

Solid State Lighting Annex: Life Cycle Assessment of Solid State Lighting

FINAL REPORT

Energy Efficient End-Use Equipment (4E)
International Energy Agency

SSL Annex Task 1

4E 17 SEPTEMBER 2014

Solid State Lighting Annex – Life Cycle Assessment of Solid State Lighting Final Report

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The authors are grateful for the reviews by and support from all Annex experts and Management Committee members. Particular thanks to Mike Scholand, Operating Agent Support who provided editing of text and figures. Thanks also to Peter Bennich, Management Committee chairman and Nils Borg, Operating Agent of the IEA 4E SSL Annex.

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About the IEA 4E Solid State Lighting Annex

The SSL Annex was established in 2010 under the framework of the International Energy Agency's Energy Efficient End-use Equipment (4E) Implementing Agreement to provide advice to its member countries seeking to implement quality assurance programs for SSL lighting. This international collaboration brings together the governments of Australia, Denmark, France, Japan, The Netherlands, Republic of Korea, Sweden, United Kingdom and United States of America. China works as an expert member of the 4E SSL Annex. The SSL Annex closed its first term in June 2014 and started on its second five-year term in July 2014. This report is part of the final reporting from the Annex's first term. Further information on the 4E SSL Annex is available from: <http://ssl.iea-4e.org/>

About the IEA Implementing Agreement on Energy Efficient End-Use Equipment (4E)

4E is an International Energy Agency (IEA) Implementing Agreement established in 2008 to support governments to formulate effective policies that increase production and trade in efficient electrical end-use equipment. Globally, electrical equipment is one of the largest and most rapidly expanding areas of energy consumption which poses considerable challenges in terms of economic development, environmental protection and energy security. As the international trade in appliances grows, many of the reputable multilateral organisations have highlighted the role of international cooperation and the exchange of information on energy efficiency as crucial in providing cost-effective solutions to climate change. Twelve countries have joined together to form 4E as a forum to cooperate on a mixture of technical and policy issues focused on increasing the efficiency of electrical equipment. But 4E is more than a forum for sharing information – it initiates projects designed to meet the policy needs of participants. Participants find that pooling of resources is not only an efficient use of available funds, but results in outcomes which are far more comprehensive and authoritative. The main collaborative research and development activities under 4E include:

- Electric Motor Systems (EMSA)
- Mapping and Benchmarking
- Solid State Lighting (SSL)
- Electronic Devices and Networks

Current members of 4E are: Australia, Austria, Canada, Denmark, France, Japan, Korea, Netherlands, Switzerland, Sweden, UK and USA. Further information on the 4E Implementing Agreement is available from: www.iea-4e.org

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Acronyms and Abbreviations

4E	Energy Efficient End-use Equipment
AP	acidification potential
CFL	compact fluorescent lamp
CFLi	compact fluorescent lamp with integrated ballast
CFLni	compact fluorescent lamp with non-integrated ballast
CMH	ceramic metal halide
EP	eutrophication potential
GWP	global warming potential
HPM	high-pressure mercury
HPS	high-pressure sodium
IEA	International Energy Agency
JRC	Joint Research Centre (European)
LCA	life cycle assessment, life cycle analysis
LCI	life cycle inventory
LCIA	life cycle impact assessment
LCC	life cycle cost
MH	metal halide
ODP	ozone depletion potential
PCR	product category rule
POCP	photochemical ozone depletion potential
RoHS	restriction of certain hazardous substances
SSL	solid-state lighting
WEEE	waste electrical and electronic equipment

List of the environmental impact categories chosen for the Life Cycle Assessment

Environmental impact category	Abbreviation	Method	Unit (eq.)
Primary energy	PE	NF P01-010	MJ
Renewable energy	RE	NF P01-010	MJ
Non-renewable energy	NRE	NF P01-010	MJ
Abiotic depletion potential	ADP	NF P01-010	kg Sb eq.
Water consumption	WaC	NF P01-010	L
Hazardous waste	HW	NF P01-010	kg
Non-hazardous waste	NHW	NF P01-010	kg
Inert waste	IW	NF P01-010	kg
Radioactive waste	RW	NF P01-010	kg
Global warming potential	GWP	NF P01-010	kg CO ₂ eq.
Acidification potential	AP	NF P01-010	kg SO ₂ eq.
Air pollution	AiP	NF P01-010	m ³
Water pollution	WaP	NF P01-010	m ³
Ozone depletion potential	ODP	NF P01-010	kg CFC-11 eq.*
Photochemical ozone creation potential	POCP	NF P01-010	kg C ₂ H ₄ eq.
Eutrophication potential	EP	NF P01-010	kg PO ₄ eq.

* CFC- 11 refers to trichloro-fluoromethane.

Executive Summary

The goal of the IEA 4E SSL Annex is to provide the governments with information and tools to implement policies on solid-state lighting (SSL). The transition from traditional lighting based on incandescent, fluorescent and other discharge lamps to SSL is based on the promising properties of light-emitting diodes (LEDs) used as white light sources. LED technology offers opportunities for a new kind of lighting design and a potential for cost-efficient reduction of greenhouse gases together with energy savings. And, the quality of LED products is rapidly evolving, with products in the market today ranging from poor performing to well accepted, energy-efficient products.

For this reason, the SSL Annex is carefully addressing quality and performance aspects of SSL (mainly LEDs). In addition, the SSL Annex is also examining the effect of SSL on the environment and its potential risks for human health. This report addresses the environmental aspects of SSL, while health aspects are dealt with in a separate report.

This report presents an overview of published life-cycle assessments (LCA) of lighting equipment, answering the following questions on the basis of current research:

- What are the environmental impacts of LED products over their whole life cycle?
- What are the strongest contributors to the environmental impacts of LED products?
- How do SSL products compare with conventional lighting technologies?
- What are the main difficulties to perform a LCA of an LED lamp or luminaire?

The LCA methodology is used to assess the environmental impacts of LED products, including a comparison with different lighting technologies. In addition, the challenges and uncertainties associated with the published LED LCA studies are discussed, as the actual environmental impact of LED products can be difficult to assess.

Dominance of the use stage and most influential parameters

When the environmental performances of an LED product life cycle were assessed, the use stage was found to dominate the environmental impacts over the manufacturing and the end-of-life stages. On average, 85% of the environmental impact is linked to the use phase, while the remaining 15% is shared mainly between manufacturing and end-of-life treatment. The environmental impact of the transport phase only accounts for 1% to 2%. Thus, the two most significant parameters contributing to the environmental impacts are luminous efficacy (lm/W) and useful life (hours of operation during lifetime). Studies have found that the replacement of low efficacy lighting (e.g., the incandescent lamp, high-pressure mercury lamp) with high-efficiency, long-life LED-based lamps and luminaires brings a strong environmental benefit. However, lifetime of SSL products should be accurately and realistically specified, taking into account renovation rates and the potential for premature failure.

Importance of the electricity production

The magnitude of the environmental impacts during the use stage is strongly influenced by the mix of generating technologies used to produce the electricity in a given region. Next to the replacement of low efficacy lamps with more efficacious sources, the use of renewable electricity sources such as hydro-power has the largest positive environmental impact.

Comparison of LED with conventional technologies

In the domain of domestic lighting, energy inefficient lamps, such as halogen lamps, have much greater environmental impacts compared to an LED lamp. High quality compact fluorescent lamps (CFL) with lifespan of more than 12,000 hours and efficacy up to 65 lm/W has an impact comparable to good quality LED products (assuming the average lifespan of an integral LED lamp is 20,000 hours). As LED technology is improving, LEDs will have less environmental impact in the next few years.

In the domain of professional lighting, the T5 linear fluorescent lamp luminaire was the best-rated product in 2009. In studies published in 2013, the T5 lamp remains the product with the lowest environmental impacts, but thanks to the advances of LED technology, LED tubes are nearly at the same level of performance.

In the domain of outdoor lighting, a study found that the environmental impacts of LED street lighting luminaires are comparable with those of existing efficient, long-life technologies such as induction lamps with 100,000 hours average life. Common lighting technologies like high pressure sodium lamps and metal halide lamps have high efficacies (150 lm/W for sodium and 120 lm/W for metal halide) but relatively short lifespans (usually 12,000 to 24,000 hours). Compared to induction and LED technology in street lighting applications over a 100,000 hour period, Dale et al., 2011 found impacts were about 30% lower in global warming potential, respiratory effects and ecotoxicity compared to high pressure sodium and metal halide luminaires.

Highest contributors to the environmental impacts of LED product manufacturing

The components currently causing the largest environmental impact during the production of LED lighting products are the aluminium parts (e.g., heat sink), electronics (the driver) and LED packaging. The aluminium parts tend to have the greatest mass of all the components, however, the recent development and use of ceramic heat sinks in LED products will help to reduce the environmental impact. The production of an LED electronic driver also has a significant impact, as it often includes many discrete components as well as integrated circuits, and many processes involved in the manufacturing of a printed circuit board.

Data gaps concerning LED product manufacturing

The most difficult aspect of data collection to assess the environmental impacts of LED lighting product manufacturing is information concerning the production of the LED itself. Both the die manufacturing and the LED packaging are extremely confidential and complex processes. Even if they were fully characterised, LED manufacturers use parts and materials supplied by other companies, for which the processes involved in manufacturing are unknown (i.e., supplier intellectual property). Therefore, the extraction of “sensitive” raw materials such as indium and rare materials (yttrium, cerium, etc. used in phosphors) is extremely difficult to take into account.

End-of-life of LED products

Although they contain recyclable components and materials, LED products are often not recycled. The end-of-life for LED products is thus comparable to other electronic waste. These wastes contain rare materials as gallium and indium that are considered strategic metals, however standard waste recycling processes can't recover these materials today. With or without recycling, the impacts of the end-of-life of LED products appear to be very low compared to the use stage. Several national initiatives are being undertaken to investigate recycling LED products to extract valuable materials.

Improvements and further work

The LCA prevalence of the use stage is also applicable for other energy-efficient lighting technologies (e.g., T5 linear fluorescent and compact fluorescent lamps). However, LED efficacy is now moving ahead of other energy-efficient technologies. The lifetime is also longer than these other efficacious lighting technologies, but that might be of less importance, as replacement might be beneficial because LED efficacy is increasing.

According data from literature analysed by the IEA 4E SSL Annex, the energy used for the manufacturing of an LED product is almost 1.5 times higher than that used for the manufacturing of traditional light sources. But data on this aspect is limited because the fierce market competition combined with an accelerating development of LED design and production methods make manufacturing data sensitive and confidential.

Detailed analysis of LED product manufacturing is currently only available in the public domain in a recent series of US Department of Energy LCA publications¹. The first part of the report series contains a literature review, analysis and summary of LCA findings for LED lamps. The second part includes a LCA comparison of a LED lamp, an incandescent lamp and a CFL. To perform this analysis, experts collected data from LED manufacturers and their consultants on manufacturing processes and materials. Although this report provides detailed analysis of LED fabrication and lamp manufacturing, there are processes that are not described or addressed. The third part of that study was undertaken to augment the LCA findings with chemical analysis

¹To view the three US DOE LCA reports, visit: http://www1.eere.energy.gov/buildings/ssl/tech_reports.html

of a variety of LED, CFLs, and incandescent lamps using standard hazardous material testing procedures in order to complete the missing data.

This report uses data collected by the US DOE and published in other recent LCA studies. The rate of technological improvement in LED reflected by the comparison of older and more recent LCA publications shows that there is a need for more research about the environmental impacts of LEDs and lighting, including the possibility of establishing a LCA environmental impact category for light pollution. Collaboration between academic teams and the LED industry would greatly improve the quality of the research in this field. Funding of this activity by public agencies or other independent organisations seems preferable to avoid conflicts of interest that could arise when sensitive environmental and health aspects are investigated.

1 Introduction

Interest in environmental impacts has increased over the last few decades. The concern has widened from local environmental impacts, such as oil spills and the use of chemicals, to a more global perspective including issues such as the acceleration of climate change. The interest in environmental concerns has increased simultaneously with the increase of wealth and the flow of information and global communication, and is linked with the energy crisis and the effort of increasing energy-efficiency.

Lighting is one of the areas where environmental concern has risen, and there are three principle reasons for this increase. First, energy use for lighting represents a sizable share of global electricity consumption - approximately 15% in 2010 (UNEP, 2014). Second, lighting and measures within the field of lighting have been identified as highly cost-efficient areas for reducing the energy consumption and greenhouse gas emissions (McKinsey 2010, European Commission 2009a). And third, there are more energy-efficient LED products entering the market, and their performance is improving while prices are decreasing.

Until recently the lighting market has been dominated by inefficient technologies, such as incandescent lamps and high pressure mercury lamps. There are now more energy-efficient options and thus more environmentally friendly alternatives available, such as compact fluorescent lamps, high-pressure sodium (HPS) lamps, and LED lamps and luminaires. The market penetration of energy-efficient light sources is supported by sound policy measures such as those found in Australia, China, Denmark, France, Japan, the Netherlands, Korea, Sweden, the UK and the USA.

The energy efficiency of light sources is a major environmental aspect. However, it has been questioned whether the energy efficiency of light sources is more important than other environmental aspects of lighting products, such as the efforts in manufacturing or recycling and disposal. In order to take the environmental impacts into account in a holistic manner, a standardised scientific method was developed call life cycle assessment (LCA). The LCA was introduced in the 1970's, and is a well-established scientific method for quantifying and comparing environmental impacts. There are several subtypes and other possibilities in the LCA methodologies that would allow them to be modified so it can be used for many purposes, including decision-making, conducting design for environment in R&D, and marketing.

This report aims at reviewing current knowledge in the LCA studies and reports to assess the impact of LED products. This report consists of three parts: (1) introduces the LCA method, as defined in the standards; (2) reviews LCA studies of light sources (lamps, luminaires), concentrating on the studies of LED products; and (3) conclusions are drawn and future recommendations provided. This report is not a LCA in itself, but rather is an introduction, analysis and review of LCAs found in the literature. This report attempts to draw conclusions based on the assessments reviewed and to identify the areas that would benefit from more work, e.g., missing data and notable sources of uncertainties.

2 Life Cycle Assessment

Life cycle assessment is a tool to systematically evaluate the potential environmental impacts of a product, process, or service. It compiles the material and energy flows (inputs and outputs) of each stage of the life cycle and calculates related environmental impacts. There are numerous environmental impacts to consider in an LCA, such as energy use, water use, land use, toxicity, creation of waste, and emissions to air, water and soil. Commonly used environmental impact categories are for example the following:

- Acidification
- Climate change
- Depletion of abiotic resources
- Ecotoxicity
- Energy consumption
- Eutrophication
- Human toxicity
- Landfill use
- Ozone depletion
- Photochemical oxidation
- Water use

The LCA is basically a study “from cradle to grave”. It takes into account all the following elements:

- Materials, components, sub-components, parts and their packaging
- All flows needed in the manufacturing process of the product and its parts, such as the energy and water flows and the flows of process chemicals
- Transport of the materials and components from the producer to the assembly plant (the whole transport chain) and the final product from the assembly plant to the distributor, further to the use location, and finally to the point of end-of-life
- Product maintenance (manufacturing of replacement products) and their installation
- Use of the product
- Recycling, incineration, disposal (landfill)

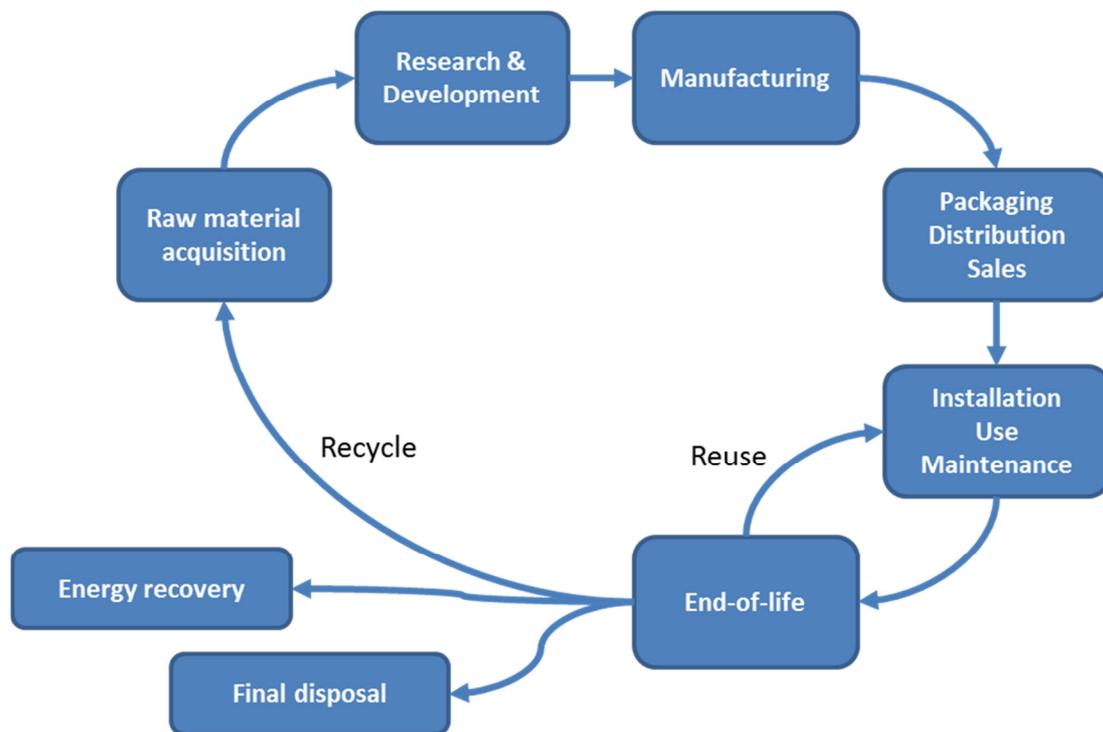


Figure 2-1. Life cycle of a product (from Tähkämö 2013).

Life cycle may be defined in an LCA as a whole life cycle or to only consider a few stages. An example of a life cycle is illustrated in Figure 2-1. There are several possibilities to divide the life cycle into stages. Traditionally, the life cycle starts from raw material acquisition, such as mining, refining. Second, the product is designed (R&D) and manufactured. Then, the product is packaged, transported and sold, after which it is installed and used. During the use of the product, it may be maintained. Finally, the product reaches the end-of-life in which there are several possibilities. The product may be repaired and reused. The materials and components may be recycled as raw material input. The energy embodied in the product may be recovered in incineration. The last option is to place the raw materials of the product to a landfill to its final disposal.

LCA enables the identification of environmental “hotspots”, i.e., the factors contributing the most to a significant environmental impact. These identified factors can be stages of the life cycle or a material/component of the product. The identification of the main causes for environmental impacts facilitates environmentally friendly product design (ecodesign, design for environment).

One may conduct a simplified LCA taking into account only one or a few stages of the life cycle. An LCA may also be simplified regarding the environmental impacts it considers, such as a carbon footprint, or it may be a life cycle energy analysis considering only the energy flows during the life cycle.

LCA is a standardised method and it can be used for many purposes. The LCA helps in identifying the energy and environmental performance of a manufacturing process and makes it possible to make cost- and energy-efficient changes in the process (ecodesign). LCA assists in the creation of environmental profile of a product (ecoprofile) and mandatory or voluntary environmental product declarations (EPD).

The European Commission Joint Research Centre (JRC) has published in a reference guide on conducting LCAs (European Commission et al. 2010a). The JRC has also published in a second document the framework and requirements for life cycle impact assessment models and indicators, a document on the environmental indicators that are widely accepted within the LCA community (European Commission et al. 2010b).

2.1 Life cycle assessment methodology

The basic LCA methodology is defined in the ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b) standards. They define the general method for LCA including the phases of the LCA and the terms used in the field of LCA. The LCA standards are broad so that they can be applied to any type of a product or service. Yet, this creates the need for more product-specific guidelines, product category rules (PCR), which define more in detail the LCA of a specific product.

The LCA generally refers to the environmental LCA while the economic aspects are calculated in life cycle cost (LCC) analysis and social impacts in social LCA. However, LCA may be defined so that it includes also economic and social impacts as environmental impacts.

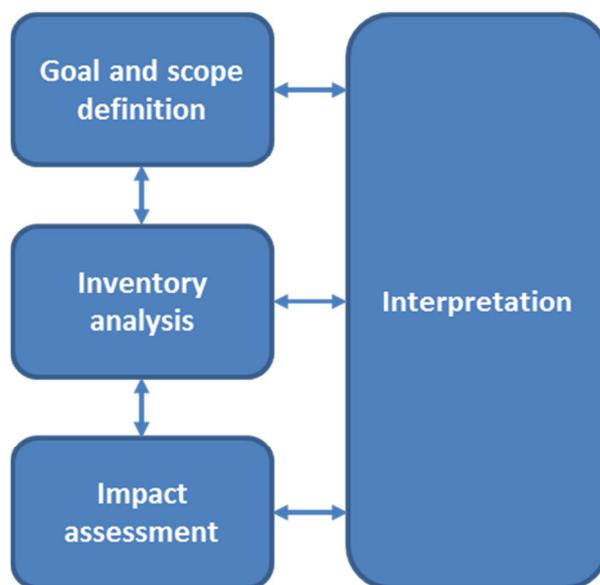


Figure 2-2. Phases of the LCA method (adapted from ISO 14040 (ISO 2006a))

There are four phases in the LCA: goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 2-2). It is an iterative technique where the phases are

linked together. The first phase defines the goal and scope of the assessment, including the product system to be studied, the system boundaries, cut-off rules, the functional unit and the assumptions. Second, the data is collected in the life cycle inventory (LCI) analysis (Figure 2-3). All the data of the product system defined in the first phase is collected, such as the energy, raw material and ancillary inputs.

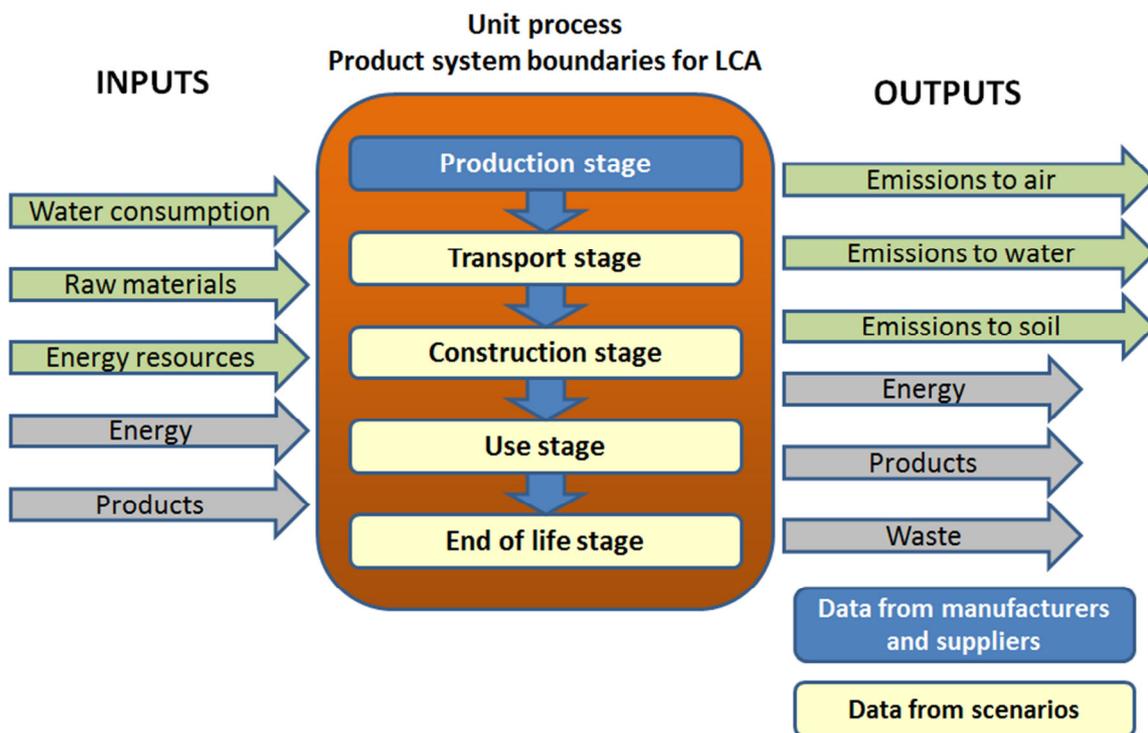


Figure 2-3. Life cycle inventory (necessary data are coming, ideally, from manufacturers and missing values are completed from various scenarios proposed in the literature).

The input data may be collected from several sources, e.g., the literature, manufacturers, previous LCAs, and measurements. If there is limited data or not sufficiently representative data, proxies may be used. Third, the impact categories, environmental indicators and models are selected in life cycle impact assessment (LCIA). The potential environmental impacts of each flow are calculated as assigning the LCI results into environmental impact categories (Figure 2-4). LCIA may also include the data quality assessment, such as uncertainty and sensitivity analyses, and the weighting and grouping of the results. Finally in interpretation, the LCI and LCIA results are combined and main findings are concluded in accordance with the goal and scope definition.

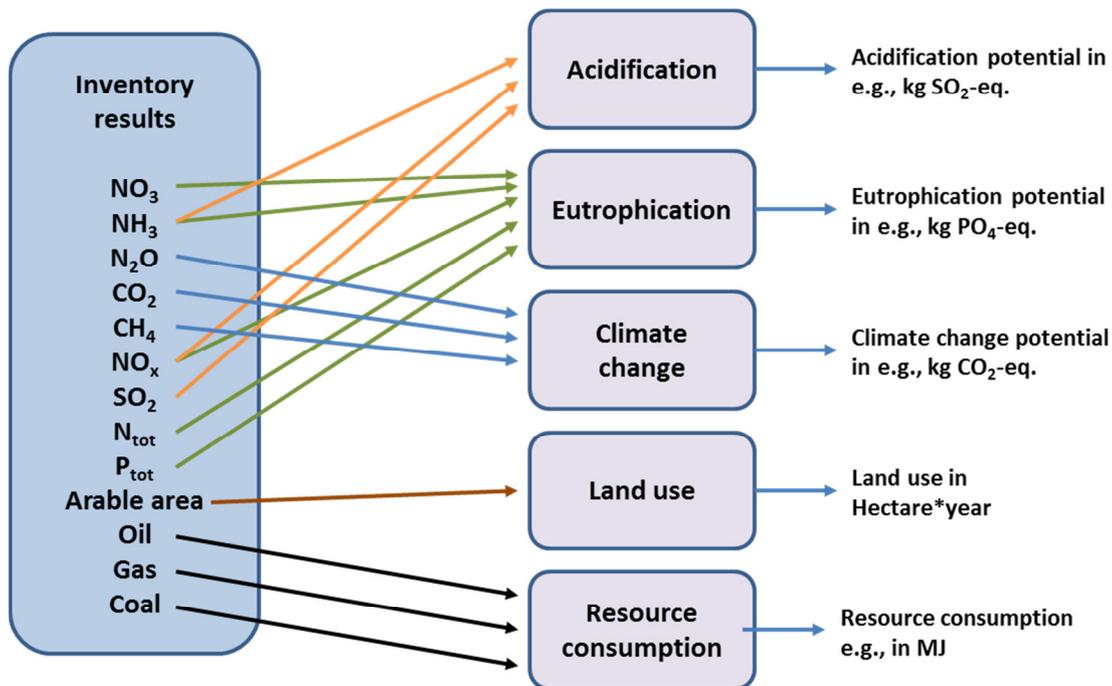


Figure 2-4. Example of life cycle impact assessment: Translation of inventory results into environmental indicators and their contributions to different environmental impacts (JRC 2011).

2.2 Review of life cycle assessments of light sources

A number of LCA studies on lighting products have been conducted starting in the 1990’s and continuing to today. Mainly, they are comparative or stand-alone (non-comparative) LCAs of lamps. A list of the light source LCAs is provided in Table 2-1, which gives information on their method, i.e., the product(s) and functional unit. The previous LCAs have also been the subject of review in Tähkämö et al. (2012) and in US DOE (2012a).

The initial data on materials consumption used in manufacturing was collected from the LCAs of incandescent lamps, CFLs and LED lamps (see Figure 2-5). No unified model was found in the references, and the shares of materials reported in the literature varied even within the 60-W incandescent lamps, which were considered as simple and uniform products.

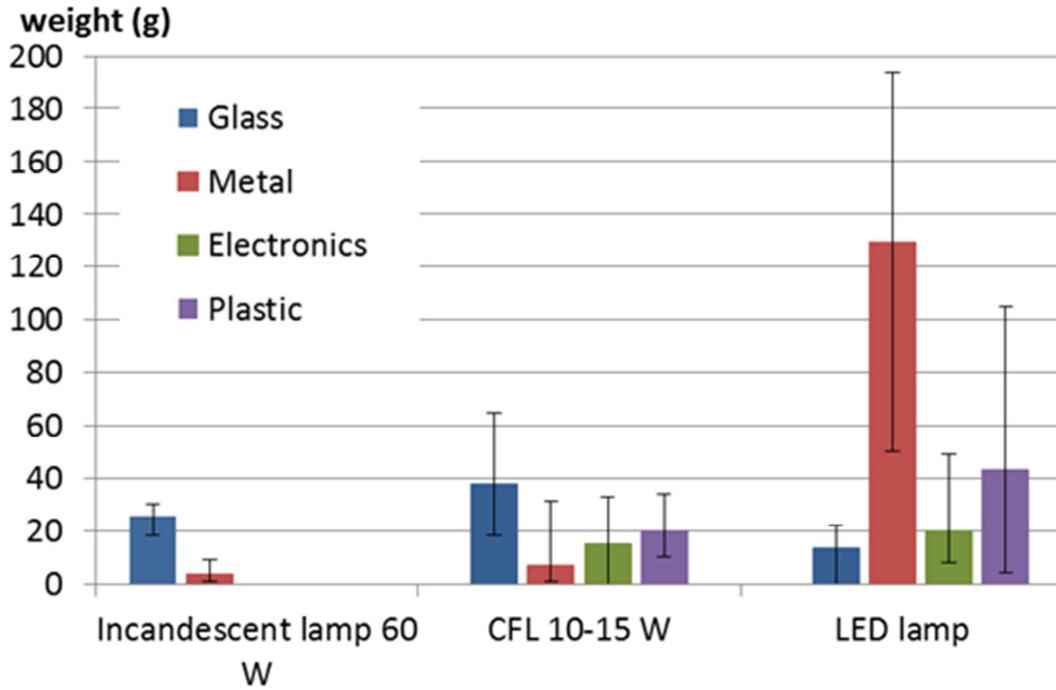


Figure 2-5. Initial data of the material composition of non-directional lamps used in households.

From the LCAs of light sources listed in Table 2-1, nine of them (shaded blue) are chosen for closer review on the basis of their date of publication and/or containing LED light sources. Each of these nine assessments includes an LED lamp or luminaire and they all are published between 2009 and 2013.

Table 2-1. Summary of light sources, functional units and environmental impacts in LCAs of light sources (Adapted from Tähkämö 2013, updated)

Light sources	Functional unit	Environmental impact categories	Reference	Year
250 W CMH 180 W LED	60 000 h	energy, carcinogens, respiratory organics and inorganics, GWP, radiation, ODP, ecotoxicity, AP/EP, land use, minerals, fossil fuels, water consumption	Abdul Hadi et al.	2013
19 W LED	50 000 h and 1140 lm (57 Mlmh)	primary, renewable and non-renewable energy; ADP; water consumption; hazardous, non-hazardous, inert and radioactive wastes; GWP; AP; air pollution; water pollution; ODP, POCP; EP	Tähkämö et al.	2013a
2x49 W FL	80 000h and 8600 lm (688 Mlmh)	ADP; AP; EP; GWP; POCP; ODP; freshwater aquatic and sediment, marine aquatic and sediment, and terrestrial ecotoxicities; HTP	Tähkämö et al.	2013b
60 W IL 15 W CFL	10 000 h	ADP, AP, EP, GWP, ODP, POCP	Eljošutė et al.	2012
60 W IL 12.5 W LED lamp 15 W CFL 6.1 W LED lamp*)	20 Mlmh	GWP; AP; POCP, ODP; HTP; freshwater aquatic, marine aquatic, and terrestrial ecotoxicities; EP; ecosystem damage; ADP; land use; hazardous, non-hazardous, and radioactive wastes	US DOE	2012b
60 W IL 14 W FL 11 W CFL	1 h	Cumulative energy demand, GWP, EcoIndicator'99	Welz et al.	2011
150 W HPS 163 W MH 105 W LED	100 000 h	GWP, respiratory effects, ecotoxicity	Dale et al.	2011
100 W IL 20 W CMH 23 W CFL 10 W LED lamp 2x28 W FL 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, non-hazardous, and radioactive wastes	DEFRA	2009
40 W IL 8 W LED 8 W CFL	345-420 lm during 25 000 h	GWP, AP, POCP, HTP, EP, ADP, energy consumption	Osram	2009
60 W IL 6 W LED 13 W CFL 6 W LED*)	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 & Belle	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
60 W IL 15 W CFL	1 Mlmh	Energy consumption	Slocum	2005
60 W IL 13 W CFLi 15 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 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 & Maimann	1991

Note: IL=incandescent lamp, HL=halogen lamp, (C)FL=(compact) fluorescent lamp, CFLi=CFL with integrated ballast, HPS=high pressure sodium lamp, (C)MH=(ceramic) metal halide lamp, IND=induction 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, *)=future, **)=hypothetical).

2.2.1 LCA study by Abdul Hadi et al.

The LCA by Abdul Hadi et al. in 2013 compared LED and ceramic metal halide (CMH) technologies in street lighting. The wording of the study was not clear (lamp, bulb, light) but it was understood that the assessment considered the luminaire including all the components inside (lamp/package, ballast/driver, ignitor, luminaire cover/housing). The LCA included raw material acquisition, manufacturing, use and end-of-life. Aluminium content was excluded from the base case, as it was estimated to be similar in both luminaires. The functional unit was 60 000 h of lighting with no direct comparison of luminous flux. Lamps were reported to have CRI greater than 80 and luminous efficacy greater than 90 lm/W. The LCI data was collected from the publications by Hartley et al. (2009) (data for outdoor CMH luminaire without ballast) and DEFRA (2009) (data for indoor LED luminaire and CMH lamp).

The results indicated that the manufacturing of LED luminaire caused greater environmental impacts compared to CMH luminaire but the total life-cycle environmental impacts of LED technology were found to be somewhat lower due to its greater energy efficiency (Figures 2-6 and 2-7).

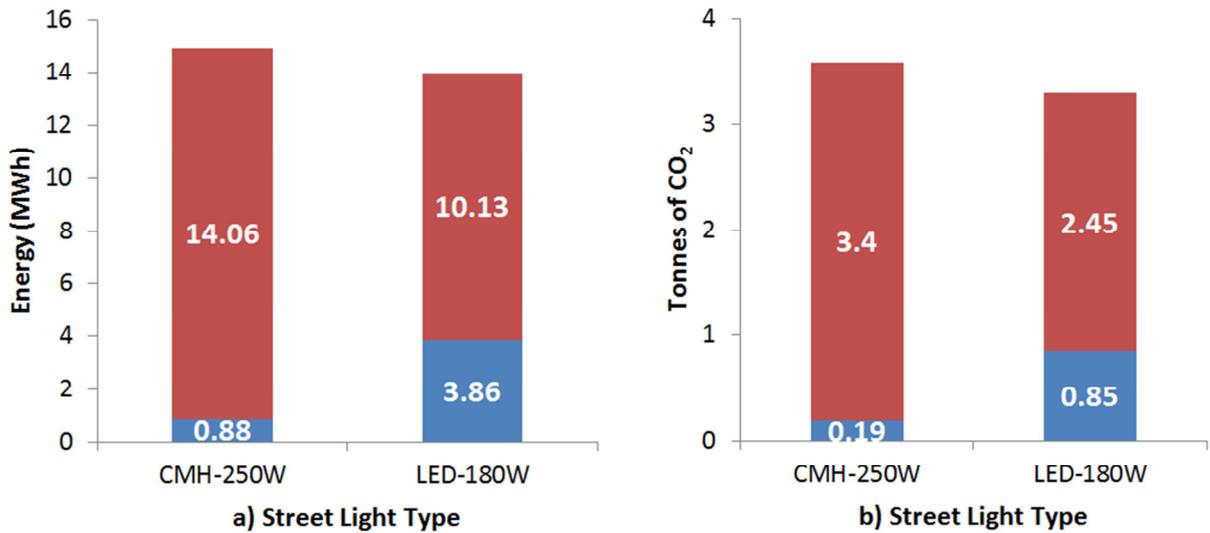


Figure 2-6. Energy consumption and the production of CO₂ emissions of CMH and LED luminaire during manufacturing and use (Abdul Hadi et al. 2013)

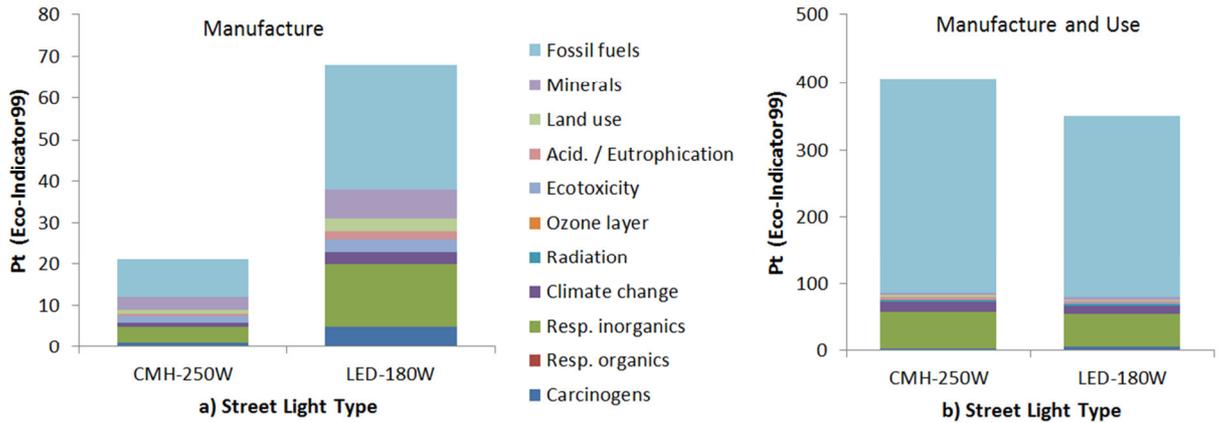


Figure 2-7. Environmental impacts of “manufacturing in detail” and “manufacturing and use”, expressed in units of single-score (Eco-Indicator99) (Abdul Hadi et al. 2013).

The manufacturing and use of the CMH luminaire consumed only one third of the amount of water compared to LED luminaire (Figure 2-8).

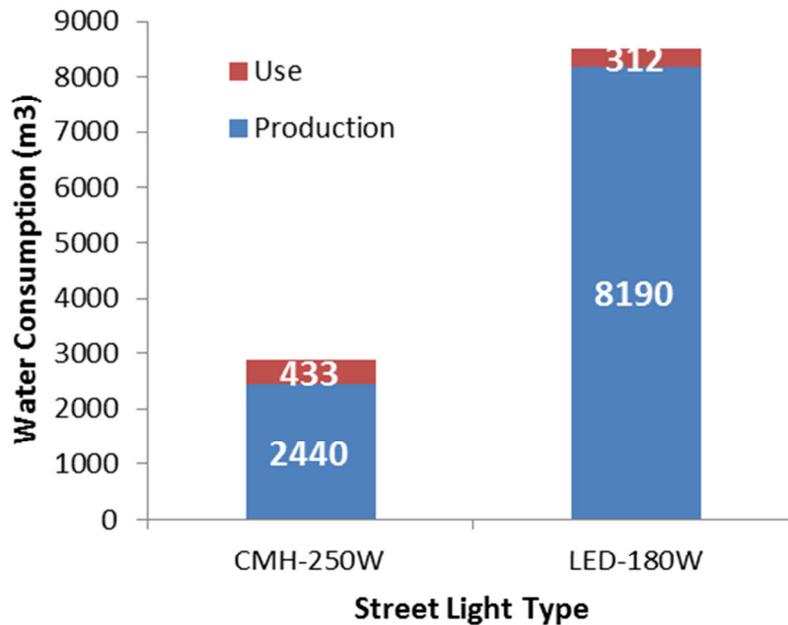


Figure 2-8. Water consumption of manufacturing and use of CMH and LED street lighting luminaires (Abdul Hadi et al. 2013)

2.2.2 LCA study by Tähkämö et al. (2013a)

The LCA of an LED downlight luminaire was conducted as a stand-alone study (not a comparative LCA). All the parts in the LED luminaire were included, such as the LED array,

remote phosphor cover, driver and luminaire cover. The functional unit was equal to 57 megalumen-hours. The assessment considered manufacturing, transport, installation, use, and end-of-life. In the base case, the life of the luminaire was 50 000 h, it modelled the use of electricity generated in France, and the products were assumed to be 95 % landfilled and 5 % recycled in the end-of-life.

The results show that the energy in use is the dominating impact (average 93 %) in case of European electricity production in use (Figure 2-9), whereas the use of French electricity increases the environmental contribution of other life cycle stages, especially manufacturing (average 23 %). End-of-life was found to be somewhat negligible, except in waste categories (Figure 2-10). It was also found that the life of the luminaire affects the environmental impacts: In case of a short life, the manufacturing of the original and replacement luminaires has a clear role in causing environmental impacts. The manufacturing impacts of the LED luminaire were divided mostly among the driver, LED array and aluminium heat sink. For both Figures 2-9 and 2-10, abbreviations and associated metrics are given on *page vi* of this document.

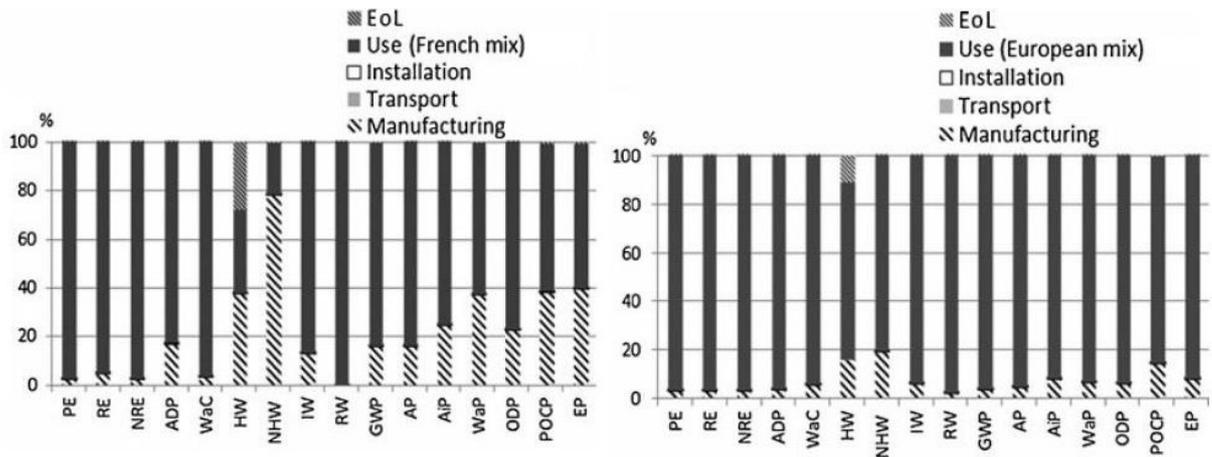


Figure 2-9. Results of the LCIA of an LED luminaire using French and European electricity production in use (Tähkämö et al. 2013a).

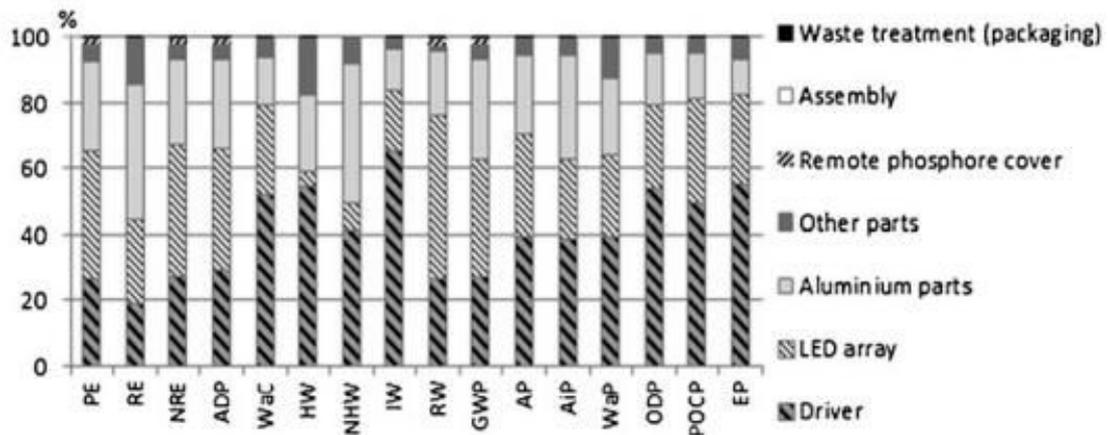


Figure 2-10. . Division of the environmental impacts of LED luminaire manufacturing (Tähkämö et al. 2013a).

2.2.3 LCA study by Tähkämö et al. (2013b)

The LCA of a fluorescent lamp luminaire evaluated the environmental impacts of a two 49 W T5 fluorescent lamps, their ballast (electronic), and the luminaire. The functional unit was established as 688 megalumen-hours (20 years, 4000 hours/year, 8600 lm). The LCA took into account the manufacturing, transport, use, and end-of-life. Electricity generated in Finland was used in manufacturing and use phases of the LCA. A sensitivity analysis of the electricity production was conducted using peat and hydropower during the use phase.

The results of the LCA showed that the life-cycle environmental impacts are caused mainly by energy in use (93 %) and manufacturing (7%). Other life cycle stages cause no notable impacts. The electricity production in use was found to impact greatly the environmental impacts and their division into life cycle stages (Figure 2-11).

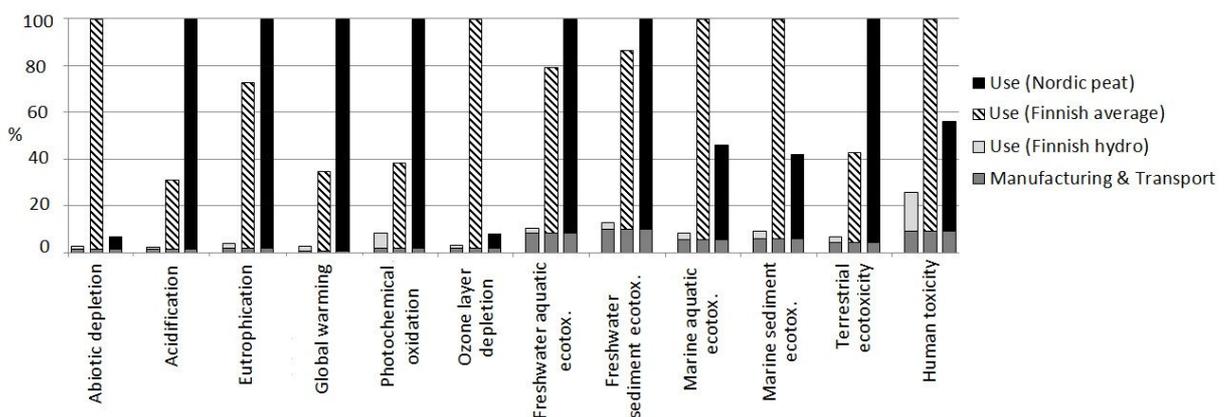


Figure 2-11. Relative environmental impacts of FL luminaire using hydropower, Finnish average and peat in use (Tähkämö et al. 2013b).

2.2.4 LCA study by US DOE

The United States Department of Energy (US DOE) has researched the LCA of light sources concentrating on LED lighting products. The environmental concern of LED products is focused on its material contents and manufacturing but also to the comparison of LED technology and other light source technologies and their comparison. The US DOE has provided three reports on the subject. The first report concentrated on the life cycle energy analysis (US DOE 2012a). The second part analysed in detail the manufacturing process of LED lighting products and conducted a comparative LCA of incandescent lamp, CFL and LED lamp (US DOE 2012b). The third part of the research focused on the material contents of the lamps and studied their compliance to the US national and state-wide hazardous material restrictions (US DOE 2013). The LCA published in part 2 (US DOE 2012b) is summarised in this chapter.

The LCA by US DOE (2012b) used the same functional unit as in their life cycle energy analysis in part 1, 20 megalumen-hours of lighting service. The assessment compared the environmental performance of incandescent lamp, CFL, LED lamp and a future (2017) LED lamp. The LED manufacturing process was very thoroughly described with all the material and energy inputs and outputs.

It was found that the environmental impacts of incandescent lamp are by far the greatest (Figures 2-12 and 2-13).

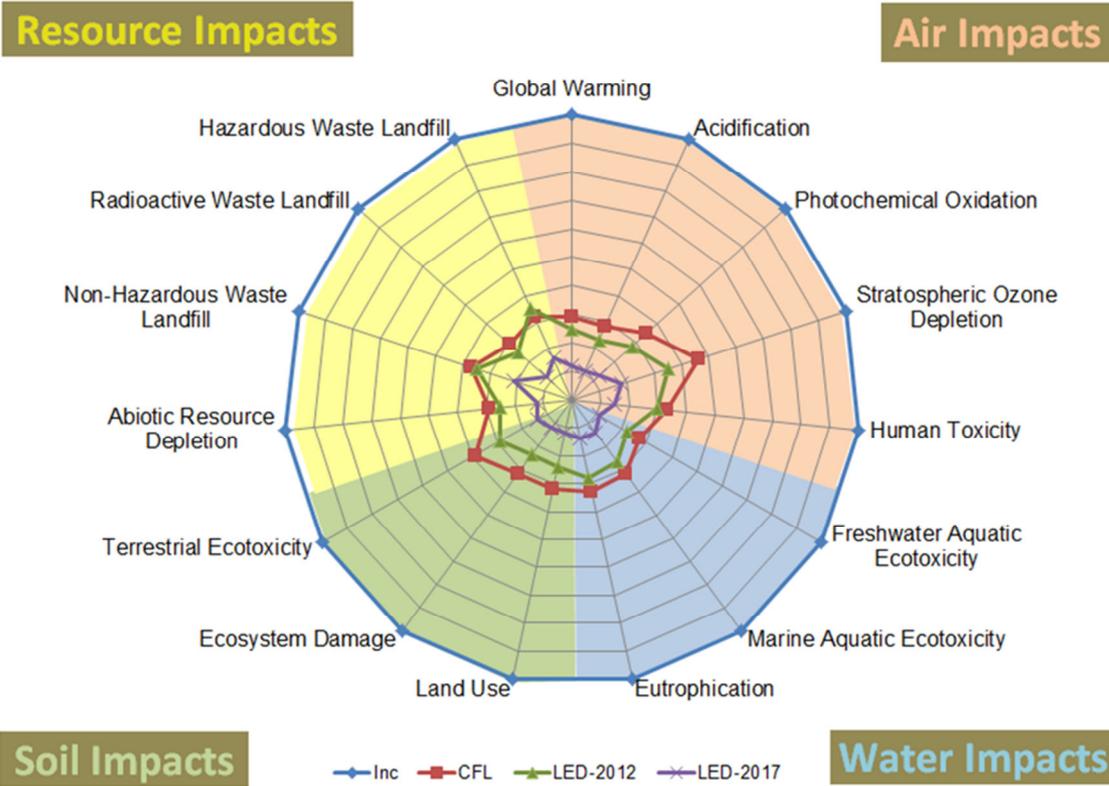


Figure 2-12. Life-cycle environmental impacts of three household lamp technologies including current (2012) and future (2017) LED lamps (US DOE 2012b).

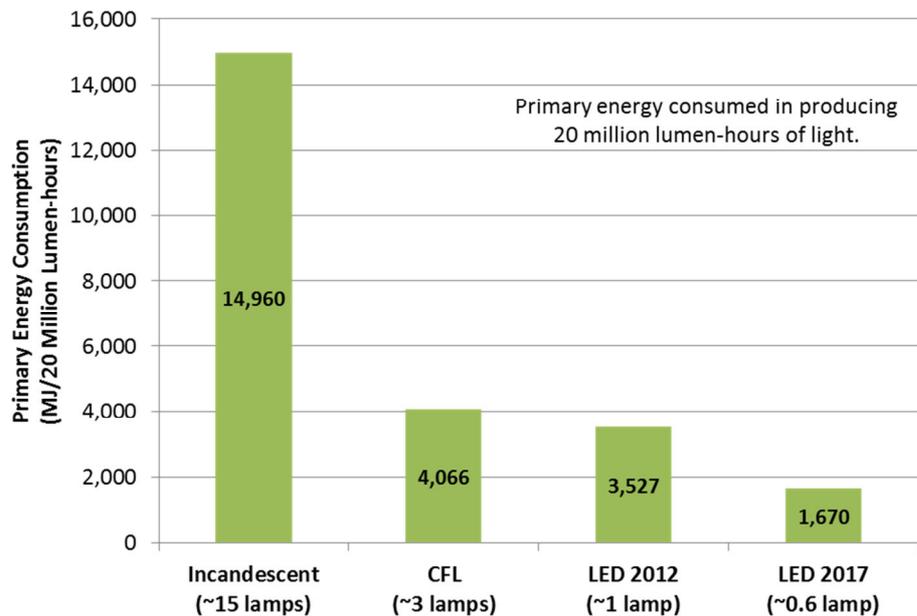


Figure 2-13. Primary energy consumption over the life cycle of three lamp technologies (US DOE 2012b).

The following lines give the key findings as enumerated in the Life-Cycle Assessment of Energy and Environmental Impacts of LED Lighting Products fact sheet.²

- The average life-cycle energy consumption of LED lamps and CFLs was similar, and was about one-fourth the consumption of incandescent lamps.
- If LED lamps meet their performance targets by 2015, their life-cycle energy is expected to decrease by approximately one-half, whereas CFLs are not likely to improve nearly as much.
- The use phase of all three types of lamps accounted for 90 percent of total life-cycle energy, on average, followed by manufacturing and transport. Most of the uncertainty in the life-cycle energy consumption of an LED lamp was found to centre on the manufacturing of the LED package. Various sources estimated this at anywhere from 0.1% to 27% of life-cycle energy use.
- The energy these three lamp types consumed in the use phase constituted their dominant environmental impact.
- Because of its low efficacy, the incandescent lamp was found to be the most environmentally harmful of the three types of products, across all 15 impacts examined in the study.
- The LED lamp had a significantly lower environmental impact than the incandescent, and a slight edge over the CFL.
- The CFL was found to be slightly more harmful than today's LED lamp on all impact measures except hazardous waste landfill, because of the LED lamp's large aluminium heat sink. As the efficacy of LED lamps continues to increase, aluminium heat sinks are expected to shrink in size—and recycling efforts could reduce their impact even further.
- The light source that performed the best was the LED lamp projected for 2017, whose impacts are expected to be about 50 percent lower than the 2012 LED lamp and 70 percent lower than the CFL
- The selected models were generally found to be below restrictions for elements that are regulated at the national level in the US.
- Nearly all of the lamps (regardless of technology) exceeded at least one California restriction—typically for copper, zinc, antimony, or nickel.
- Examination of the components in the lamps that exceeded the California restrictions revealed that the greatest contributors were the screw bases, drivers, ballasts, and wires or filaments. Concentrations in the LED lamps were comparable to concentrations in cell phones and other types of electronic devices, and usually came from components other than the LEDs themselves.

2.2.5 LCA study by Welz et al.

This LCA compared four types of lamps: incandescent lamp, low-voltage halogen lamp, CFL and CFLi. The functional unit was 1 hour of lighting. Luminous fluxes or other luminous characteristics were not provided. The life cycle contained manufacturing (no indication of processes, only raw materials), use and end-of-life.

² DOE factsheet: http://apps1.eere.energy.gov/buildings/publications/pdfs/ssl/lca_factsheet_apr2013.pdf

The energy in use phase dominated the environmental impacts of all four technologies due to the environmental burdens caused by the electricity. Manufacturing represented between 0.3-1% of the overall impacts. No notable difference was found in the environmental impacts between low-cost, no-name and more-expensive brand-name CFLi lamps. Energy in use was also found to be the dominant stage regardless of the energy source mix used (assumed Swiss electricity mix, average European, wind/photovoltaic, hydropower). The choice of the electricity production in use stage was found to affect the results notably (Figure 2-14).

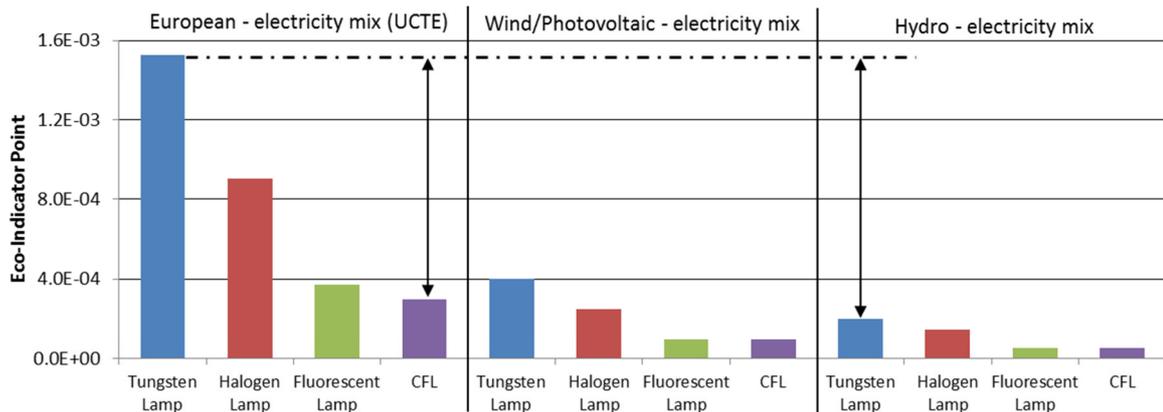


Figure 2-14. Environmental impacts in Eco-Indicator points (EIP) of four lamp types for a functional unit of 1 hour using three electricity production mixes (Welz et al. 2011)

End-of-life of lamps and their ballasts, if any, was modelled as two scenarios: WEEE recycling and municipal waste incineration. An appropriate recycling technology was found to reduce the environmental impacts by a maximum of 15% for the halogen and the compact fluorescent lamps.

2.2.6 LCA study by Dale et al.

Dale et al. published an LCA study in 2011 based on a previous LCA report (Hartley et al. 2009). In the scientific paper by Dale et al., the LCA compared HPS, MH, fluorescent induction and LED luminaires in street lighting. The functional unit was 100 000 hours of light, and the differences in the luminous flux were ignored. The assessment covered manufacturing and use. The manufacturing of ballasts and drivers were excluded due to the assumption of them being similar. Three electricity production scenarios were considered: US average, regional average and wind power.

The main conclusions were that the impacts of electricity in the use stage clearly dominated the results (note: consistent finding with the preceding report by Hartley et al. 2009) and that the choice of electricity production had a noticeable affect on the environmental impacts resulting from the analysis. LED and induction luminaires were found to have similar environmental performance (Figure 2-16) but LED technology is estimated to be more environmentally friendly

in the future advancements (mainly the increase of luminous efficacy and reliability). The environmental friendliness of LED and induction technologies was based on their lower luminaire powers and longer life compared to HPS and MH luminaires (Table 2-2). There were however, great uncertainties in the LED manufacturing data (note: also a consistent finding with the preceding report by Hartley et al. 2009).

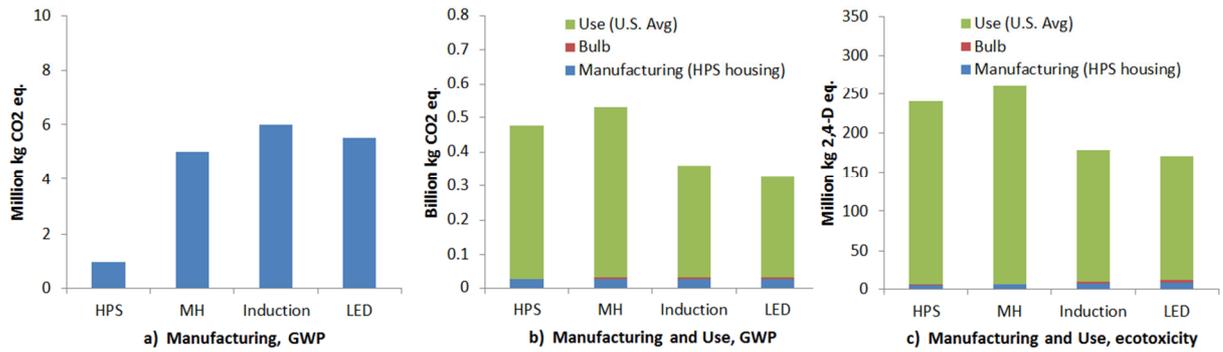


Figure 2-15. Results from the original LCA report (Hartley et al. 2009): global warming potential (GWP) impacts of street lighting luminaires from (a) manufacturing and (b) the whole life cycle, and (c) ecotoxicity emissions of the whole life cycle.

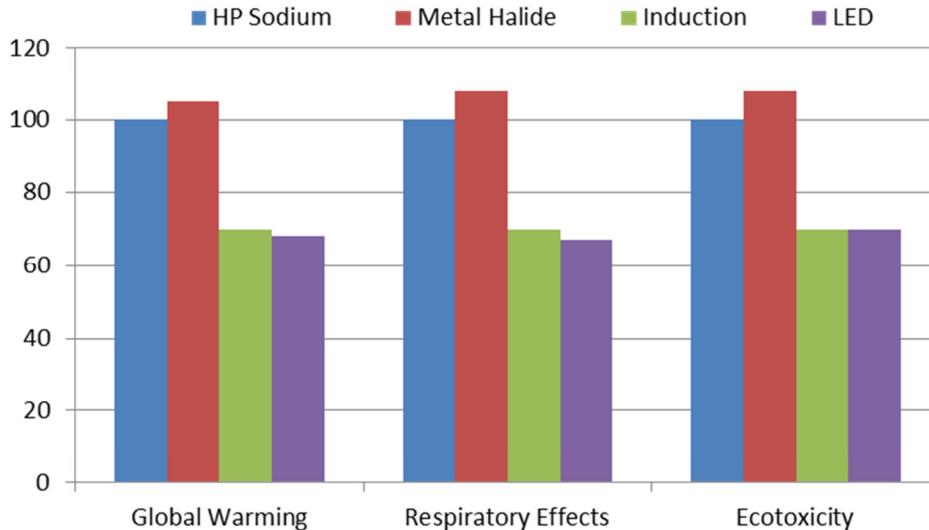


Figure 2-16. Total life-cycle impacts of 4 street lighting technologies. 100 % represents the impacts of the HPS luminaire (Dale et al. 2011).

Table 2-2. LCI data of the four street lighting luminaires (Dale et al. 2011).

Technology	Housing data	Bulb cost	Life span (h)	Replacements required	Peak wattage
High pressure sodium	Physical model	\$12.39	23,980	4.17	150
Metal halide	I/O estimate	\$27.29	12,150	8.28	163
Induction	I/O estimate	\$280	100,000	1	109
Light-emitting diode	Manufacturer data	\$9.2, \$250, \$322	58,823	1.7	105

2.2.7 LCA study by DEFRA

The LCA by DEFRA (2009) compared five lamp and luminaire technologies used in indoor lighting (Table 2-3). The functional unit was megalumen-hours. The assumed life of LED product was 20 000 h for the LED lamp and 50 000 h for the LED luminaire.

Table 2-3. Information on the five technologies analyzed in the LCA (DEFRA 2009)

Characteristics	Units	LED int.	LED lum.	CMH	T5	CFL	Incand.
Power Consumption per Lamp	Watts	1	1	20	28	23	100
Number of Lamps per Luminaire	Die / Lamps	10 die	16 die	1 lamp	2 lamps	1 lamp	1 lamp
Power Consumption per Luminaire (including ballast losses)	Watts	12	18	23	59	23	100
System Efficacy (including ballast) in 2009	Lumens per Watt	60	65	77	93	69	16
Projected System Efficacy (including ballast) by 2014	Lumens per Watt	102	143	104	102	76	16
Typical Lamp Lifetime	Hours	20,000	50,000	12,000	24,000	10,000	1,000
Typical Luminaire System Lifetime (i.e., ballast life)	Hours	n/a	50,000	36,000	48,000	n/a	n/a
Total Electricity Consumed	Kilowatt-Hours	240	900	720	2,688	230	100
Total Light Emitted (in 2009)	Mega-Lumen-Hours	14.4	58.5	55.4	263.0	15.9	1.6

The results of the LCA clearly indicated that the incandescent lamp causes the greatest environmental impacts (Figure 2-17), while the fluorescent lamp luminaire (T5) created the lowest environmental burdens in 2009. In contrast, the future development of technologies was projected to change the results so that it would be the LED luminaire in 2014 that caused the

lowest environmental impacts. However, the differences between CMH, LED and FL technologies were small compared to the difference between them and the incandescent lamp. This report mentions the high score of LEDs in the human toxicity potential (HTP) indicator caused by the aluminium heat sink.

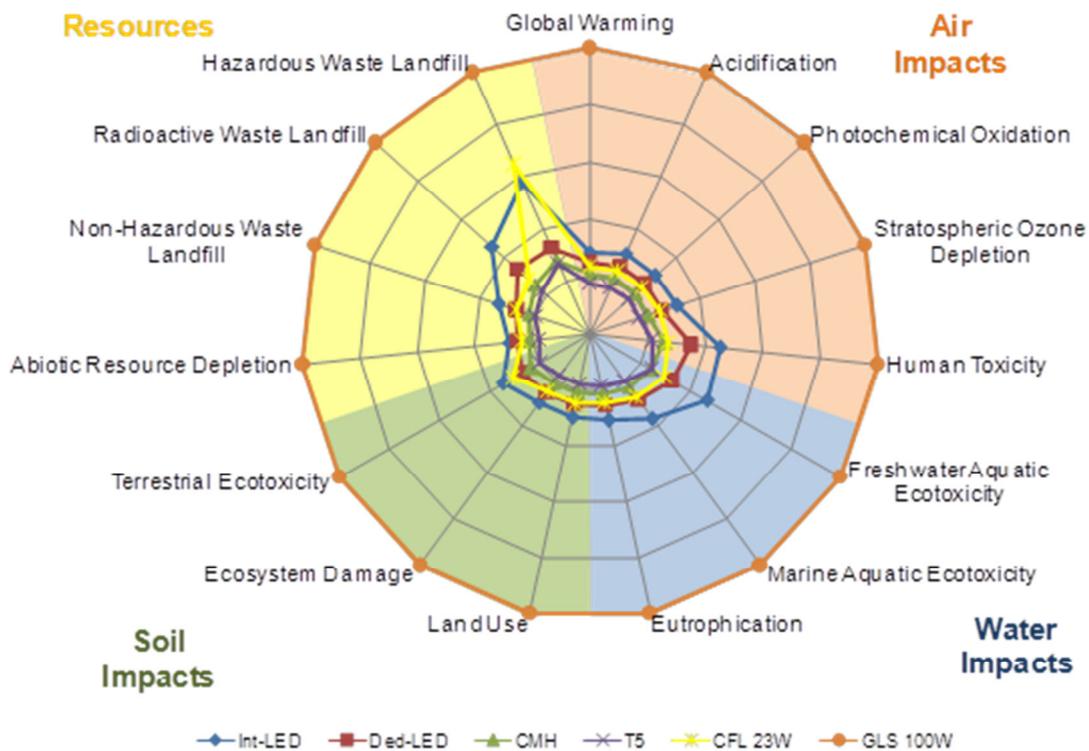


Figure 2-17. Relative impacts of six types of light sources (DEFRA 2009).

2.2.8 LCA study by OSRAM

OSRAM conducted a comparative LCA of three household lamp types (Figure 2-18). The assessment included manufacturing (including detailed LED manufacturing but no data was provided on that), use and end-of-life. The electricity production in use was EU-27 electricity production was considered with additional scenarios of Chinese and nuclear power production. Functional unit was not clearly defined but it ranged from 345 lm to 420 lm over 25000 h.



Figure 2-18. Three lamp types in the LCA by Osram (2009).

The electricity use dominated the life cycle environmental impacts. Less than 2% of the total energy demand is needed for the manufacturing of any of the lamps, including LED lamp (Figure 2-19). The manufacture of LEDs was found not to be energy-intensive: 0.4 kWh was needed for production of an LED (OSRAM Golden Dragon Plus), while 9.9 kWh was required for the manufacturing of the LED lamp including 6 LEDs. Incandescent lamps have the greatest environmental impacts, while CFL and LED lamp have similar environmental profiles. Different electricity mixes (Chinese or nuclear power) affect the results significantly. The results strongly depend also on the assumed lamp life.

In contrast to the primary energy consumption of incandescent lamps (3 305 kWh), CFL and LED lamps use less than 668 kWh of primary energy during the life cycle. Thus, using CFL or LED lamps can save 80% of energy. Future improvements of LED lamps will further cut down the energy demand in use.

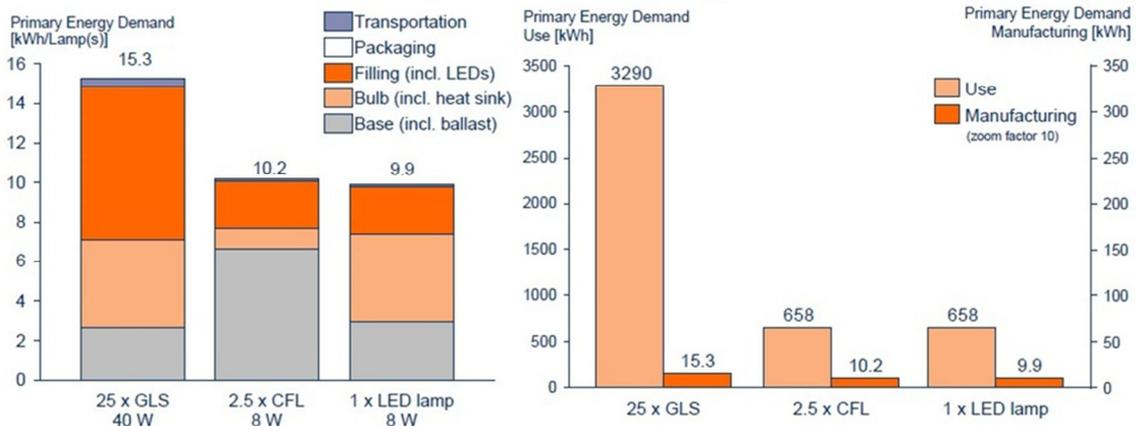


Figure 2-19. Detailed primary energy demand for manufacturing, and primary energy demand for manufacturing and use (OSRAM 2009).

2.2.9 LCA study by Quirk

The LCA report by Ian Quirk in 2009 compared four types of lamps used in residential lighting: incandescent lamp, CFL, LED lamp and a hypothetical LED lamp (Table 2-4). The functional unit

was one megalumen-hour. Manufacturing of the lamps took place in China. However, this study doesn't offer an equivalent comparison given that the LED lamp chosen only has a lumen output of 300 lumens, which is only half of the other products in the comparison and is very low compared to modern products.

Raw materials, assembly processes and transport was taken into account. The LCA contained a sensitivity analysis regarding the use-stage energy production: it was varied among electricity production in China, average US, California (base scenario) and a mix of 33 % renewable energy sources.

Table 2-4. Description of lamps studied by Quirk (2009).

Lamps	Life	Power	Flux
Incandescent (GE)	1000 hours	60 W	800 lumens
CFL (Philips)	8000 hours	13 W	800 lumens
LED (EarthLED)	40,000 hours	6.7 W	300 lumens
<Future LED> (60% better)	40,000 hours	6.7 W	500 lumens

The study concluded that CFL and LED lamps are four times more energy efficient in use compared to the incandescent lamp. The manufacturing of an LED lamp was found to consume more primary energy compared to the incandescent lamp (Figure 2-20). The error bars show the uncertainty in the manufacturing of electronic components (including LEDs). Percentage-wise, manufacturing accounted for less than 1% of life-cycle CO₂ emissions of incandescent lamp and approximately 20% of CFL (12-29%) and LED (17-24%) lamp life-cycle CO₂ emissions. End-of-life (recycling or disposal) was found to account less than 1 % of life-cycle emissions of each lamp type.

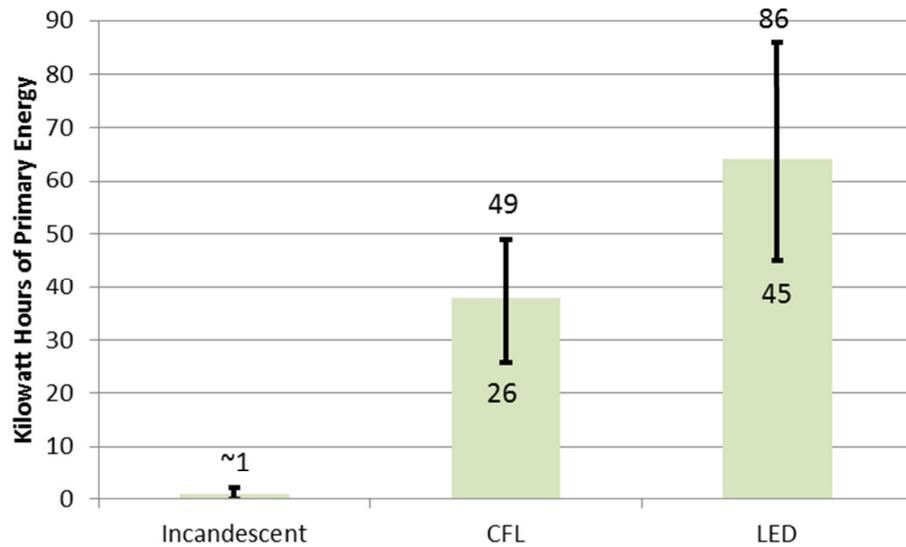


Figure 2-20. Primary energy consumption of manufacturing of one piece of each of three lamp-types (Quirk 2009).

The energy in use phase was found to be the greatest contributor to the impacts in the whole life-cycle environmental assessment (see Table 2-5). The low values correspond to the Californian electricity production, whereas the high values correspond to the Chinese electricity production with a greater proportion of fossil fuels.

Table 2-5. Energy efficiency results in kWh of primary fossil energy per 1 Mlmh (Quirk 2009).

Lamps	Use phase only	Whole life cycle
Incandescent (GE)	60-190 kWh	61-196 kWh
CFL (Philips)	14-47 kWh	18-55 kWh
LED (EarthLED)	18-58 kWh	21-65 kWh
<Future LED> (60% better)	11-34 kWh	13-39 kWh

2.3 Environmental impacts of SSL products

Besides the evaluation of the environmental impacts of LED lighting products by LCAs, a few studies focus on a specific environmental impact of the SSL technology.

First, the end-of-life of LED lamps and luminaires has been studied by Hendrickson et al. (2010). They stated that it is possible to reduce the environmental impacts of SSL products by implementing design for end-of-life in the product development process, e.g., by facilitating the disassembly and thus enabling the recovery of components, parts and materials in order to improve the material reuse and recycling. The end-of-life is a complex stage of the life cycle to model due to its inputs and outputs and common lack of data for disposal or recycling rates.

Second, the material composition of LED products has become a concern especially in the US. The concern has risen from the study by Lim et al. (2011). Their leaching tests proposed that the indicator-type LED components of different colours may contain copper, lead, nickel and silver so that some of them are classified as hazardous according to the Californian regulations. It must be noted that this study considered an indicator-type, through-hole technology LED, which does not correspond to the structure of the current LED products used in general lighting applications. The later study by the group (Lim et al. 2013) included whole LED lamps and comparing their metal contents by the leaching tests. It was found that the studied CFLs and LED lamps were classified as hazardous waste under existing Californian regulations and US federal regulations. CFLs exceeded the limits of copper, lead and zinc, and LED lamps exceeded the limits of copper and lead. This finding underpinned the importance of how the lamps are treated in the end-of-life phase.

To understand this issue in more detail, LED product material composition was studied in detail by the US DOE (2013). This report evaluated the materials present in a variety of incandescent lamps, CFLs and LED lamps by the leaching test method according to the US federal and Californian rules for the hazardous waste. They found that the concentrations of the regulated elements were at the same level in LED lamps as in other types of electronic devices, such as cellular telephones (US DOE 2013). The tested lamps generally complied with the federal requirements but few CFLs and LED lamps exceeded the Californian regulations for hazardous waste (i.e., lead, copper, nickel, antimony, zinc).

Third, the LCAs of light sources do not adequately address the system-level, e.g., the whole building or a building electrical installation system. Typically, the LCAs of light sources evaluate only the lamp or a luminaire including its components but some studies widen the scope. For instance, Dubberley et al. (2004) analysed the environmental impacts of an intelligent lighting system for commercial buildings in the US. The lighting system consisted of a sensor, wireless network, ballast and batteries. The main finding was that the intelligent system causes significantly lower potential environmental impacts than a conventional lighting system. This affirmation is mainly due to the fact that use of intelligent lighting systems that produce light “on-demand” and adapts light quantity as function of the real-time needs, consumes definitively less energy than a classic system. However, an intelligent lighting system incorporates more components (e.g. sensors) that may increase the environmental impact calculated by the LCA. In order to evaluate the environmental impacts of a lighting system, it would be necessary to think on the system-level and to clearly define the scope of the LCA.

2.4 Uncertainties in the LCAs of SSL products

Life-Cycle Assessments have always some degree of subjectivity when it comes to the choice of system boundaries, cut-off rules, allocation, and impact categories, and due to usually limited resources available to conduct an LCA study. In spite of the use of the most comprehensive and up-to-date databases and other sources of information, the LCA contains a large number of input parameters for which the accuracy is unknown. This creates uncertainties in the results. It

must be noted that the LCA results cannot be stated to an uncertainty less than 5 to 20 %. Is not possible to compare two LCA studies unless all similar impact indicators have been defined rigorously and are identical. As example, in not possible to compare CO₂ footprint of the system if the quantity of releases CO₂ per kilo-watt-hour is not identical: the CO₂ footprints for the same product will then be different from one country to another.

In case of LCAs of SSL products, the specific source of uncertainty is the data of the LED component. In the LCIA databases, there is no up-to-date data on the LED component available. The newest data was provided by US DOE (2012b), which stated that the high-power LED component actually caused 94.5 % lower environmental impacts compared to the 5 mm indicator LED found in the Ecoinvent (2010) database when compared on the basis of lumen output (US DOE 2012b). This difference in impact is largely due to the increase in the luminous flux package of the LED component, from 4 lumens produced by one indicator LED in the 2010 Ecoinvent database to 100 lumens produced by one high-brightness LED.

There is one major remaining question concerning not only specifically the LCAs of SSL products but LCAs of any type of product: the data quality. It must be noted that there is no sufficiently accurate data available on every component or product. The data even in the newest environmental databases does not cover all the unit processes involved in manufacturing and other LCA stages. Even if there was a unit process for the production of exactly the exact material/component, the LCIA data is often based on global data that may not correspond to the one in question. The data may not be correct from the point of view of geographic location or time. A one hundred percent accuracy is not possible in LCA studies, but rather LCAs should be used as an indicator of the main environmental impacts and their causes.

3 Conclusions

The LCAs found in the literature compare incandescent lamps, halogen lamps, CFLs, HPS luminaires, induction luminaires, FL luminaires, CMH luminaires, LED lamps, and LED luminaires. The methods of the LCAs varied. The differences were found in the stages of life cycle they included, how the life cycle stages were divided and modelled, what functional unit was chosen, and which energy source or average energy production mix was chosen for the use stage. Despite the apparent differences (especially the functional unit), the LCAs were found to conclude somewhat similar results.

Use (energy consumption) rules the environmental impacts of the light sources

The main conclusion practically in any LCA of a light source (lamp, luminaire) is that the use of the product causes the greatest environmental impacts over the life cycle due to the emissions from the energy production. The dominance of the use stage is the clearest in incandescent lamp (90 % or greater) due to its low luminous efficacy and simple manufacturing process free of hazardous materials. The manufacturing of CFL and LED lamps tends to have a higher share (up to 30 % of the total life cycle impacts from manufacturing but usually less than 10 %). The dominance of the use stage in the environmental performance of light sources including SSL products implies that the most significant environmental parameters are the luminous efficacy (lm/W) and the useful life. Thus, the replacement of low-efficacy lamps (incandescent lamp in indoor and HPM lamp in outdoor applications) by more energy efficient options brings a strong overall environmental benefit.

The LCAs reviewed use various electricity generation mixes, such as European, French, Finnish, UK and US average electricity. Few assessments consider the impact of the electricity production in a sensitivity analysis. It is evident that the environmental impacts of the energy in use-stage are sensitive to the mix of electricity generation. This is an issue that the consumer/user may affect themselves - i.e., the environmental impacts of the light sources are reduced when using low-emission electricity, such as hydropower. In addition, the energy production is pushed by political decisions towards low-emission energy sources, thus reducing the importance of the use stage and increasing the environmental importance of other life cycle stages of the energy using products. As a conclusion, the change towards light sources of high luminous efficacy is recommended regardless of the energy source used. However, the greatest environmental benefits are achieved when the two changes (lamps of high luminous flux and low-emission energy production) occur simultaneously. The change to renewable energy production may reduce the environmental impacts more than the change from an incandescent lamp to a CFL (Welz et al. 2011) but this strategy doesn't account for additional infrastructure requirements of a higher current carrying capacity of the electricity distribution system.

Manufacturing stage causes the second greatest environmental impacts

The manufacturing was modelled to include either the raw material acquisition and the manufacturing processes or only one or the other. The LCAs found that the manufacturing of an incandescent lamp caused approximately 1-7 %, a CFL 1-30 % and an LED lamp 2-20 % of the

total life cycle impacts on the average. It must be noted that single environmental impact categories may have higher scores, e.g., in case of CFL or LED lamp the manufacturing was found to cause approximately 50% of hazardous waste to landfill and 40% of human toxicity potential (DEFRA 2009). Generally, the environmental impacts in CFL manufacturing are due mainly to the ballast (printed circuit board and components), while the LED lamp manufacturing caused environmental impacts primarily due to the aluminium heat sink. However, today there are several new LED lamp designs on the market that have greatly reduced or completely eliminated aluminium heat sinks. Some use thermoplastic materials for heat sinks, and others, such as the new Philips SlimStyle lamp have completely eliminated the aluminium heat sink.

Thus while the overall environmental impact of efficient lighting such as CFL and LEDs is significantly lower than incandescent lighting, challenges still remain in terms of manufacturing and disposal stage impacts for these lamps. It should also be noted that in these stages, LED lamps do not currently offer a significant benefit over CFLs. Now, if we suppose that energy is now coming at major part from renewable sources, then use phase of the product will be less impacting for the environment. In that case and assuming that we need at least 4 or 5 CFL to achieve the same number of megalumen-hours than 800 lm LED lamp with 50000 h of lifespan, LEDs will be less impacting than CFLs. The impact linked to manufacturing and disposal phase for 4 or 5 CFLs would be larger compared to that expected for just 1 LED lamp. However, if LED lamp lifespan is limited to 20000 h (due mainly to its driver lifespan) then CFL and LED solutions are equivalent if LED lamp overall efficacy stays lower than 80 lm/W.

Other life cycle stages, such as transport, packaging and end-of-life, are negligible in the total life-cycle perspective. However, in certain environmental impact categories, they may have a notable effect.

A variety of functional units

A number of different functional units are used in the LCAs of light sources. The functional unit is a key term in the LCA and it is defined as the “quantified performance of a product system for use as a reference unit” (ISO 2006a). It is a unit to which all the inputs; outputs and the possible environmental impacts are proportioned. It should be related to the function of the product system, which, in case of lamps and luminaires, is generally to illuminate, to provide light.

The lumen-hour seems to be an appropriate and easy-to-use functional unit of light sources. However, it does not relate to the actual illumination but only to the luminous flux and time (quantity of light). Yabumoto et al. (2010) and Tähkämö (2013) showed that the choice of the functional unit affects the results of the LCA. Yabumoto et al. (2010) compared CFL, FL and LED lamps (both cool and warm white light sources). In case of a functional unit combining luminous flux and time, FL lamp was the most favourable, while the comparison based on floor illuminance and time created the lowest impacts by the LED and FL lamp. However, the results depend on the lamp type (warm/cool white). They also considered a future LED lamp that will perform very well to the luminous efficacy point of view, all other aspects like materials, components, etc., have been neglected.

Tähkämö (2013) analysed an incandescent lamp, CFL, and LED lamps, and used four functional units in this streamlined LCA study: 1 piece of lamp, 1 megalumen-hours, 1 h, and a direct illuminance at 1 m distance on a 1 m² square surface per hour. It was found out that the primary energy consumption of the life cycle (manufacturing and use) was similar in case of any functional unit except for a lamp-based comparison. However, this applies only to the comparison of the light sources for the same application, e.g., omnidirectional household lamps.

As has been explained above the choice of the functional unit is fundamental for LCAs. Our analysis shown that the most coherent functional unit that is applicable in any case is the megalumen-hour. But, for specific applications, like interior and street lighting the flux is not the main parameter, in these applications the illuminance and its special distribution are more important facts. Using a functional unit as megalumen-hour/lx@1m in the domain of interior lighting may be more relevant. In any case, we still recommend using the megalumen-hour for any future study because it allows technology comparison regardless of the usage.

Answering the research questions of life-cycle and comparison

The environmental impacts of SSL (LED) products are similar with the ones of other energy-efficient light sources, such as CFLs. LED lamps and luminaires, likewise (C)FL technology, have generally found to cause significantly less environmental impacts than conventional, inefficient light sources, such as the incandescent lamp. The LCAs indicate that the environmental impacts from the manufacturing of LED products are greater than the manufacturing of other light sources, but if lifespan of LED lamps is at least equal to 40000 and its luminous efficacy higher than 90 lm/W this impact is compensated by less energy consumed during the use phase of the product. The material contents of the LED lamp have been found to be similar with the material contents of other electronic devices (cell phone). However, the LCA results have found to depend strongly on the assumed useful life of the product. However, the definition of the useful lifespan of the product is not strait forward the L70 metrics used today may not be appropriate because difficult to verify and may neglect some issues like driver failures. The best metrics could be the average observed life in a real situation, but today this is impossible to establish.

It should be noted that the comparison of LED-based products with conventional lighting technologies is not always in favour of solid-state lighting. In professional indoor lighting (tertiary, offices, etc.), the T5 linear fluorescent lamp luminaire was the best-rated product (DEFRA 2009).³ In the consumer market, LED lamps represent an interesting alternative to the CFL but the environmental benefits were not clearly established, given the 5% to 20% typical uncertainty of the published LCAs. In outdoor lighting, Dale et al. (2011) showed that the environmental impacts of LED street lighting luminaires are comparable with those of existing efficient and long-lasting technologies such as the induction luminaire. However, the improvement of LED technologies implies that LED lighting products would be even more

³ This is one of the first studies for this technology area. We need to remind readers that performance has changed much since.

environmentally friendly due to the development of luminous efficacy, life, manufacturing process yield and resource consumption in the future. To verify this, regular updating is needed.

Strongest contributors to the environmental impacts of SSL products

The main contributor to the environmental impacts of LED products is the energy consumption in use. The energy consumption in use is very sensitive to the used energy source. In case of a low-emission electricity production, the manufacturing may become dominant of the life cycle impacts. We recommend here to develop an algorithm for calculating the impact of energy consumption during "use" phase by adjusting the energy mix. This would make each set of research findings transferable to different economies with different energy mixes.

The environmental impacts from the manufacturing of LED lighting products are mainly caused by the manufacturing of the LED package, the driver (electronics) and aluminium parts.

Main challenges and difficulties in LCA of LED lamp/luminaire

Many difficulties were identified in the analysis of LCAs of LED products and other light sources. The lack of data makes it difficult to model especially the raw materials, manufacturing processes and end-of-life. The life of the LED product is uncertain, since its testing is challenging and it is not only the technological life (25 000 h to 100 000 h according to the manufacturers) that affects the LCA results. The definition of an LED product requires attention so that they are compared to other light source technologies in a consistent manner. Especially the definition of the functional unit and the system boundaries need to be clearly defined.

The life of an LED product affects the LCA results. The life of the LED light source in LCAs is generally assumed to be the rated life given by the manufacturer. This life is often based on theoretical assumptions. Reliability tests and field studies often reveal premature failures, whose rate was not accounted for. Similarly, gradual lumen depreciation was not taken into account in the LCAs. Only few LCAs (Osram 2009, DEFRA 2009, Slocum 2005) acknowledge the lumen depreciation but none of them provide clear method or results on it. Osram (2009) stated the lumen depreciation to be too small to impact the results but no details were provided. In addition, the actual product life may not be the same as the useful life of the product: In case of technological development, the product may be replaced before its rated life ends. In addition, it is not only the life of the LED package but the whole LED luminaire including all the components whose life is of interest. Casamayor et al. (2013) reported that the failures of LED lighting products were often due to the driver failures according to the LED lighting product manufacturers.

Related to the life of the LED product, another difficulty is to assess the user behaviour. A long-life product may be replaced before it reaches its end of useful life for several reasons: the premises reach their end of life or are refurbished, or the product becomes obsolete, out of fashion, or a new generation of products provides greater energy savings. These reasons may cause the allegedly long-life products to be replaced before the end-of-life. Thus, it is a significant risk to base an LCA on a life assumption that is long compared to the unknown real

usages. A sensitivity analysis on this is recommended. A suggested approach is to **compute the environmental indicators as a function of time of use, not the product life.**

Analytical Uncertainties

Despite the efforts put into the research of environmental aspects of LED lighting products, uncertainties remain in this field. First, the environmental databases should provide updated LCIA data of LEDs and other electronics. Second, there is a need for creating common rules which to use in the LCAs of light sources. Two simplified models for light source LCAs have been created (Tähkämö 2013) for general use but detailed PCRs are potentially needed in the evaluation of the environmental impacts of lighting applications. Third, the scarcity of the materials used in LED products remains a concern. Fourth, more data is needed on the end-of-life of LED products (recycling statistics, recycling process data). Overall, one cannot emphasize enough the importance of the correct terminology, the transparency of the LCA method, and the details, data and data sources provided in the LCA report in order to reduce the uncertainty of the LCA and to make the most of its results.

The most difficult aspect of assessing the environmental impacts of an SSL product is **the collection of data concerning the manufacturing and composition of the LED package.** Both the die manufacturing and the packaging (front-end and back-end processes) are extremely confidential and complex. The US DOE (2012b) report gives a view to the LED product manufacturing including raw materials, process energy consumption and process chemicals. However, data updating is needed as LED manufacturing develops constantly. In addition, manufacturers may use various manufacturing technologies.

The concern in material contents of LED lighting products can be addressed by testing products compliant to RoHS Directive (and/or increased transparency by manufacturers). The studies by US DOE (2013) and Lim et al. (2011, 2013) were conducted for LEDs and lamps available in the US market, where no federal legislation on the hazardous substances in electrical and electronic equipment exists, except for a state-wide regulation in California similar to the RoHS Directive in the EU. A comparison of the LED lighting products to other electronic products would clarify the level of the environmental impacts of LED products.

Another interesting question is the extraction of indium and rare earth elements (yttrium, cerium, etc. used in phosphors). These substances would be most likely cut off (i.e. be excluded) from the bill of materials, given their weak mass fraction⁴ and the cut-off rules usually applied by LCA engineers (1% to 5%), which may not therefore fully reflect the contribution of lighting

⁴ Yttrium, cerium and other rare earth elements are crucial to the production of phosphors for white LEDs. The fast growth of electronics technologies goes with an increasing extraction of rare earth elements. The SSL industry is largely involved in this growth, together with other electronics sectors. In performing an LCA, the environmental indicators do not take this acceleration into account. The abiotic (resource) depletion potential (ADP) indicator, expressed in kg equivalent Sb (antimony), is particularly concerned with this phenomenon, as its values are calculated from quantities still available at the surface of the Earth and the exploitation rate.

manufacturing to the cumulative impact of the growth of electronics consumption to impacts of the increased extraction rates of these elements.

Light Pollution

One of the most obvious environmental impacts of lighting is the light emitted or reflected towards the sky that contributes to the light pollution. This light contributes to the formation of a night halo resulting of optical diffusion by the air molecules and aerosols.

A defect in the LCA of light sources is the lack of an environmental impact category for the light pollution. Light pollution and light at night affects humans, fauna and flora on many levels, such as the hormone levels and circadian rhythms, predator-prey relationships, and blooming. An environmental impact category is needed in order to consider also the environmental impacts of the light itself in an LCA. This would tie the impact of the light spectrum to the environmental impacts. LED luminaires are able to produce shorter (bluish) wavelengths and replace the yellowish HPS luminaires. Another benefit of the LED luminaires is that the light may be distributed very precisely avoiding light pollution. However, this additional analysis would require specification of the installation and application details.

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