing on Sustainable materials Management, 25-27 October 2010, Mechelen, Belgium
OSRAM. 2009. *Life cycle assessment of illuminants: A comparison of light bulbs, compact fluorecent lamps and LED lamps.* 2009.
Pandharipande, Ashish and Caicedo, David. 2011. Daylight integrated illumination control of LED systems based on enhanced presence sensing. *Energy and Buildings.* 2011, 43, pp. 944–950.
Plepys, A. and Schischke, K. 2004. *Beyond the walls of Semiconductor Fabs: Energy Intensity of High-grade Chemical Manufacturing.* Berlin : Fraunhofer Institute, 2004. Proceedings of Electronics Goes Green 2004+: Driving Forces for Future Electronics.
Porter M.E., Van der Linde C., 1995. Toward a New Conception of the Environment-Competitiveness Relationship. The Journal of Economic Perspectives. 9: 97-118
U.S. Dept. of Energy. 2012b. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part 2: LED Manufacturing and Performance.* Washington D.C. : Solid State Lighting Program. Office of Energy Efficiency and Renewable Energy. U.S. Department of Energy, 2012b.
—. 2012a. *Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products. Part I: Review of the Life-Cycle Energy Consumption of Incandescent, Compact Fluorescent, and LED Lamps.* Washington. D.C. : Solid State Lighting Program. Office of Energy Efficiency and Renewable Energy. U.S. Department of Energy, 2012.
Umicore: Mark Cafferey. 2012. The Changing Dynamics of Recycling. *Carolina Recycling Association Conference.* [Online] 2012. http://cra.myecoville.com/assets/2012-Conference/2012-Presentations/Markets-and-Creating-the-Material-Supplies-of-the-Future-Caffarey.pd.
UNEP: Buchert, M., Schuler, D. and Bleher, D. 2009. *Critical Metals for Future Sustainable Technologies and Their Recycling Potential.* s.l. : UNEP, 2009.

United Nations. 1989. *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal.* 1989.
—. 1998. *Kyoto Protocol to the United Nations Framework Convention on Climate Change.* 1998.
United Nations University, 2007. 2008 review of Directive 2002/96 on WEEE (page 60-65)
Von Weizsacker, E., Lovins, A. B. and Lovins, L. H. 1997. *Factor four-doubling wealth, halving resource use.* 1997.
Vogler, O, Wee, D and Wunderlich, F. 2011. *LED at the Crossroads. Scenic route or expressway?* Munich : McKinsey & Company, 2011.
Welz, Tobias, Hischier, Roland and Hilty, Lorenz M. 2011. Environmental impacts of lighting technologies — Life cycle assessment and. *Environmental Impact Assessment Review.* 2011, Vol. 31, pp. 334–343.
White, Charles D, et al. 2003. Product recovery with some byte: an overview of management challenges and environmental consequences in reverse manufacturing for the computer industry. *Journal of Cleaner Production.* 2003, Vol. 11, pp. 445-458.
Williams, E. D., R. U. Ayres and M. Heller, 2002. The 1.7 Kilogram Microchip: Energy and Material Use in the Production of Semiconductor Devices. Environmental Science and Technology **36**(24): 5504 -5510
Williams, J.A.S. 2006. A review of electronics demanufacturing processes. *Resources Conservation & Recycling.* 2006, Vol. **47**, pp. 195-208.
Williams, E. D., N. Krishnan and S. B. Boyd, 2008. Case studies in energy use to realize ultra-high purities in semiconductor manufacturing. 2008 IEEE International Symposium on Electronics and the Environment, Proceedings of, San Francisco, CA, The Institute of Electrical and Electronics Engineers, Inc. (IEEE)
Wolf, M.I., Colledani, M. and Gershwin, S.B. 2010. Modeling and design of multi-stage seperation systems. *IEEE Int. symp. on sustainable systems and technology, Washington D.C..* 2010.
WRAP, 2011. Market flows of Electronic Products & WEEE Materials. http://www.wrap.org.uk/category/materials-and-products/electrical-and-electronic-goods?page=6