Life Cycle Assessment of Lighting Technologies

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Abstract

Lighting is a major global energy consumer, and as such, it causes notable environmental impacts. The environmental impacts of lighting products are researched by life cycle assessment, a method that takes the whole life cycle of the product into account. It is important to study the product life cycle as whole so that the major environmental hot spots are identified and the environmental impacts are not shifted from one stage to another when choosing a different type of technology on the basis of environmental impacts.

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This chapter presents the basics of the life cycle assessment for evaluating the environmental impacts of light sources in particular. The typical results of the life cycle assessment of light sources in general are presented, but the chapter concentrates only on the lamps used in households. Household lighting is changing in several countries in the world from old, inefficient technologies (incandescent lamp) to more modern light sources of a higher luminous efficacy (CFLs, LED lamps). The change is often justified by environmental reasons. The environmental assessments of household lamps show clearly that the change from incandescent lamps to lamps of higher luminous efficacy is a beneficial decision from the environmental point of view.

Introduction

As a major global electricity consumer, lighting causes notable environmental impacts particularly due to the energy consumption in use. The electricity consumption in use accounts for approximately more than 90 % of the total life cycle environmental impacts of a light source. However, the energy consumption during use is not the only environmental impact of light sources but the total life cycle needs to be taken into account. The entire life cycle and its environmental impacts are evaluated in the life cycle assessment (LCA) method. The LCA enables the identification of the causes for environmental impacts over the life cycle of a product. The LCA may compare two or more products in order to verify which product is the most environmentally friendly. It is possible to concentrate on one product or even on one stage of the life cycle and to reduce the environmental impacts by changing the product design.

The basic method of the LCA is introduced in this chapter. The phases of the assessment are described after which the main results and special characteristics of the LCA of light sources are presented with the examples of LCA case studies. The LCA as a current methodology does not take the environmental impacts of light into account, but they are excluded. However, it must be noted that there are also other causes for environmental impacts than material or energy flows.

Life Cycle Assessment

Life cycle assessment is a tool to systematically evaluate the potential impacts of a product or a service over its life cycle. It collects the inputs and outputs for a system and can be used to quantify the environmental, energy, water, or cost impacts of a system. The formal LCA methodology was established in the 1990s. Numerous LCAs have been conducted and published on various products and services during the last two decades. The LCA provides a mechanism for evaluating the performance of the products for many purposes, such as the public procurement, enactment of the legislation, and the ecologically aware consumers to make a purchase decision.

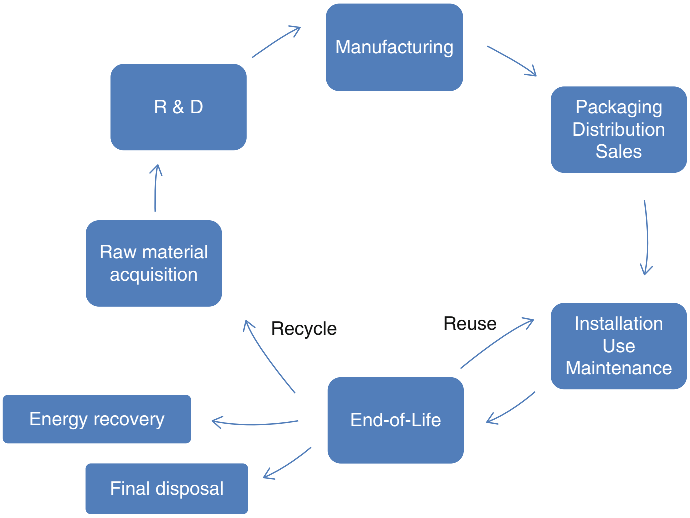

Fig. 1 Example of life cycle stages (Adapted from Tähkämö (2013))

The life cycle consists of several stages, e.g., raw material acquisition, manufacturing, distribution, use, maintenance, and end-of-life. An example of a product life cycle is presented in Fig. 1, where the life cycle starts from the raw material acquisition and ends in the end-of-life that is modeled to contain multiple alternatives including reuse, material recycle, incineration, and final disposal. It is possible to divide the processes in different ways; for example, the transport (distribution) may be tracked separately or in each process. The packaging, transport, and installation could also be combined as implementation. The LCA may be conducted concerning the whole life cycle or a part of the life cycle. The partial life cycle enables the comparison of certain stages of the life cycle in detail, while the LCA of a whole life cycle gives an overview of the total product impacts and is thus a holistic approach. The total LCA requires a large amount of data on each unit process in the system analyzed.

The stages considered in an LCA depend on the product system to be analyzed and the purpose of the assessment. No specific rules or recommendations exist for the unit processes in an LCA of light sources. However, a proxy may be used, such as the European Telecommunications Standards Institute (ETSI) 103 199 technical specification for LCA of information and communication technology (ICT) (ETSI 2011).

Methodology of LCA

There are three main types of the life cycle assessment: process LCA, economic input–output LCA (EIOLCA), and hybrid LCA. The process LCA is the conventional LCA method that evaluates the impacts as described in the following chapter. It concentrates on the examination of single processes in detail and is thus a process-specific method. It enables product comparisons and identification of the improvement potential or the environmental “hot spots.” The EIOLCA is an input–output LCA that uses economic and environmental data to produce the LCA. It takes the entire industry sector into account and sets broad boundaries and scope of the product. It is a comprehensive technique. EIOLCA data is available for the US economies but less outside the USA, which restricts its use. Hybrid LCA combines the advantages of the two LCA methods as it may use EIOLCA for part of the processes and process LCA for the rest. In this way, the economy-wide effects are taken into account but also detailed data is used where possible.

The general LCA method is established in standards ISO 14040 (ISO 2006a) and 14044 (ISO 2006b). The standards introduce the procedure for conducting the LCA and define the basic terms, such as the functional unit. Yet, the LCA standards are sufficiently broad that they can be applied to any product or service. Due to the generic nature of the ISO LCA standards, there is often a need for more detailed rules for conducting an LCA of a certain product or service. These detailed rules are product category rules (PCR). No established rules exist for the lighting product parameters, e.g., the choice of functional unit and used energy sources for the LCA of light sources. For this reason, different authors may use different methods, but the reader should use caution when comparing the results of different LCA methods.

The LCA is framed on the use of *functional unit*. The functional unit is a unit to which the assessment is quantified and proportionated. It should be related to the function of the product. It enables the comparison of the environmental impacts of products in relation to their function. The functional unit is a key parameter in LCA, especially in comparative LCAs in which two or more products are compared to each other. There are no specific rules for choosing the functional unit, but ISO 14044 standard defines it to be “consistent with the goal and scope of the study,” “clearly defined,” and “measurable.” For example, in case of electricity production, the functional unit may be the production of 1 kWh of electrical energy. When it comes to light sources, an appropriate functional unit may be lumen-hours, since it takes both luminous flux and operating hours into account. The functional unit may be one piece of a lamp if the lamps are intended for the same application and possess comparable qualities, such as luminous flux, color characteristics, and luminous intensity distribution curve. To be more precise and to take the actual illumination into account, the functional unit of a light source may also consider the illumination on a surface, e.g., the illuminance on a 1 m^2 square surface at 1 m distance. However, in this case, the LCA should compare light sources of the same application.

The structure of a LCA process is described and defined in ISO 14040. The LCA process contains four phases as shown in Fig. 2.

Goal and Scope Definition

The goal and scope define the parameters of the assessment, such as the product system to be studied, the system boundaries, the functional unit, and assumptions used in the assessment. The system boundaries establish the inputs and outputs

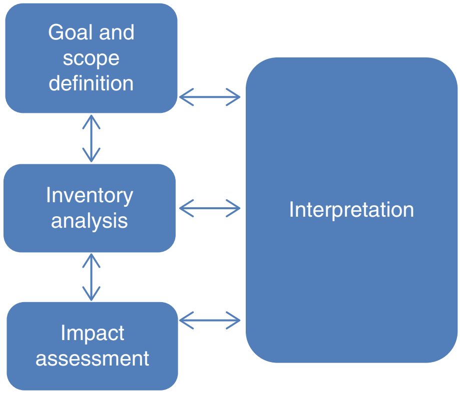

Fig. 2 Phases of life cycle assessment (Adapted from ISO (2006a))

included in the LCA. Cut-off rules are also defined. The cut-off rules are needed, since it is often impossible to retrieve data on every input or output in the LCA. The inputs and outputs of the system may be cut off on the basis of their mass, energy, or environmental significance (ISO 2006b).

Inventory Analysis

The life cycle inventory (LCI) focuses on the data collection, data calculation, and allocation. The data is collected on the inputs, including energy, raw material, and ancillary inputs. The data is calculated relating it to the system by the functional unit. Allocation partitions the inputs and outputs between the product system in question and other product systems. Allocation is needed, since industrial processes that would yield a single output rarely exist. The inventory analysis is often performed using an existing commercial or freely available database of common unit processes and material inputs.

Impact Assessment

The life cycle impact assessment (LCIA) calculates the potential impacts. The impact assessment includes the selection of impact categories, category indicators, and characterization models. The LCIA assigns the LCI results into impact categories. There are numerous impact categories to choose from, but the most common for environmental LCA is the global warming potential. Other common categories for environment analysis include acidification potential, ozone depletion potential, and human toxicity potential (see Chapter Environmental Impacts). The LCIA should also include a data quality assessment that often takes the form of uncertainty and sensitivity analyses, and optional grouping and weighting of the results.

Interpretation

The interpretation phase combines the findings of the LCI analysis and the LCIA. It concludes the main findings in accordance with the goal and scope definition. The interpretation phase identifies the findings and presents them clearly and consistently.

Total Sustainability Assessment

Life cycle assessment may be considered as the umbrella term under which the economic and social impacts are, i.e., costs and social impacts, considered as environmental impact categories. On the other hand, the assessments may be defined and divided so that the umbrella term is total sustainability assessment in which environmental, economic, and social aspects form its three pillars. Sustainability, or sustainable development, aims at meeting the needs of the present generation without compromising the ability of future generations to meet their needs. The sustainability may refer to environmental, economic, and social needs. The life cycle sustainability assessment (LCSA) is defined as

$$LCSA = LCA + LCC + SLCA \tag{1}$$

in which LCA stands for the (environmental) life cycle assessment, LCC for life cycle costing, and SLCA for social LCA (Swarr et al. 2011; Klöpffer 2003, 2008).

The life cycle cost analysis has the longest history of the three pillars, as the monetary values have been of interest for decades. However, the life cycle costing as a sustainability measure may differ from the conventional costing. The life cycle costing may be similar with the conventional costing by including, for example, the time value of the money and calculating present value. The environmental approach may be included in the costs, e.g., in the costs of environmental protection.

The total sustainability assessment is a large, challenging entity to calculate over a product. Yet, it gives a very profound overview to the sustainability of a product system. The environmental and economic assessments are rather established techniques. They can be conducted from different perspectives, e.g., from the manufacturer's, consumer's, or municipality's point of view (Swarr et al. 2011). The social life cycle assessment suffers from difficulties in establishing the methodology and lack of data, and it is currently being developed, as the general interest in it is increasing in sustainability discussions (Klöpffer 2008). The social aspects include organization-specific aspects, and they may be classified according to the stakeholders, such as the workers, the society, and the customers, or to the impact categories, such as human rights, health and safety, and the cultural heritage (UNEP 2009). No international standards exist for SLCA.

Life Cycle Assessment of Light Sources

The environmental impacts of lighting may be studied from several points of view. The environmental impacts of the total life cycle of light sources have been studied in a few LCAs, which represent the product life cycle approach. Another approach is the comparison of use-stage performance, e.g., on the basis of energy consumption or related costs. This is a streamlined, simplified LCA. The environmental impacts of the light sources may be studied from the point of view of the light itself and its environmental impacts. Light causes multiple effects on human beings, fauna, and flora. The effects depend on the time, location, and characteristics of the light. There is no method for quantifying the environmental impacts of light in an LCA. Neither the visual characteristics, such as correlated color temperature or color rendering index, are included in the previous LCAs, but they affect the application of the light source, and they should be at least discussed.

Light sources, i.e., lamps and luminaires, have been the subject in several life cycle assessments during the last two decades. A summary of the previous LCAs is presented in Table 1. The early studies have mainly compared the incandescent lamp and the compact fluorescent lamp (CFL) (e.g., Gydesen and Maimann 1991; Pfeifer 1996; Parsons 2006; BIOIS 2003), while the more recent assessments include also LED light sources (U.S. DOE 2012a, b; Osram 2009; Quirk 2009) or even a wide range of lighting technologies (DEFRA 2009; Dale et al. 2011).

A variety of functional units have been used in the LCAs of light sources. The functional unit is typically expressed in megalumen-hours, e.g., 1 Mlmh (Table 1). The lumen-hour seems to be an appropriate functional unit for light sources, as it considers both the burning hours and the luminous flux. The luminous flux of an incandescent lamp remains constant during its life. In contrast, the luminous flux of a lamp of fluorescent, high intensity discharge, or LED technology is not constant but depreciates over the operating time. None of the LCAs in Table 1 take the depreciation of the luminous flux into account in the calculations, yet some of the assessments acknowledge it (DEFRA 2009; Osram 2009; Slocum 2005). The lumen depreciation is stated to be too small to impact the results (Osram 2009). A lighting engineering approach for functional unit is presented by Yabumoto et al. by using two functional units: total luminous flux of 800 lm during 40,000 h and 100 lx floor illuminance at a distance of 1 m directly under the light source during 40,000 h (Yabumoto et al. 2010). In a methodology study of comparing nondirectional lamps (incandescent, CFL, LED lamp) (Tähkämö 2013; Tähkämö et al. 2012b), it was found that using Mlmh, hour, or illuminance as the functional unit did not significantly change the results of the comparison.

The data has been collected on the material contents of the light sources used in the LCAs (Tähkämö 2013). The materials of incandescent lamps were divided into glass (70–94 % of the total weight of the lamp) and metals (4–29 %). The weights of incandescent lamps varied between 15 and 38 g. No correlation between the weight and the wattage was found: the weight of the 60 W incandescent lamps ranged between 23 and 38 g. The weight of the CFLs was found to range between 46 and 120 g, and no correlation was found between the lamp weight and wattage. CFL consisted of glass (30–73 % of the weight of the lamp), metals (2–40 %), electronics (up to 31 %), and plastics (16–38 %). However, there are differences in the grouping of the materials in the references. For instance, electronic components may have been modeled as metals. The amount of mercury was between 3 and 5 mg per CFL. Only few references were found that provided the detailed material data for LED lamps. These references showed that LED lamps contained glass (0–13 % of the weight of the lamp), metals (45–78 %), electronics (3–21 %), and plastics (2–37 %).

Despite the differences found in the previous LCAs of light sources, the findings of the assessments were unanimous on two things: the use-stage energy consumption

Table 1 Summary of previous life cycle assessments of light sources (*IL* incandescent lamp, *HL* halogen lamp, *(C)FL* (compact) fluorescent lamp, *CFLi* CFL with integrated ballast, *CFLni* CFL with nonintegrated ballast, *CMH* ceramic metal halide lamp, *IND* induction lamp luminaire, *GWP* global warming potential, *AP* acidification potential, *EP* eutrophication potential, *POCP* photochemical ozone creation potential, *ODP* ozone depletion potential, *HTP* human toxicity potential, *ADP* abiotic (resource) depletion potential, a = future, b = hypothetical) (Adapted from Tähkämö (2013), based on Tähkämö et al. (2012a))

Light sources		Functional unit	Environmental impact categories	Reference
60 W IL	15 W CFL	10,000 h	ADP, AP, EP, GWP, ODP, POCP	Elijošiutė et al. (2012)
60 W IL 15 W CFL	12.5 W LED lamp 6.1 W LED lamp[a]	20 Mlmh	GWP; AP; POCP, ODP; HTP; freshwater aquatic, marine aquatic, and terrestrial ecotoxicities; EP; ecosystem damage; ADP; land use; hazardous, nonhazardous, and radioactive wastes	U.S. DOE (2012b)
60 W IL 35 W HL	14 W FL 11 W CFL	1 h of lighting	Cumulative energy demand, GWP, EcoIndicator’99	Welz et al. (2011)
150 W HPS 163 W MH	109 W IND 105 W LED	100,000 h of light	GWP, respiratory effects, ecotoxicity	Dale et al. (2011)
100 W IL 23 W CFL 2 × 28 W FL	20 W CMH 10 W LED lamp 16 W LED luminaire	1 Mlmh	GWP; AP; POCP, ODP; HTP; freshwater aquatic, marine aquatic, and terrestrial ecotoxicities; EP; ecosystem damage; ADP; land use; hazardous, nonhazardous, and radioactive wastes	DEFRA (2009)
40 W IL 8 W CFL	8 W LED	345–420 lm during 25,000 h	GWP, AP, POCP, HTP, EP, ADP, energy consumption	Osram (2009)
60 W IL 13 W CFL	6 W LED 6 W LED[a]	1 Mlmh	Primary energy consumption, GWP	Quirk (2009)
60 W IL	15 W CFL	1 kWh	Energy consumption	Landis et al. (2009)
60 W IL 13 W CFLi		500–900 lm during 10,000 h	Minerals, fossil energy sources, land use, GWP, EP, AP, ODP, POCP, ecotoxicity, respiratory effects, ionizing radiation, carcinogens	Michaud and Belley (2008)
100 W IL	23 W CFL	16 Mlmh	GWP, emissions of mercury, arsenic, and lead	Ramroth (2008)
100 W IL 18 W CFL		Equivalent luminous flux during 8,000 h	ADP; GWP; ODP; HTP; AP; EP; POCP; freshwater aquatic, marine aquatic, and terrestrial ecotoxicities; carcinogens; respiratory effects; minerals; fossil fuels	Parsons (2006)

(*continued*)

Table 1 (continued)

Light sources		Functional unit	Environmental impact categories	Reference
60 W IL 15 W CFL	7.5 W LED[b]	1 Mlmh	Energy consumption	Slocum (2005)
60 W IL 15 W CFLi	13 W CFLi 11 W CFLni	10 Mlmh	GWP, AP, primary energy, ADP, ODP, POCP, EP, HTP, ecotoxicity, costs of environmental impacts, metals, carcinogens	BIOIS (2003)
60 W IL 11 W CFLi	13 W CFLi 11 W CFLni	1 Mlmh	Primary energy consumption, Hg emissions, radioactive materials	Pfeifer (1996)
60 W IL	15 W CFL	1 Mlmh	GWP, SO_2, NO_x, CH_4, ashes, Hg, solid waste	Gydesen and Maimann (1991)

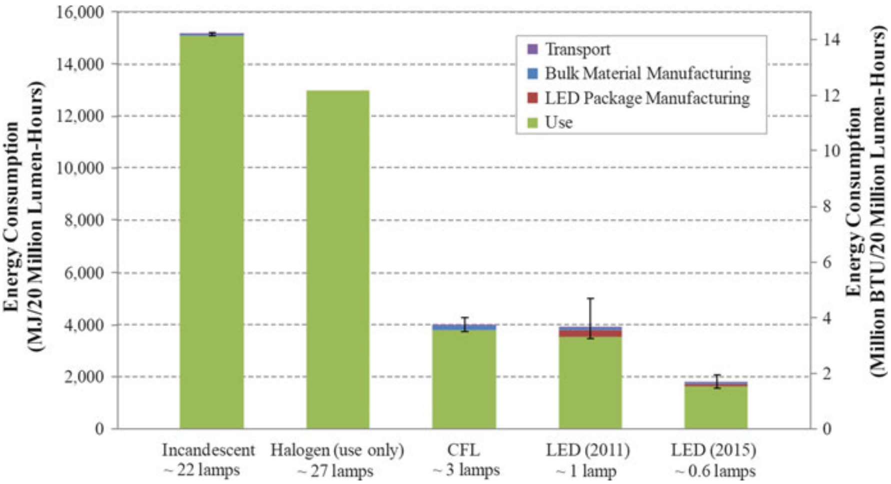

Fig. 3 Life cycle energy of incandescent lamps, CFLs, and LED lamps (DOE 2012a). The error bars indicate the variation between the 10 LCA reports summarized in the study

is the most important environmental aspect, and thus, the energy-efficient light sources, such as the CFLs and LED lamps and luminaires, are more environmentally friendly than their conventional counterparts from the life cycle point of view. This is also shown in Fig. 3, a summary of ten LCA results on the basis of energy compared by the US Department of Energy (U.S. DOE 2012a). The lamps are here compared on the basis of their primary energy consumption in manufacturing and use. Figure 3 illustrates that the primary energy consumption of incandescent and halogen lamps are clearly greater than the ones of CFL or LED lamps.

Generally, the LCAs of light sources include the raw material acquisition and manufacturing (often combined), use, and end-of-life. The relative impact of the use is expected to be reduced when the luminous efficacy of the light source increases. This increases the significance of other life cycle stages, notably the manufacturing and raw material acquisition, in terms of environmental impacts. In addition, the relative significance of the use-stage electricity consumption will be reduced when the electricity production is shifted towards low-emission electricity production, such as renewable energy sources or nuclear power.

Environmental Impacts

There are numerous environmental impacts to consider in an LCA. The LCIA methodologies introduce several impact categories from which to choose. The chosen environmental impact categories depend on the scope and purpose of the LCA. In general, it is recommended that authors include several impact categories in the LCA so that environmental impacts are taken into account in a wide range. In addition, it is possible to calculate the environmental impacts as single-scale indices, such as Ecoindicator'99, that weigh and factor several impact categories into one number.

The following subchapters describe briefly the most common environmental impact categories used in LCAs.

Acidification

Acidification is caused by the emissions of sulfur dioxide and nitrogen oxides. These oxides form acids in the atmosphere with water vapor and fall down as acid rain, acid snow, or dry acid depositions. It acidifies water and soil, corrodes buildings, and affects vegetation. It is measured in kilograms of SO_2 equivalents.

Eutrophication

Eutrophication is caused by nitrogen and phosphorus that originate from landfills, sewage, and fertilizers. Eutrophication causes excessive plant growth and oxygen depletion in water. It is measured in kilograms of PO_4 equivalents.

Global Warming

Global warming refers to the enhanced greenhouse effect. The atmosphere retains the heat due to the greenhouse gas emissions, such as carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride. Global warming causes global impacts, such as melting of the polar ice, change in ocean and wind patterns, droughts, and floods. It is measured in kilograms of CO_2 equivalents.

Land Use

Land use refers to the occupation of the land and the change in land use. It relates to the loss of wildlife habitat and decrease in the land space. Land use affects the biodiversity. It is measured in square meter years (m^2a).

Ozone Depletion

Ozone depletion refers to the thinning of the stratospheric ozone layer. It is caused by chlorinated and brominated substances, such as chlorofluorocarbons (CFCs) and halons. Ozone depletion increases the ultraviolet radiation on the surface of the earth. It is measured in kilograms of CFC-11 equivalents.

Photochemical Ozone Creation

Photochemical ozone creation (photochemical smog, summer smog) originates from the reaction of volatile organic compounds (VOCs) and nitrogen oxides with heat and sunlight in troposphere. It is formed generally in urban areas during summer. It decreases visibility, causes respiratory effects, and damages vegetation. It is measured in kilograms of ethylene equivalents or of formed ozone.

Resource Depletion

The depletion of natural resources describes the consumption of natural resources, such as fossil fuels and minerals. It may be divided into renewable and nonrenewable resources or to biotic and abiotic resources. Abiotic resource depletion is measured in kilograms of antimony equivalents.

Toxicities (Human Toxicity, Aquatic Ecotoxicity, Terrestrial Ecotoxicity)

Toxicities are caused by many substances, such as dioxins, heavy metals, and hydrochloric acid. The challenge in the toxicity categories is to know which quantity is harmful and in which time frame (long-/short-term impacts). The variety of toxicity categories enables the consideration of a specific toxicity target, e.g., marine or freshwater, aquatic or sediment, terrestrial or human. All the toxicity categories are measured in kilograms of 1,4-dichlorobenzene equivalents.

Waste

There are several waste categories, such as solid, radioactive, hazardous, and nonhazardous. They are usually measured in kilograms of waste.

Water Use

Water use reduces the availability of groundwater and surface water resources. It is measured in liters of water.

In addition to the environmental impact categories, it may be useful to calculate the LCIA results in primary energy consumption. Primary energy is the energy embodied in natural resources (raw materials, energy) that has not gone through any transformation. It is generally measured in joules (J). There are also other environmental impacts, such as noise and odor in air and water. In case of light sources, additional environmental impacts include the light pollution and the impacts of light on living organisms. However, they are difficult to calculate in a relative manner in an LCIA.

A recently completed LCA (U.S. DOE 2012b) compared the relative environmental impact of LED lighting products when compared to CFL and incandescent as shown in Fig. 4. Many of the environmental impact categories described above are

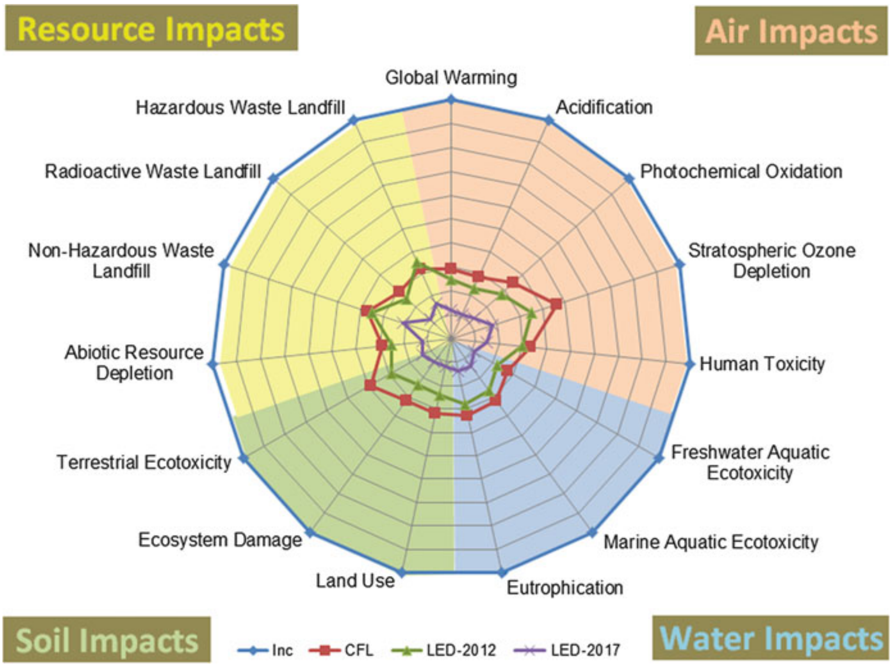

Fig. 4 Life cycle assessment impacts of the lamps analyzed relative to incandescent lamp (U.S. DOE 2012b). The data in the graph are normalized for the quantity of lighting service (20 Mlmh)

shown relative to the incandescent lamp on a relative scale. While it has substantially lower impacts than incandescent lamp, the CFL is slightly more harmful than the 2012 integrally ballasted LED lamp against all but one criterion – hazardous waste landfill – where the manufacturing of the large aluminum heat sink used in the LED lamp causes the impacts to be slightly greater for the LED lamp than for the CFL. The best performing light source is the projected LED lamp in 2017, which takes into account several prospective improvements in LED manufacturing, performance, and driver electronics (U.S. DOE 2012b).

Life Cycle Assessment of LED Lighting Products

The environmental impacts of LED lighting products have recently been studied in an LCA by the US Department of Energy (2012b). They compared three household lamp technologies: incandescent, CFL, and LED lamp. However, the especially valuable part of the study for the LCA community is the detailed description of the LED product manufacturing and its material and energy flows, since until this publication, there was no up-to-date data on LED manufacturing freely available. Figure 5 illustrates an example of the system boundaries of an LED lamp. The LED

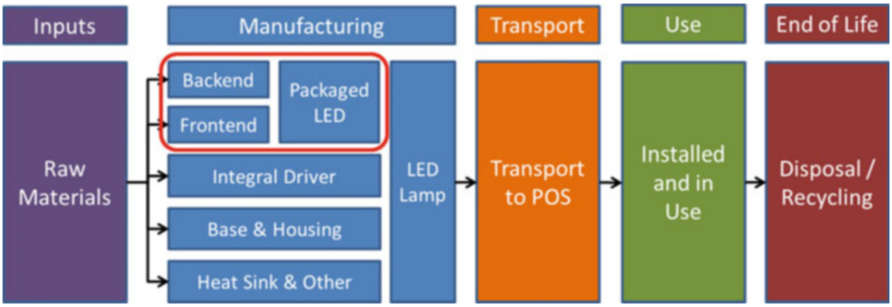

Fig. 5 Example of a system boundary of the life cycle assessment of LED lighting products (U.S. DOE 2012b)

lamp LCA and notably the manufacturing process are described in the following subchapters. The study had also two additional parts: the energy assessment of light source LCAs (U.S. DOE 2012a) and the report on the environmental testing of incandescent, CFL, and LED lamps (U.S. DOE 2013).

Manufacturing

The manufacturing of an LED package for lighting applications is the least defined part of an LCA of LED lighting products. The proprietary nature of most manufacturers' products has limited the typical methods for inventory analysis. The manufacturing process of LED lighting products was recently quantified in detail (U.S. DOE 2012b). In this work, the manufacturing was broken into three parts: (1) substrate production, (2) LED die fabrication, and (3) packaged LED assembly (Fig. 6).

Substrate Production

The substrate production focuses on preparing polished, cleaned sapphire wafers to use in a metal organic chemical vapor deposition (MOCVD) reactor for LED die fabrication (U.S. DOE 2012b).

The processing steps for sapphire wafers are described in more detail in the report (U.S. DOE 2012b). The energy and material summary for this unit process is shown in Table 2. This table provides both the quantity consumed per wafer both in terms of volume and in terms of mass.

LED Die Fabrication

The LED die fabrication process is divided into epitaxial growth and other front-end processes. In the epitaxial growth, the substrate is mounted in an MOCVD reactor, and it is heated, followed by the deposition of the nucleation layer, the n-type layer, the active layers (multi-quantum well), and finally the p-type layer. The result of this process is the LED epitaxial wafer (U.S. DOE 2012b).

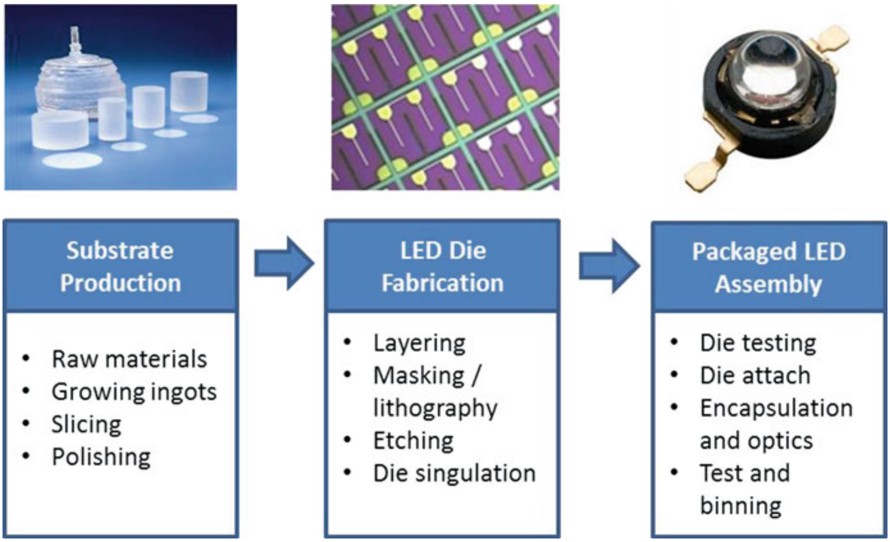

Fig. 6 Three main stages of packaged LED manufacturing and the major steps within (U.S. DOE 2012b)

Table 2 Energy and material consumption for three-inch sapphire wafer manufacturing (Adapted from U.S. DOE (2012b))

Stage	Material used	Amount	
		Volume per wafer	Mass per wafer
Material	Alumina (Al_2O_3)	16.6 g/wafer	16.6 g/wafer
Material	Cleaning chemical (alkali detergent)	3.5 l/wafer	3.5 kg/wafer
Production	Energy consumption	18.3 kWh/wafer	18.3 kWh/wafer
Material	Diamond slurry	830.0 g/wafer	0.83 kg/wafer
Material	Water	105.3 l/wafer	105.3 kg/wafer

From the LED epitaxial wafer, several steps are needed to make the device and to prepare it for packaging. The wafer is inspected, subjected to masking and lithography, and etched, and then the contacts are attached (metallization) on the LED. These steps create the LED mesa-structure, and it results in visible LED dies on the wafer. Once these are developed, the substrate is separated from the LED dies. The dies are cut (die singulation) and tested and binned according to their performance. After these steps, the LED dies are ready to be packaged (U.S. DOE 2012b).

Table 3 summarizes the amounts of materials and energy consumed in the LED die fabrication. The table combines the material and energy consumption of both the epitaxy and p-n junction deposition stage and post-epitaxy steps associated with contacts, patterning, substrate removal, and preparing the finished LED die.

Table 3 Energy and material consumption for LED die fabrication (U.S. DOE 2012b)

Material	Quantity consumed	
	Volume/wafer	Mass/wafer
Acetone	0.59 l/wafer	467 g/wafer
AuSn solder	14.8 mm^3/wafer	0.29 g/wafer
Developer	115 ml/wafer	115 g/wafer
Etchant Ag	30 ml/wafer	30 g/wafer
Etchant metal	60 ml/wafer	60 g/wafer
GaN etchant	0.192 l/wafer	192 g/wafer
H_2	1.62 m^3/wafer	136 g/wafer
N_2	4.42 m^3/wafer	5,527 g/wafer
NH_3	0.447 kg/wafer	447 g/wafer
O_2	2 l/wafer	2.3 kg/wafer
Photoresist	19 ml/wafer	19 g/wafer
Energy	42.57 kWh/wafer	42.57 kWh/wafer
SF_6	0.1 l/wafer	13 g/wafer
SiH_4	0.242 g/wafer	0.242 g/wafer
Slurry	2.3 l/wafer	2.3 kg/wafer
Target Ag	0.44 mm^3/wafer	0.005 g/wafer
Target Al	1.27 mm^3/wafer	0.003 g/wafer
Target Ni	0.417 mm^3/wafer	0.004 g/wafer
Target Ti	0.467 mm^3/wafer	0.002 g/wafer
Target W	3.089 mm^3/wafer	0.06 g/wafer
TMAl	0.003 g/wafer	0.003 g/wafer
TMGa	1.47 g/wafer	1.47 g/wafer
TMIn	0.01 g/wafer	0.01 g/wafer
UPW	240 l/wafer	240 kg/wafer

Packaged LED Assembly

The third phase of LED manufacturing is referred to as the packaging of the device. A LED package is shown in Fig. 7. The packaging process includes the mounting of the LED die in housing, making electrical connections, and applying phosphor, encapsulant, and optics. In addition, the LED is tested and binned into the correctly classified product (U.S. DOE 2012b).

The substrate is cut into the individual packaged LEDs for use. Table 4 presents the aggregate consumption per LED produced including all the inputs for LED packaging and assembly.

Lamp Assembly

After the packaged LED, a self-ballasted LED lamp is created from several packaged LEDs. This self-ballasted LED lamp may be inserted into a mains voltage socket without auxiliaries.

An example of the LED lamp assembly was provided in US DOE (2012b) for the Philips EnduraLED lamp introduced in 2011. This particular LED lamp was commonly available in the US market in 2012. Table 5 presents the materials used in manufacturing of the LED lamp, the energy involved in the assembly and

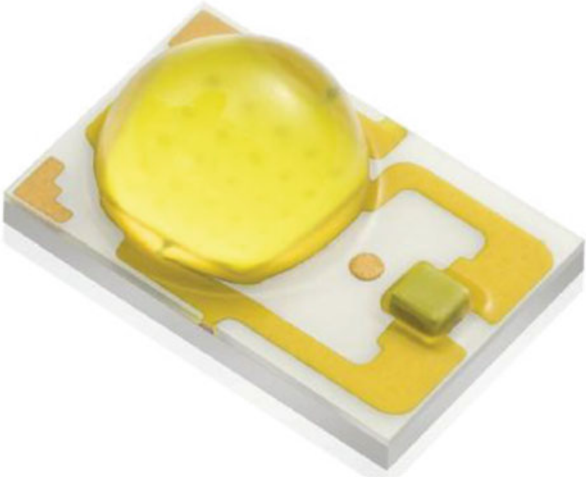

Fig. 7 Example of the finished packaged LED, the Philips Luxeon Rebel (U.S. DOE 2012b)

Table 4 Energy and material consumption for LED packaging assembly (Adapted from U.S. DOE (2012b))

Stage	Material used	Amount	
		Volume per LED	Mass per LED
Material	Ceramic substrate (2-layer alumina)	13.5 mm^2/LED	0.0135 g/LED
Production	Energy (kWh)	0.03 kWh/LED	0.03 kWh/LED
Material	ESD diode (Silicon)	0.22 mm^2/LED	0.055 g/LED
Material	Gold	0.004 mm^3/LED	0.00006 g/LED
Material	Underfill	0.05 mm^3/LED	0.0196 g/LED
Material	Silicone	8.4 mm^3/LED	0.00006 g/LED

manufacturing, the estimated transportation of the lamp, the use-stage energy consumption during the lifetime of the lamp (12.5 W, 25,000 h), and the recycling rates of the lamp and packaging materials. The finished LED lamp weighs 178 g and the card-stock packaging 37 g.

There is a lack of information on the extent to which materials used in the manufacturing of LEDs are reused and recycled. If these materials are recovered, processed, and then reused, this would reduce the per unit production environmental impacts. To make the LCA conservative, relatively low rates of recycling or reuse of material is often assumed. To the extent that materials are recovered and recycled, the environmental impacts will be less than those reported in an LCA that uses conservative estimates for recycling.

Use

The use of the light sources – LED or other technologies – causes environmental impacts that depend strongly on the energy source. In case of a renewable,

Table 5 Life cycle inventory for an example 12.5 W LED lamp in 2012 (Adapted from U.S. DOE 2012b)

Stage	Material used	Amount	Stage	Material used	Amount
Material	LEDs (blue light)	12 units	Material	Resistor SMD	35 pcs
Material	Remote phosphor	1.0 g	Material	Resistor	3 pcs
Material	Plastic phosphor host	11.1 g	Material	Transistor	6 pcs
Material	Aluminum heat sink	68.2 g	Material	Resin glue	4.5 g
Material	Copper	5.0 g	Material	Solder paste	0.3 g
Material	Nickel	0.003 g	Production	Power	5.0 MJ
Material	Brass	1.65 g	Production	Manufacturing	178 g
Material	Cast iron	4.0 g	Material	Packaging	37 g
Material	Chromium	0.0002 g	Transport	Sea – 215g	10,000 km
Material	Inductor	5 pcs	Transport	Road – 215g	1,000 km
Material	IC chip	2.0 g	Use	Energy in use	312.5 kWh
Material	Capacitor SMD	8 pcs	End of life	Lamp, recycling	20 %
Material	Electrolytic capacitor	6 pcs	End of life	Lamp, landfill	80 %
Material	Diode	6 pcs	End of life	Package, recycling	30 %
Material	Printed wiring board	15.0 g	End of life	Package, landfill	70 %

low-emission energy sources, the environmental impacts are significantly lower compared to nonrenewable, high-emissions energy sources, such as coal. For example, in CFLs, the primary source of mercury on an LCA basis in the USA is driven by the upstream production of electricity from coal power plants that emit mercury rather than in the lamp.

It is important to note different electricity productions used in the LCA. The energy consumption in manufacturing is often modeled using an average electricity production for China (if product manufactured in China),while use is modeled as another electricity production, e.g., the one in the USA or Europe. It is important that the energy in use stage reflects the mix where the lamp is being actually used because the magnitude of the impact associated with the electricity consumed in use has been found to be very important.

End-of-Life

The end-of-life (EoL) includes several alternatives for the reuse or disposal of the product. The product or part of the product may be reused after repair or maintenance to prolong its lifetime. In many cases, the materials of the product could be recycled into "new" raw materials. The energy embodied in the certain materials, e.g., most plastics, may be utilized by incineration.

The EoL is a complex stage of the life cycle to model in an LCA. It may contain several possibilities (scenarios and recycling techniques), and the inclusion of by-products or recycled raw materials makes the calculation challenging. The EoL stage shall include also the collection of the products from the users and the separation of the material fractions.

Reuse

After reaching the end of useful lifetime (usually 70 % of initial luminous flux), the LED luminaire is "scheduled" to be replaced in an optimal replacement scenario. At this point, the LED luminaire is still working, but the luminous flux has deteriorated so that it needs to be replaced. For this kind of situation, it is not likely for the LED luminaire to be repaired so that it would be used for a longer period of time because usually LED luminaires are not modular, and thus, there is no part to replace. Yet, the modularity may become more common thanks to global standardization collaboration regarding the LED products. In case of an LED lamp, the situation is similar: At the end of the useful lifetime, the whole product, i.e., the lamp, needs to be replaced.

Recycling

The material fractions of the LED product (lamp or luminaire) need to be separated, e.g., by dismantling and shredding. Screw fastening enables efficient separation of parts. The aluminum heat sink is a part of the LED product that is especially important to recycle due to the energy-intensiveness of the production of virgin aluminum. It has been found out that the CFL products outperform LED products in an environmental impact category primarily because of the aluminum heat sink (U.S. DOE 2012b).

The electronic components in the LED products should be recycled as waste electrical and electronic equipment (WEEE). There are no specific recycling processes for LED products, since the amount of LED products to be recycled is currently low. LED products are collected together with other light sources (fluorescent lamps, other discharge lamps) or as WEEE.

Landfill

Landfill is the worst option of the product to end up in from the raw material point of view, but it is useful to evaluate it in an LCA to determine a worst-case scenario for a product. There is often significant embodied energy in raw materials that would not be utilized in a landfill. Some countries and regions have adopted mandatory requirements that would prevent any WEEE from entering a landfill due to high concentrations of copper, aluminum, and other metals.

Challenges in LCAs of Lighting Technologies

Several challenges have been identified in the LCAs of light sources. First, the energy source affects the significance of the use-stage environmental impacts. It causes uncertainty in the results affecting the stage of the life cycle that has typically the greatest impacts – use. Using a specific energy source may distort the LCA results, while the use of average energy production of an area (country, state, continent) brings the average results. Second, there is a need for more detailed

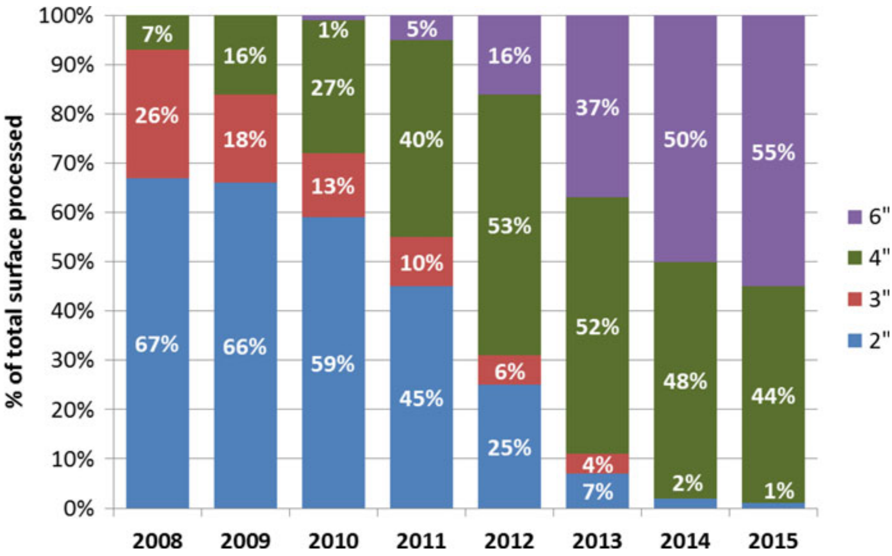

Fig. 8 Trends in diameter of sapphire substrates for LED manufacturing (U.S. DOE 2012b)

data in the environmental databases for manufacturing of light sources, especially the LED component. Up-to-date data is essential for reliable LCA results, and the industry is developing LED manufacturing methods at a rapid pace (e.g., sapphire substrate diameters in Fig. 8). Third, there is a wide variety of LED products on the lighting market: luminaires, lamps, modules, arrays, and components. This makes the comparison of products difficult. Yet, the comparison of different products is possible if the functional unit is carefully chosen. Finally, there are environmental impacts of light sources that cannot be taken into consideration in current LCA methodology: the environmental impacts of light itself.

There are uncertainties in the LCA of electronic products due to the complexity of the components. The electronic products are developed fast, and there is practically immeasurable number of different electronic components on the market. In addition, there is not always detailed, accurate data available on the exact component in a certain geographical location. Thus, it is not possible to analyze every component in detail, but proxies are necessary. For example, assuming a smaller wafer diameter will make the LCA conservative, while assuming larger diameter will make the LCA more accurate but may underestimate energy or environmental impacts. Some LCA authors have chosen to bind a study by including more modern estimates as a separate case. As detailed the life cycle inventory of a self-ballasted LED lamp presented in this chapter is, it is likely to need updating and possibly elaborating to cover other LED manufacturing technologies in the future.

There are only two unit process estimates currently available for manufacturing of an LED. Prior to 2012, all LCA studies had been based on manufacturing estimates for an indicator LED based on LED manufacturing technology from 2007.

The indicator LED was found to have a luminous flux of 4 lm, while the high-brightness LED was found to have a luminous flux of 100 lm (Radio-Electronics 2012; Philips 2012). A study showed that the environmental impacts were reduced by 94.5 % on average in a per-lumen comparison of the 2007 indicator LED and the 2012 LED (U.S. DOE 2012b). It was concluded that the high-brightness LEDs manufactured in 2012 are significantly less harmful for the environment than the 5 mm indicator LEDs produced in 2007.

Discussion and Conclusions

The LCAs of light sources typically conclude that the use (energy consumption) of the light source causes the greatest environmental impacts. This is, however, sensitive to the used energy source, and the environmental impacts differ if low-emission or high-emission energy source is used. Other stages of the life cycle tend to cause only small environmental impacts in the scope of total life cycle. Yet, more detailed modeling is recommended especially regarding manufacturing and end-of-life of the product. In addition, the shift towards renewable energy sources that is happening globally will change the dynamics of the LCA of light sources and generally all energy-using products. Thus, it is likely that manufacturing and end-of-life become more important in the LCA in the future.

Lighting design requires numerous factors to be taken into account. They depend on the lighting application, since the requirements differ in different applications, such as indoor, outdoor, road, area, general and local lighting. On the basis of the LCAs of light sources, it can be concluded that the main parameter in the design of environmentally friendly lighting is the luminous efficacy of the light source. The higher the luminous efficacy is, the lower the life cycle environmental impacts the light source has on the average. In design of a light source, other environmental parameters may be considered to reduce the environmental impact, such as reducing the weight of the light source, designing for easy dismantling (for recycling), avoiding the use of hazardous materials, and ensuring the long operating life by design of the electronic components and the heat transfer.

As light sources and other lighting-related products have been the subject of several LCAs, new topics may be introduced in the research of environmental performance of lighting. A method for including the environmental impacts of light may be created, similarly with the noise or odor impact calculation methods. The uncertainties could be analyzed and ways to reduce them may be developed. More accurate data for the life cycle inventory of light sources should be made available. The LCA of new products may be conducted, including especially the evaluation of OLED products. The discussion of the functional unit remains valid: it may be directed towards an application-specific functional unit or towards a functional unit that could be used for *all* light sources.

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