Department of Electronics, Lighting Unit

Life cycle assessment of light sources – Case studies and review of the analyses

Leena Tähkämö

Aalto University

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Abstract

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Abstract

Lighting is a major global consumer of electricity and undergoing drastic changes due to legislative and voluntary measures. Widely-used conventional light sources, such as incandescent lamps and high pressure mercury lamps, are banned from the European Union market. The number of light sources on the market is expanding especially regarding the LED lamps and luminaires. These major changes in the lighting sector create a need for evaluating the environmental performance of light sources, especially as the changes are justified by the environmental aspects, such as energy consumption.

The life cycle assessment method is standardized on a general level, but no established rules exist for conducting a life cycle assessment of light sources in detail. In most cases, it is impossible to directly compare the results of different assessments. Because of the major changes in the lighting market, it is useful to assess the environmental impacts of various light sources in similar methods.

The work addresses this problem by presenting two models, a simple and an extensive one, for conducting the life cycle assessment of light sources rapidly and in a transparent, comparative way. The models are developed on the basis of four case studies presented in the work and a review to the life cycle assessment found in the literature. Both models are simplified, and they recommend the key parameters of the life cycle assessment: functional unit, stages of the life cycle, environmental impacts, and energy source in use stage.

Four case studies were conducted in the work: two life cycle assessments of a fluorescent lamp luminaire and an LED downlight luminaire, one life cycle cost analysis of street lighting luminaires, and one analysis combining both life cycle assessment and life cycle cost analysis of non-directional lamps.

The case studies and the review of the previous life cycle assessments concluded similar findings despite the differences in the methods, scopes and evaluated light sources. The main conclusion of the life cycle assessments was the clear dominance of the use stage energy consumption. The environmental impacts of the use were found to be sensitive to the life of the light source and the used energy source. The dominance of the use stage was the clearest in light sources of low luminous efficacy and low manufacturing efforts and when using high-emission energy sources. The manufacturing was usually the second significant cause for average environmental impacts. The importance of the manufacturing is estimated to increase by a more detailed assessment of the manufacturing processes. The average environmental impacts of other life cycle stages, such as transport and end-of-life, were found practically negligible, but possibly notable in a certain environmental impact category.

Keywords life cycle assessment, life cycle cost, environmental impacts, lighting

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Tiivistelmä

Valaistus on merkittävä globaali sähkönkuluttaja ja sen takia siihen kohdistuu sekä lainsäädännöllisiä että vapaaehtoisia muutospaineita. Euroopan unionin markkinoilta on poistumassa paljon käytettyjä perinteisiä valonlähteitä, kuten hehkulamppu ja suurpaine-elohopealamppu. Markkinoille on tullut ja on tulossa paljon uusia tuotteita, erityisesti LED-lamppuja ja -valaisimia. Nämä muutokset ovat luoneet tarpeen arvioida valonlähteiden ympäristövaikutuksia, erityisesti koska muutoksia usein perustellaan ympäristöseikoin.

Elinkaariarviointi on standardisoitu yleisellä tasolla mutta yksityiskohtaisia ohjeita nimenomaan valonlähteiden elinkaariarvioinnille ei ole. Sen vuoksi on yleensä mahdotonta verrata arviointien tuloksia. Koska tuotekirjo kasvaa ja muuttuu, on tarpeellista arvioida eri valonlähteiden ympäristövaikutuksia samoin menetelmin.

Väitöskirjassa kehitetään kaksi mallia valonlähteiden elinkaariarviointimenetelmälle. Nämä kaksi mallia, yksinkertainen ja laaja, yksinkertaistavat elinkaariarviointia, jotta se nopeutuisi ja olisi läpinäkyvä. Mallit kehitettiin neljän väitöskirjatyössä tehdyn arvioinnin ja jo olemassa olleiden, kirjallisuudesta löytyneiden elinkaariarviointien pohjalta. Mallit esittävät suositukset valonlähteiden elinkaariarvioinnin merkittävimmille määreille: toiminnalliselle yksikölle, huomioitaville elinkaaren vaiheille, ympäristövaikutuksille ja käytönaikaisen energian mallintamiselle.

Väitöskirja esittelee neljä osatutkimusta: kaksi elinkaariarviointia LED-syväsäteilyvalaisimelle ja loistelamppuvalaisimelle, yksi elinkaarikustannusanalyysi katuvalaisimille ja yksi yksinkertaistettu elinkaariarvioinnin ja elinkaarikustannusanalyysin yhdistävä tutkimus ympärisäteileville lampuille.

Osatutkimusten ja kirjallisuuden elinkaariarviointien tarkastelun johtopäätökset ovat samansuuntaisia menetelmien, soveltamisalan ja tarkasteltujen valonlähteiden eroavaisuuksista huolimatta. Käytönaikaisen energiankulutuksen todetaan olevan määräävä tekijä valonlähteiden ympäristövaikutuksissa. Väitöskirjassa havaitaan käytönaikaisten ympäristövaikutusten riippuvan valonlähteen polttoiästä ja käytetystä energiamuodosta. Käyttövaiheen havaitaan olevan merkittävä erityisesti heikon valotehokkuuden valonlähteillä, joiden valmistusvaihe on yksinkertainen. Käyttövaiheen merkittävyyteen vaikuttaa käytönaikainen energialähde. Valmistusvaihe todettiin tyypillisesti toiseksi merkittävimmäksi elinkaaren vaiheeksi. Valmistuksen merkitys kasvaa valmistusprosessien ja materiaalien yksityiskohtaisemmalla tarkastelulla. Muiden elinkaaren vaiheiden, kuten kuljetuksen ja käytöstä poiston, keskimääräiset ympäristövaikutukset ovat käytännössä merkityksettömiä, mutta yksittäisissä ympäristövaikutusluokissa jopa merkittäviä.

Avainsanat elinkaariarviointi, elinkaarikustannus, ympäristövaikutus, valaistus

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Résumé

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Résumé

Le domaine de l'éclairage, gros consommateur mondial d'électricité, connaît actuellement des changements de part des mesures législatives et volontaires. Les sources lumineuses conventionnelles, comme les lampes à incandescence et à mercure haute pression, sont interdites à la vente dans l'Union européenne. Ces changements dans le domaine de l'éclairage ont ainsi créé un besoin d'évaluation de performance environnementale des sources de lumière, d'autant plus que les changements sont souvent justifiés par les aspects environnementaux.

La méthode d'analyse du cycle de vie est normalisée à un niveau général. Pourtant, il n'existe pas de règles établies pour réaliser une analyse de cycle de vie en détail pour les sources de lumière. Par conséquent, il est impossible de comparer directement les résultats qui proviennent généralement d'analyses différentes. En outre, le nombre de sources lumineuses, en particulier des lampes et luminaires à LED, augmente sur le marché. Ainsi, il serait utile d'évaluer des sources de lumière de façon similaire.

Ce travail aborde le problème en présentant deux modèles, l'un simple et l'autre étendu, afin d'effectuer une analyse du cycle de vie des sources lumineuses rapidement et en toute transparence. Les modèles sont développés sur la base de quatre études de cas présentées dans la thèse et l'examen des analyses du cycle de vie trouvées dans la littérature. Les deux modèles simplifiés recommandent les paramètres clés de l'analyse du cycle de vie: une unité fonctionnelle, les étapes du cycle de vie, et la source d'énergie en phase d'utilisation.

Quatre études de cas ont ici été réalisées: deux analyses du cycle de vie d'un luminaire à lampe à fluorescence et d'un luminaire encastré à LED, une analyse des coûts du cycle de vie des luminaires d'éclairage public , et une analyse combinant à la fois l'analyse du cycle de vie et l'analyse du coût du cycle de vie des lampes non-dirigées.

Des résultats similaires ont été trouvés dans les études de cas et l'examen des analyses de cycle de vie antérieures malgré les différences dans les méthodes, et les champs de l'étude. De tous les impacts environnementaus du cycle de vie, c'est la consommation d'énergie durant la phase d'utilisation qui prédomine. Il a été constaté que les impacts environnementaux sont corrélés à la durée de vie de la source lumineuse ainsi que la source d'énergie utilisée. La phase d'utilisation prédomine le plus clairement sur les impacts en cas de faible efficacité lumineuse et fabrication simple. Généralement, la fabrication est la deuxième cause la plus importante des impacts environnementaux moyens. L'importance de la fabrication devrait augmenter par l'analyse plus détaillée des procédés et matériaux de fabrication. Les impacts moyens des autres étapes du cycle de vie, tels que les transports et la fin de vie, sont pratiquement négligeables. Cependant, ils pourraient peut être s'avérer notables dans une certaine catégorie d'impacts.

Mots-clés analyse du cycle de vie, coût du cycle de vie, impacts environnementaux, éclairage

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Preface

The research work in this jointly-supervised thesis was conducted at the Lighting Unit of Aalto University School of Electrical Engineering and at the LAPLACE (Laboratoire Plasma et Conversion d'Energie) Laboratory of Université Paul Sabatier. Part of the work was carried out in the project "SolarLED" funded by the Finnish Funding Agency for Technology and Innovation; the Finnish Transport Agency; the city of Helsinki, Espoo, Vantaa, Tampere and Porvoo; Helsingin Energia; Oy Turku Energia; SITO Oy; Philips Oy; Oy Osram Ab; Naps Systems Oy; iGuzzini Finland & Baltic Oy; Easy Led Oy; Lumi Group Oy; Valopaa Oy; Oy Modines Ltd; Tepcomp Oy; Laukamo Plastcomp Oy; Insinööritoimisto Lausamo Oy; and Sähkötekniikka Oy. Part of the work was carried out in the project "CITADEL" funded by the French Agency for the Environment and Energy Management (ADEME). I acknowledge the collaboration with Helvar Oy Ab and Toni Anttila from Alppilux Oy in one of the case studies.

It would have been impossible to finish the thesis without the support of several people. I start by thanking my supervisors Professors Liisa Halonen and Georges Zissis for their support throughout the thesis project and enabling the jointly-supervised doctoral thesis in the first place. It has been a real challenge and an unforgettable journey. I am grateful to my thesis advisor Dr Marjukka Puolakka for her advice and support in the process.

I would like to thank the pre-examiners Professor Sermin Onaygil from Istanbul Technical University and Research Professor Ilkka Savolainen from VTT Technical Research Centre of Finland. I thank Professor Christian Glaize from Montpellier II University for being the pre-examiner in the thesis acceptance process in Université Paul Sabatier. Your valuable comments have helped me to improve the thesis. I wish to thank Professor Marc Fontoynont from Aalborg University and again Research Professor Ilkka Savolainen from VTT for agreeing to be my opponents in the defence.

I acknowledge the Doctoral Program in Electrical Energy Engineering (DPEEE), Walter Ahlström Foundation, French Institute of Finland, Research Foundation of Helsinki University of Technology, and Finnish Society of Electronics Engineers for financially supporting the work. I want to thank Pia Lindh for taking care of the administrative work regarding the research exchange in spring 2011.

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I cannot thank enough my friends in Finland and abroad, who ensured that I have life outside the thesis working process. Special thanks goes to the friends abroad that have made me feel at home during my journeys. Thank you Hanna, Miika, Arwa, Natalia and Silvia.

I am deeply grateful to my family. I want to express my deepest gratitude to my parents who have given me a feeling that I am able to do whatever in life if I just put my mind to it. I express my warm gratitude to my grandmother Linda for her great example of perseverance and hard work. I am grateful to my sister for all the support she has given me and her proofreading services. Last I thank Petri for being my rock. Thank you for your love, care and incredible patience.

Espoo, June 2013

Leena Tähkämö

Contents

List of abbreviations and symbols

Abbreviations

ADP	abiotic depletion potential
AP	acidification potential
CCT	correlated colour temperature
CFL	compact fluorescent lamp
CIE	Commission Internationale de l'Eclairage
	International Commission on Illumination
CMH	ceramic metal halide
CMOS	complementary metal oxide semiconductor
CRI	colour rendering index
CO_2-eq.	carbon dioxide equivalent
CSTB	Centre Scientifique et Technique du Bâtiment
	French Scientific and Technical Centre for Building
DEFRA	Department for environment, food and rural affairs
DIALux	lighting design software
DOE	Department of Energy
DRAM	dynamic random access memory
EIO	economic input-output
ELCD	European Reference Life Cycle Database
EoL	end-of-life
EP	eutrophication potential
ETSI	European Telecommunications Standards Institute
EU	European Union
GDP	gross domestic product
GWP	global warming potential
HID	high intensity discharge
HPM	high pressure mercury
HPS	high pressure sodium
HTP	human toxicity potential
ICT	information and communication technology
ISO	International Organization for Standardization
LCA	life cycle assessment
LCC	life cycle cost

LCIA	life cycle impact assessment
LCI	life cycle inventory
LCSA	life cycle sustainability assessment
LED	light-emitting diode
MH	metal halide
NF	norme française; French norm
ODP	ozone depletion potential
PB	payback time
PCB	printed circuit board
PCR	product category rule
POCP	photochemical ozone creation potential
REACH	registration, evaluation, authorisation and restriction of chemical substances
RoHS	restriction of the use of certain hazardous substances
RV	residual value
SLCA	social life cycle assessment
SPB	simple payback time
SR	surround ratio
THT	through-hole technology
TI	threshold increment
UNEP	United Nations Environment Programme
US	United States (of America)
WEEE	waste electrical and electronic equipment

Symbols

C_i	investment cost
C_o	operating cost
i	rate of interest
L_{ave}	average road surface luminance
n	year
U_l	longitudinal luminance uniformity
U_o	overall luminance uniformity

1 Introduction

Environmental impacts in general have become a concern increasingly from the 1960's. The scope of the concern was first local but has grown to global questions with the globalization and internationalization. Traditionally, the environmental concerns have lain in heavy process industry, intensive agriculture and use of chemicals. Numerous methods have been introduced to tackle the environmental hazards, such as changing the legislation, creation of voluntary programs, informing the consumers, market surveillance, and commercial sanctions. The energy consumption became an environmental concern in the 1970's. Since then, energy efficiency has been an increasingly important issue not only from pollution perspective or as a marketing argument but also from the point of view of the sufficiency of energy sources.

The energy efficiency is related to the discussion of the enhancement of global warming. It has been stated that unless fast, drastic measures are taken to reduce the global greenhouse gas emissions, the overall costs of the climate change will be equivalent to losing at least 5 % of global gross domestic product (GDP) annually [1]. In addition, Stern [1] estimates that the costs of the actions to avoid the worst impacts of climate change would remain below 1 % of global GDP annually. It is debatable whether the impacts of the enhanced climate change are noticeable already today [2] or after decades [1].

The environmentalism has evolved from the energy concerns to a wider scope: life cycle. The life cycle environmental impacts have become an issue in the 2000's when the holistic approach has been emphasized. The environmental impacts of energy-related products, including electrical and electronic equipment, have become an issue over the last decade. In the European Union (EU), the energy-related products, to which light sources belong, are noted as a significant cause for environmental impacts due to the consumption of energy and raw materials. The increasing concern of climate change and other environmental impacts has made the life cycle approach increasingly used, since, by addressing the total life cycle, the *overall* picture of the environmental aspects can be seen. The study of the environmental aspects is becoming mainstream in many industry sectors, and consumers and organizations acknowledge increasingly the environmental aspects of their actions.

Lighting sector consumes approximately 19 % of the global electrical energy [3]. Thus, lighting is undisputedly an important part of the reduction of energy consumption. As the lighting sector is undergoing major changes due to the targets to increase energy efficiency and improve the quality of lighting, it is appropriate to study the environmental aspects of light sources.

This thesis is a monograph that presents four case studies of light sources from the life cycle perspective: two cases of life cycle assessments (LCAs), one case of LCA and life cycle cost (LCC) analysis combined, and one case of LCC analysis. Three of the cases are based on published scientific papers [4, 5, 6] and one based on a conference paper [7]. Studies based on publications [6] and [7] are significantly developed from the original publications in this work.

1.1 Background

The background for environmental thinking can be considered to date from the 1960's and the publication of the book "Silent spring" by Rachel Carson in 1962 [8]. At the time, the interest of the environmental movement was in the excessive, careless use of chemicals, such as pesticides.

The environmental movement has evolved from the emphasis of chemical spills and energy shortage to a more overall sustainability. The sustainability, or sustainable development, refers to a holistic view. The sustainability is defined in the Brundtland report as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" [9]. Total sustainability assessment is a recent step in the assessment of life cycle impacts. Sustainability assessment contains three pillars: environmental, economic and social sustainability. The environmental LCA and economic LCC analysis are the most established ones, while there is no established procedure for the assessment of the social aspects. It is more challenging to assess the social impacts due to the regional resolution [10, 11]. In addition, it has been argued that it may be impossible or even unnecessary to assess the social impacts in detail but in a larger scale [12].

The environmental aspects of electrical and electronic equipment have originally concentrated on the substance restrictions, e.g., the directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS) in the EU and similar legislation in China, and in defining the responsibilities in the end-of-life (EoL), e.g., the directive on waste electrical and electronic equipment (WEEE) in the EU.

Depending on the type of the electrical and electronic equipment, the equipment may be in the scope of other legislation, such as low voltage directive (2006/95/EC) [13]. In addition, the material restrictions, such as the regulation on the registration, evaluation, authorisation and restriction of chemical substances (REACH) [14], apply to electrical and electronic equipment.

The EU acknowledges the importance of environmental thinking. They have introduced a so called 20-20-20 policy [15] in which three targets shall be met by 2020: reduction of greenhouse gas emissions by at least 20 % compared to year 1990 level, 20 % of the energy to be renewable, and an increase of 20 % in energy efficiency. The 20-20-20 policy is parallel to the ecodesign legislation that aims at taking the whole life cycle of the energy-related products into account.

Lighting consumes a notable share (19 %) of global electrical energy [3]. The fluorescent lamp and high intensity discharge (HID) lamp technologies have traditionally accounted for the major shares of the global lighting electricity consumption: 62 % and 27 % respectively in 2005 [3]. The share of light-emitting diode (LED) technology has risen from practically inexistent to a notable share: The share of LED technology is estimated at 6.2 % in 2010 and 9 % in 2011 in the EU, but it is strongly on the increase [16, 17]. It is estimated that 45 % of general lighting will be provided by LED technology in 2016 and 70 % in 2020 [17].

The background for environmental thinking regarding light sources lies strongly in the legislation. There have been energy-saving campaigns and programs from the early days of compact fluorescent lamps (CFLs), but it was only after the Ecodesign directive and its implementing measures when the energy efficiency of the light sources actually started to affect the buying decisions. The higher purchase price of the CFLs compared to incandescent lamp has hampered the more frequent use of CFLs despite the savings in life cycle costs.

As the energy consumption is one of the undisputed key environmental parameters of energy-related (formerly energy-using) products, it is natural that the ecodegisn legislation in the EU [18] concentrates on improving the energy efficiency of the products. Lighting products are listed in the Ecodesign directive as one of the product group having a significant environmental impact and a great potential for reducing environmental impacts without causing excessive costs [18]. In addition, lighting, more precisely the switch from incandescent lamps to LED lamps in residential application, is acknowledged as a measure in which the global greenhouse gas abatement is cost efficient (Figure 1) [19].

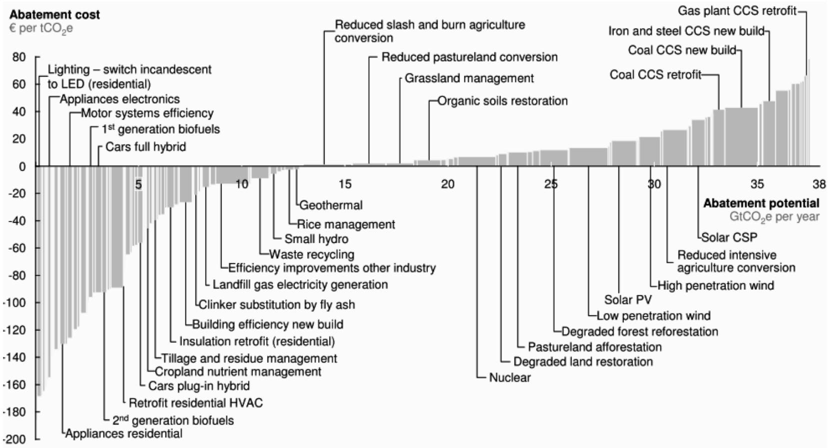


Figure 1. Global greenhouse gas abatement cost curve beyond business-as-usual in 2030 [19]. Reproduced with permission.

In the EU, there are currently three Ecodesign regulations of lighting products in force: fluorescent lamps without integrated ballast, high intensity discharge lamps, and ballasts and luminaires able to operate such lamps [20]; non-directional household lamps [21]; and directional lamps, LED lamps and related equipment [22]. In addition to establishing the regulations for luminous efficacy or energy efficiency of the lamp, the three Ecodesign regulations set product information requirements and mandatory criteria for a number of functional characteristics, such as lamp survival factor, lumen maintenance, starting time, lamp power factor, and colour rendering index.

The total life cycle environmental impacts of the light sources are currently interesting due to the importance of lighting sector in the energy consumption and the legal restrictions based on life cycle approach. The phase-out of many conventional lamps, e.g., incandescent lamps and high pressure mercury (HPM) lamps, from the EU market has created much discussion on the remaining lighting technologies and their environmental friendliness. The material contents of the LED products have become a concern after the publication of the study by Lim et al. [23]. The mercury content in the fluorescent lamps is also an environmental concern. It is estimated that the net mercury emission over life cycle is reduced when changing from incandescent to CFL lamps [24, 25, 26]. The rate of reduction depends on the used energy sources. An appropriate end-of-life waste management of fluorescent lamps is encouraged [27]. In addition, the RoHS directive in the EU restricts the amount of mercury in fluorescent lamps: e.g., in CFLs of less than 30 W only 2.5 mg per burner is allowed from 1 January 2013 [28].

1.2 Research problem

It is necessary to act immediately and effectively in order to reduce the energy consumption and the greenhouse gas emissions. Lighting in general is a notable global energy consumer, and as such, the measures for reducing the energy consumption of lighting are effective and appropriate. However, there is debate on the environmental aspects of light sources other than the energy consumption during operation, such as the material contents and end-of-life treatment. In addition, the characteristics and function of the light sources are generally excluded from the environmental discussion but, depending on the application, it is very important to determine where, when and what kind of light is needed.

The research problem of the thesis is the lack of established rules for the LCA of light sources. The lack of such rules and common methods creates distortion and makes it difficult to numerically compare the results of the LCAs. Yet, the comparison is possible on a qualitative level, e.g., in Tähkämö et al. [29]. A qualitative comparison is possible if the results are translated into a common unit, e.g., primary energy [30].

The lighting sector is filled with different light sources of different shapes and sizes, which makes it difficult to compare their environmental and economic performance. In addition, the LED technology provides new possibilities for manufacturers to design luminaires, lamps, components and packages containing LED chips. It is challenging to compare these various-shaped LED light sources to conventional lamps and luminaires. It is a major question in the LCA of light sources that on which basis the light sources should be compared. The basis for the comparison in the LCA is the functional unit that can be luminous flux, lumen-hours, hour, illuminance, or something else.

1.3 Aim of the work

The primary aim of the work is to create a model for a method for conducting the LCA of light sources. The model is needed for the simplification of the LCA method in such a way that all major environmental aspects are taken into account. The standards for the LCA are broad and no detailed guidelines exist regarding LCAs of light sources. In addition, the lighting sector is undergoing a major change from conventional light sources, such as incandescent lamp in households and high pressure mercury lamps in outdoor lighting, to modern, energy-efficient alternatives, such as LED lamps and luminaires, due to legislative and voluntary measures.

The model is developed on the basis of four environmental and/or economic analyses of light sources conducted in this work. The four cases represent various lighting applications and light source technologies. The idea is to study the characteristics of each case and to discuss the methodology, conclude the findings and suggest the model.

The work addresses four lighting applications: non-directional lamps typically used in households, a downlight luminaire used in commercial buildings, a luminaire for industry premises, and street lighting luminaires. The four cases were conducted in different methods of LCA and/or LCC analysis due to the limited data and resource availability but also to study different methods in order to analyse the differences of the methods. On the basis of the case studies, the thesis concludes the findings and suggests an appropriate method for conducting the LCA of light sources in general. The LCC analyses within the work are intended for extending the sustainability point of view and not to concentrate only on the environmental aspects.

A secondary aim of the work is to analyse the previous LCAs of light sources and the LCAs conducted in this work to increase the knowledge on the environmental aspects of light sources. The main findings of the LCAs are identified in the work.

2 Life cycle assessment

Life cycle assessment (LCA) is a tool for systematically evaluate the potential environmental impacts of a product or a service over its life cycle. It compiles the inputs, outputs and the potential environmental impacts of the analysed system. Numerous LCAs have been conducted and published on various products and services during the last decade, and the LCA has been established as an environmental tool for decision-making. The LCA provides information on the environmental performance of the products for many purposes, such as for the public procurement, enactment of the legislation, and in purchase decision of the ecologically aware consumers.

The LCA is conducted including a whole life cycle from raw material acquisition to end-of-life, i.e., from cradle to grave, or for a part of the life cycle. The partial life cycle enables the analysis of certain stages of the life cycle in detail, while the LCA of a whole life cycle gives an overview of the total environmental impacts and is thus a holistic approach. Nevertheless, the total LCA requires a large amount of data.

There are several ways to divide the life cycle into stages. An example of a life cycle is presented in Figure 2. In the example, the life cycle starts with the raw material acquisition and ends in the end-of-life containing multiple alternatives from reuse to final disposal. Similarly, it is possible to divide the stages differently, e.g., including the transport (distribution) separately or in each stage, or combining packaging, transport and installation into one stage: implementation.

There are no absolute rules on which stages to consider in an LCA, but it depends on the product system to be analysed. 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) [31]. In the LCA of light sources, use is typically the life cycle stage causing the greatest environmental impacts due to the energy consumption [29]. Generally, the LCAs of light sources analyse the raw material acquisition together with manufacturing, use, and end-of-life.

The LCA refers to an *environmental* LCA as a distinction among the economic and social analyses. The LCA method is defined in standards ISO

14040 [32] and ISO 14044 [33]. In addition, there are more detailed guidelines, e.g., product category rules (PCRs), for conducting LCA of certain products. PCRs describe the methods for creating an environmental product declaration, which is based on life cycle approach. PCRs provide detailed guidelines for conducting the LCA of a specific product.

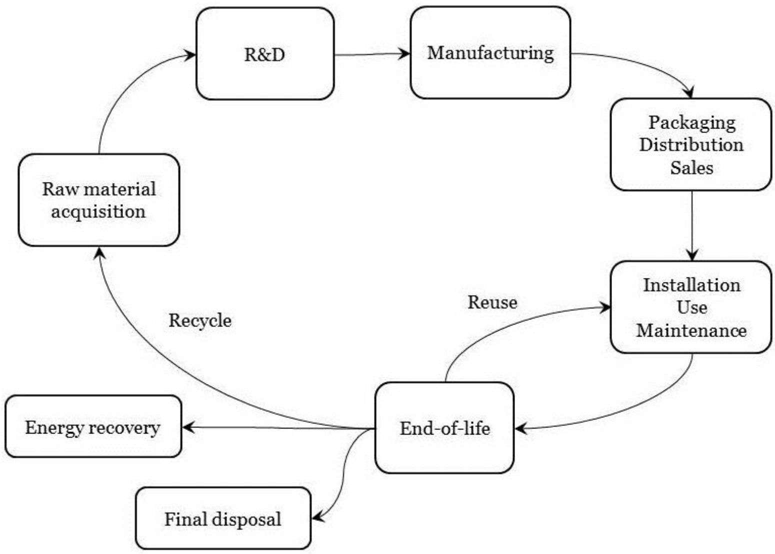


Figure 2. Example of the life cycle stages.

The ISO 14000 standard series includes a number of environmentally-related standards, such as the standards for environmental management system (ISO 14001 and ISO 14004) and the ones on environmental labels and declarations (ISO 14020-14025). ISO 14040 and 14044 standards establish the *general* methodology for LCA. The standards introduce the procedure for conducting the LCA and basic terms, such as the functional unit. Yet, the LCA standards are sufficiently broad that they can be applied to any product or service.

There are three types of LCA: process LCA, economic input-output (EIO) LCA and hybrid LCA. The process LCA is the traditional method that is described further in this chapter and used in the LCAs in this work. The process LCA is a detailed, process-specific assessment that enables the comparison of products. The EIO-LCA estimates the environmental impacts on the basis of the economy-wide, sector-level data. The EIO-LCA considers all direct and indirect environmental impacts included in the whole economic sector and is thus a comprehensive method. The hybrid LCA combines the strengths of the two other LCA types by using EIO-LCA method for some processes and conventional process LCA for the rest of the processes.

The conventional process LCA contains four phases: goal and scope definition, inventory analysis, impact assessment and interpretation (Figure 3). The LCA is an iterative method. It is a relative technique due to the use of a *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.

The goal and scope phase defines 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 included in the LCA. The cut-off rules are also defined. The inputs and outputs of the system to be analysed may be cut off on the basis of mass, energy or environmental significance [33].

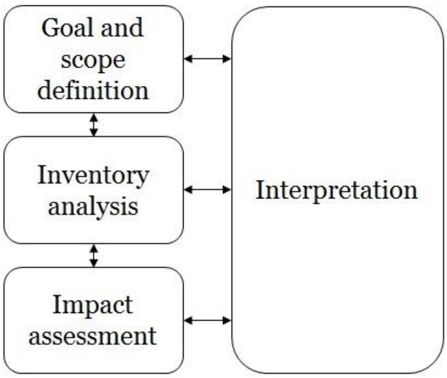


Figure 3. Phases of the life cycle assessment. Adapted from [32].

The life cycle inventory (LCI) analysis includes 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 to be studied 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 life cycle impact assessment (LCIA) calculates the potential environmental impacts. The impact assessment includes the selection of impact categories, category indicators, and characterization models. The LCIA assigns the LCI results into environmental impact categories. There are numerous impact categories to choose from, e.g., global warming potential, acidification potential, ozone depletion potential and human toxicity potential. The LCIA may include also the data quality assessment, e.g., uncertainty and sensitivity analyses, and optional grouping and weighting of the results.

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

The functional unit is a key parameter in the LCA, especially in comparative LCAs, in which two or more products are compared to each other. The functional unit should be "consistent with the goal and scope of the study", "clearly defined" and "measurable" [33]. In case of electricity production, the functional unit may be the production of 1 kWh of electrical energy. When it comes to light sources, the appropriate functional unit may be a specific amount of lumen-hours. The functional unit may be one piece of a lamp if the lamps possess comparable qualities, such as luminous flux, colour characteristics and luminous intensity distribution curve. To be more precise, the functional unit 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.

Despite the LCA standards ISO 14040 and ISO 14044 and a number of more detailed guides (e.g., PCRs), there are unlimited possibilities for conducting an LCA. There are no established rules for the parameters of the methodology, e.g., the choice of functional unit and used energy sources for the LCA of light sources. Thus, there is room for different assessments, but the results are not necessarily comparable.

2.1 Total sustainability assessment

Sustainability assessment refers to the life cycle sustainability assessment (LCSA) that contains three pillars: environmental, economic and social aspects. LCSA is defined as:

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

in which LCA stands for the environmental LCA, LCC life cycle costs, and SLCA social LCA [11, 34, 35]. The SLCA is the newest of the pillars and is currently being developed. The SLCA suffers from difficulties in establishing the methodology and the lack of data, but the general interest is increasing in acknowledging also the social aspect in the sustainability discussion [35].

The total sustainability assessment is a large and challenging entity to calculate over one product. LCA and LCC analyses are relatively easy to conduct on a single product: yet, there are many perspectives to consider, e.g., from the manufacturer's, consumer's or municipality's point of view [11]. 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 [36].

The total sustainability assessment gives a very profound view to the sustainability of a product system. However, it is difficult to conduct due to the three pillars and their differences in methodologies. In addition, there are no international standards for LCC or SLCA. Currently, the methodological difficulties lie mainly in the consistency of system boundaries in the three assessments [34, 35].

The social LCA is an assessment technique of social impacts that analyses products and services, and considers the entire life cycle. It evaluates the potential social and socio-economic impacts and gives a comprehensive view to the sustainability. In contrast to LCA that is based on physical quantities, the SLCA uses semi-quantitative and qualitative data. Thus, it is not always possible to express the impacts in relation to a functional unit in an SLCA [36]. The function of the product system needs to be defined as in the LCA. The SLCA may use subjective, organization-specific and geographic data but also generic data. The LCA uses frequently generic data for processes used worldwide, but the significance of geographical location is increasing in the LCA [36].

The SLCA provides information on the social aspects for the decision-making. It attempts to improve the performance of an organization and the well-being of the stakeholders [36]. The SLCA has the same structure as the environmental LCA and it is likewise an iterative process.

2.2 Life cycle costing

In contrast to conventional cost accounting, life cycle costing takes into account the costs occurring over the life cycle, i.e., the life cycle costs (LCCs). An example of the life cycle stages in an LCC analysis is presented in Figure 4. While the environmental life cycle in Figure 2 described the material and energy flows, Figure 4 expresses the monetary flows. Actually, each individual life cycle stage should include costs as input and revenue as output. The LCC analysis may consider the conventional costs of manufacturing, use and EoL but also environmental costs, such as recycling costs and emission fees, and social costs.

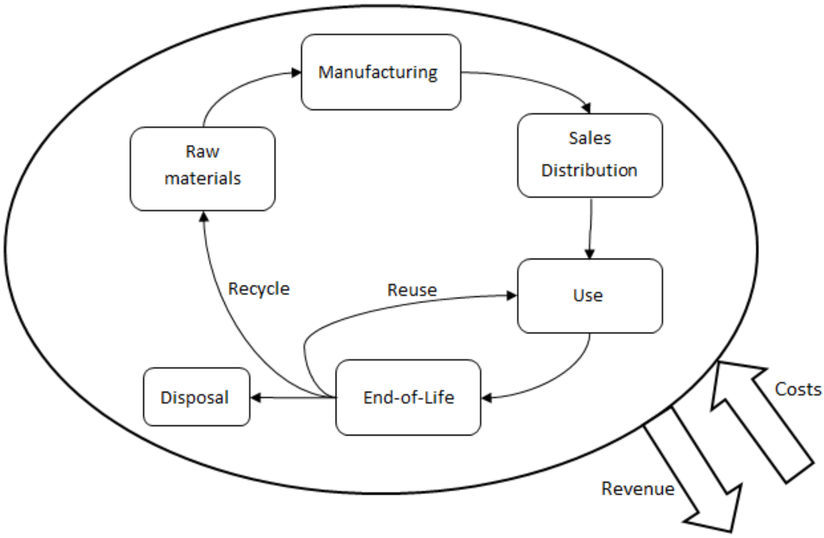


Figure 4. Example of life cycle stages and the costs and revenues in an LCC analysis.

The LCC analysis has a similar structure with the environmental LCA [11]. The LCC process has four parts: goal and scope definition, economic life cycle inventory, interpretation, and reporting and review [11]. Similarly to the environmental LCA, the LCC may be concentrate only on certain stages of the life cycle; e.g., the manufacturing, use and maintenance; and ignore the rest, depending on the scope and goal of the assessment. In addition, the cost analysis may be restricted to the environmental costs, e.g., the costs of waste management.

The LCC analysis calculates the costs and profits of the chosen scope. It is recommended to take the time value of the money into account if the time scale of the calculation exceeds two years [11]. Considering the lighting sector, the time value of the money may be ignored in case of short operating life of the light source, e.g., an incandescent lamp. In contrast, in case of street lighting, the time scale of the calculation is long, typically 30 years, and thus, the time value of the money is taken into account. Swarr et al. [11] also suggest that the LCCs may consider the costs from a certain point of view of an actor, such as the manufacturer, distributor, vendor, or end-user.

There are numerous techniques and parameters to calculate in the LCCs. Bhandari [37] states that the present value and payback time (net present value and discounted payback period in the original reference) are the most comprehensive indices in capital budgeting decision criteria. The LCC analysis of street lighting luminaires uses these two indices, present value and payback times, further explained in the following subchapters. The LCC analysis of the non-directional lamps used in households excludes the time value of the money and calculates only the purchase and operating costs with an emphasis to study the LCC methodology (mainly functional unit).

2.2.1 Present value

Present value method is a method for calculating the life cycle costs. It measures the profitability and considers all cash flows and the time value of the money [37]. It discounts all the returns and costs to present time by using the rate of interest. For instance, the present value of LCCs comprises of three parts:

$$LCC = C_i + \left(\frac{1-(1+i)^{-n}}{i}\right) C_o + \frac{RV}{(1+i)^n} \tag{2}$$

which are the investment cost (C_i), discounted operating costs (C_o) and the discounted residual value (RV) [38, 39]. The operating costs and the residual value are discounted on the basis of the rate of interest i during the number of years n. The operating costs recur annually in uniform amounts, but the residual value is assumed to occur only once at the end of the operating life. Therefore, their discounted equations are as above (e.g., in [39]).

2.2.2 Payback times

There are two methods to calculate payback times in LCC analysis: a simple payback time (SPB) and the payback time (PB). The SPB is easy to calculate, but it does not consider all the cash flows or the time value of the money, and it does not ensure profitability [37]. However, the SPB is used due to its easy calculation method: it is calculated by dividing the investment costs by the savings from the investment. If either type of a payback time is calculated in a renovation case, the savings are resulted from the renovation, e.g., reduction in the energy consumption or in the maintenance costs.

The PB, also known as discounted payback time, takes the time value of the money into account. That causes the equation to be a more complex one. In case of equal cash flows and discrete discounting, the PB is calculated as follows:

$$PB = \frac{-\ln\left(1-\frac{iC_i}{C_{o,old}-C_{o,new}}\right)}{\ln(1+i)} \tag{3}$$

where i is the rate of interest, C_i the sum of investment costs, and $C_{o,old}$ and $C_{o,new}$ are the operating costs of the old and new installation, respectively [37]. Due to the nature of the equation, however, it is not possible to calculate PB in every case. PB can be calculated and results in a positive number only if the operating costs of the new installation are smaller than the ones of the old installation, and the annual savings from operating costs divided by the rate of interest exceed the investment cost.

3 Analysis of previous life cycle assessments

Several LCAs of light sources have been published during the last two decades. The early studies have compared mainly the incandescent lamp and the CFL (e.g., [40, 41, 42, 43]), while the more recent assessments include also LED light sources [30, 44, 45, 46] or even a wide range of lighting products [47, 48].

Two review works have recently been published analysing the previous LCAs of light sources: United States (US) Department of Energy (DOE) report part 1 [30], and Tähkämö et al. [29]. The former analysed ten published LCA studies from which it collected the primary energy data for incandescent lamp, CFL, LED lamp and a future LED lamp. The future estimate of LED lamp considered the technology development in luminous efficacy and operating life by year 2015. The analysis covered the energy embodied in the materials of the lamps, the energy used in the transportation, and the energy used during the operation of the lamp, all of which were calculated for a functional unit of 20 megalumen-hours. The review concluded that the CFL and LED lamps had similar primary energy consumption of approximately 3 900 MJ per functional unit, while the incandescent lamp required three times more primary energy, approximately 15 100 MJ per functional unit.

The latter analysis by Tähkämö et al. [29] collected the data of 13 previous LCAs. It used also other sources of information, such as the Ecodesign report [49] and lighting industry (European Lamp Companies) [50]. This review article did not compare quantitatively the results but collected the key parameters of the LCAs, such as the functional units and the environmental impact categories. In addition, it identified the challenges in the comparison of the assessments, including the differences in the methodology, light sources, and impact categories.

A summary of the previous LCAs is presented in Table 1. It is based on Tähkämö et al. [29] but updated by adding two recent publications [51, 44]. Table 1 shows the main differences in the LCAs. The assessed light sources included typically an incandescent lamp and a CFL but also an LED lamp (either an actual, future or hypothetical LED lamp). Only a few studies analysed halogen lamps, fluorescent lamps or fluorescent lamp luminaires, high pressure sodium lamps, (ceramic) metal halide lamps, induction lamps, and LED luminaires, or made a distinction between self-ballasted CFLs and CFLs with separate ballast. Few LCAs considered a wide range of potential environmental impacts, such as global warming, acidification, eutrophication, abiotic resource depletion, ozone depletion, photochemical ozone creation, human toxicity, and various ecotoxicities. In contrast, there were LCAs that calculated only a few environmental impact categories, or use single-scale indices, such as EcoIndicator'99. Seven LCAs compared the environmental performance of the light sources in (primary) energy consumption.

The data on the material contents of the incandescent lamps, CFLs and LED lamps is collected in Tables 2, 3 and 4, respectively. In Table 2, the materials of incandescent lamps are divided into glass and metals, which correspond to 70 % - 94 % and 4 % - 29 % of the weight of the lamp, respectively. The weights of incandescent lamps varied between 15 g and 38 g. No correlation between the weight and the power was found, since the weight of the 60 W incandescent lamps ranged between 23 g and 38 g.

The weight of the CFLs ranged between 46 g and 120 g (Table 3), and no correlation was found between the lamp weight and power. Glass accounted for 30 % to 73 %, metals 2 % to 40 %, electronics up to 31 %, and plastics 16 % to 38 % of the weight of the CFL lamp. However, there were differences in the material categorization in the references. For instance, Elijošiutė et al. [51] probably modelled electronic component as metals, as no electronics were listed separately and the share of metals was relatively high (40 %) compared to the share of metals in other references (2 % to 21 %). The amount of mercury was between 3 mg and 5 mg per CFL.

Only few references were found that provided the detailed material data of LED lamps (Table 4). As it is seen in Table 4, there are significant differences between the LED lamp material compositions: glass 0 % to 13 %, metals 45 % to 78 %, electronics 3 % to 21 %, and plastics 2 % to 37 % of the total weight of an LED lamp. The weight of the LED lamps varied between 83 g and 282 g.

The data collection in Tähkämö et al. [29] showed the variety in the initial data of the LCAs: the energy consumption of the manufacturing of incandescent lamps, CFLs and LED lamps varied significantly. No unified model of the manufacturing energy consumption was found in the assessments.

Table 1. Summary of light sources, functional units and environmental impacts in 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 non-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). Adapted from Tähkämö et al. [29].

Light sources		Functional unit	Environmental impact categories	Reference	Year
60 W IL	15 W CFL	10 000 h	ADP, AP, EP, GWP, ODP, POCP	[51]	2012
60 W IL 15 W CFL	12.5 W LED lamp 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	[44]	2012
60 W IL 35 W HL	14 W FL 11 W CFL	1 h	Cumulative energy demand, GWP, EcoIndicator'99	[53]	2011
150 W HPS 163 W MH	109 W IND 105 W LED	100 000 h	GWP, respiratory effects, ecotoxicity	[48]	2009
100 W IL 23 W CFL 2x28 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, non-hazardous, and radioactive wastes	[47]	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	[45]	2009
60 W IL 13 W CFL	6 W LED 6 W LED*)	1 Mlmh	Primary energy consumption, GWP	[46]	2009
60 W IL	15 W CFL	1 kWh	Energy consumption	[52]	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	[54]	2008
100 W IL	23 W CFL	16 Mlmh	GWP, emissions of mercury, arsenic, and lead	[55]	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	[42]	2006
60 W IL 15 W CFL	7,5 W LED**)	1 Mlmh	Energy consumption	[67]	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	[43]	2003
60 W IL 11 W CFLi	13 W CFLi 11 W CFLni	1 Mlmh	Primary energy consumption, Hg emissions, radioactive materials	[41]	1996
60 W IL	15 W CFL	1 Mlmh	GWP, SO_2, NO_x, CH_4, ashes, Hg, solid waste	[40]	1991

Table 2. Materials of incandescent lamps in LCAs. Lamp weight excludes the weight of the package. Percentages are calculated of the lamp weight. Ref.=reference. Adapted from Tähkämö et al. [29].

Lamp power (W)	Lamp weight (g)	Glass (g)		Metals (g)		Ref.
40	15	14	*93 %*	1	*7 %*	[49]
60	23	18	*78 %*	3	*13 %*	[50]
60	26	24	*93 %*	2	*7 %*	[52]
60	27	26	*94 %*	2	*6 %*	[49]
60	31	22	*71 %*	9	*29 %*	[40]
60	33	30	*91 %*	3	*9 %*	[53]
60	33	29	*90 %*	4	*12 %*	[54] *)
60	36	29	*82 %*	4	*11 %*	[51]
60	38	27	*70 %*	1	*4 %*	[44]
100	27	25	*93 %*	2	*7 %*	[47]
100	27	24	*88 %*	2	*6 %*	[55]
100	32	24	*76 %*	3	*8 %*	[42]

*) The sum of shares exceeds 100 % due to the deduction of the packaging materials from the total weight.

Table 3. Materials of CFLs in LCAs. Lamp weight excludes the weight of the package. Percentages are calculated of the lamp weight. (B) refers to CFLs with a bare, visible discharge tube, while (E) refers to enveloped CFL with a protective cover over the arc tube. Ref.=reference. Adapted from Tähkämö et al. [29].

Lamp power (W)	Lamp weight (g)	Glass (g)		Metals (g)		Electronics (g)		Plastics (g)		Hg (mg)	Ref.
10 (B)	58	18	*30 %*	1	*2 %*	17	*30 %*	22	*38 %*	4	[49]
10 (E)	64	36	*56 %*	1	*2 %*	16	*25 %*	11	*17 %*	4	[49]
11	111	65	*58 %*	4	*4 %*	15	*14 %*	25	*22 %*	4	[53]
11	120	65	*54 %*	4	*3 %*	25	*21 %*	25	*21 %*	-	[50]
13	55	40	*73 %*	3	*5 %*	-	-	10	*18 %*	-	[50]
13 (B)	69	31	*45 %*	14	*21 %*	17	*24 %*	13	*18 %*	3	[54]*)
15	46	26	*56 %*	3	*7 %*	-	-	17	*37 %*	5	[52]
15 (B)	72	25	*35 %*	2	*2 %*	20	*28 %*	25	*35 %*	4	[49]
15	79	27	*35 %*	31	*40 %*	-	-	13	*16 %*	3	[51]
15 (E)	92	47	*51 %*	2	*2 %*	20	*22 %*	23	*25 %*	4	[49]
15 (B)	109	33	*30 %*	9	*8 %*	33	*30 %*	34	*31 %*	-	[40]
18	91	42	*46 %*	2	*3 %*	26	*29 %*	15	*17 %*	3	[42]
23	92	39	*42 %*	9	*10 %*	24	*26 %*	20	*22 %*	4	[47]
23 (B)	94	39	*41 %*	7	*7 %*	29	*31 %*	20	*21 %*	-	[55]

*) The sum of shares exceeds 100 % due to the deduction of the packaging materials from the total weight.

Table 4. Materials of LED lamps in LCAs and environmental studies. Lamp weight excludes the weight of the package. Percentages are calculated of the lamp weight. Ref.=reference.

Lamp power (W)	Lamp weight (g)	Glass (g)		Metals (g)		Electronics (g)		Plastics (g)		Ref.
-	83	11	*13 %*	50	*60 %*	12	*14 %*	11	*13 %*	[56]
-	247	22	*9 %*	194	*78 %*	8	*3 %*	4	*2 %*	[56]
-	282	0	*0 %*	167	*59 %*	10	*3 %*	105	*37 %*	[56]
12	238	20	*8 %*	107	*45 %*	49	*21 %*	53	*22 %*	[47]

Despite the found differences, the findings of the LCAs were unanimous on two things: the use-stage energy consumption is the most important environmental aspect in the LCAs, and thus, the energy-efficient light sources, such as the CFLs and LED lamps, are more environmentally friendly than their conventional counterparts from the life cycle point of view.

In addition to the above-mentioned LCAs, the environmental aspects of light sources have been the subject of several other environmentally-related studies. The end-of-life of LED lamps and luminaires was studied by Hendrickson et al. [56]. They stated that it is possible to reduce the environmental impacts of a solid-state lighting product by implementing design for end-of-life in the product development, e.g., by facilitating the disassembly and enabling the recovery of components, parts and materials to be reused or remanufactured. The material contents of indicator-type LED components of various colours have been studied by Lim et al. [23]. Their leachability tests proposed that the LED components – varying by the colour of the LED – may contain copper, lead, nickel and silver so much that some of the indicator LEDs are classified as hazardous according to the Californian regulations [57]. A new study by Lim et al. [58] continued by including the whole LED lamps and comparing their metal contents by the leachability tests. They found out that the studied CFLs and LED lamps were classified as hazardous waste under existing Californian regulations [57] and US federal regulations [59]. CFLs contained copper, lead and zinc, and LED lamp copper and lead above the limits of the regulations. In contrast, a US DOE report [60] indicated that the US federal regulations are generally complied by the tested CFLs and LED lamps, while the stricter Californian thresholds were typically exceeded by all lamps (incandescent lamps, CFLs, LED lamps) regarding copper and by CFLs and LED lamps regarding antimony and zinc.

It shall be noted that the study by Lim et al. [58] and US DOE report [60] are conducted for lamps available in the US market, where no federal legislation on the restriction of hazardous substances in electrical and electronic equipment exist, except for a state-wide regulation in California [61] similar to EU RoHS. The studies indicate that CFL and LED lamps may be classified as hazardous substances in the US. However, a study concerning the lamps in the European market should be established, and the material contents of LED lamps to be compared to other electronic products.

In addition to the comparative LCAs of lamps and luminaires, there are separate LCAs of single lighting products. Dubberley et al. [62] 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. Their main finding was that the potential environmental impacts of an intelligent system are significantly lower (18 to 344 times smaller) compared to a conventional lighting system. The LCA of an emergency light was conducted by Neri et al. [63]. They concluded that the most environmentally-relevant components are the battery, lamp and the circuit board. A fluorescent lamp was the subject of a non-comparative LCA by Techato et al. [64]. They calculated the amount of waste from fluorescent lamps and an air-conditioner. The analysis of the fluorescent lamp resulted in a significant amount of hazardous waste compared to bulk waste, but the amount of any type of waste was very low compared to the total weight of the lamp. However, the amount of hazardous waste became relevant when the scope is widened to national. The ballasts for fluorescent lamps have been analysed by Valkama and Keskinen [65] and Bakri [66]. Both of the LCAs concluded that the use-stage energy consumption was the major environmental aspect. Valkama and Keskinen stated also that the use of simplified LCA (EcoReport -tool) may cause significant changes in the LCA results of the electronic products.

3.1 Functional unit

A variety of functional units were used in the LCAs of light sources. The functional unit was typically an amount of lumen-hours, e.g., 1 Mlmh, or an amount of luminous flux over a certain operating time, e.g., 500 to 900 lm over 10 000 h (Table 1). In the latter case, the functional unit was not equivalent (500 lm compared to 900 lm). However, the functional unit shall be clearly defined according to ISO 14044 standard [33]. This was not complied in three LCAs [45, 54, 42], in which the functional units were 345-420 lm over 25 000 h, 500-900 lm over 10 000 h, or equivalent light output over 8 000 h (assumed to signify equivalent luminous flux), respectively.

The lumen-hour seems to be an appropriate functional unit for light sources, as it considers both the operating hours and luminous flux. However, it excludes all other characteristics, such as luminous intensity distribution curve or colour, and ignores the application of the light source.

The luminous flux of an incandescent lamp remains constant during its life. In contrast, the luminous flux of a fluorescent lamp, high intensity discharge lamp, or LED light source is not constant but depreciates over the operating time. None of the LCAs in Table 1 take lumen depreciation into account in the calculations, yet three assessments acknowledge it [47, 45, 67]. The lumen depreciation is stated to be too small to impact the results [45].

There were also other functional units used in the LCAs as seen in Table 1, such as an amount of hours or a kilowatt-hour. Using an hour of lighting as the functional unit, as in [53], is not clear, since it does not define the luminous flux, or whether the hour refers to an hour of the operating time or to a period of time. Kilowatt-hour is not a representative functional unit in case of light sources, since it does not reflect the function of the product.

In addition, a lighting engineering approach for functional unit was presented by Yabumoto et al. by using two functional units: total luminous flux of 800 lm during 40000 h, and 100 lx floor illuminance at a distance of 1 m directly under the light source during 40000 h [68]. This functional unit took the actual illumination into account, even though it is restricted to only one example of illuminance at a certain distance.

3.2 Life cycle assessment of electronics

The market of electrical and electronic products is expanding phenomenally. It is challenging to find an appropriate method for the LCA of electronic products to assess their environmental impacts.

Despite of the similarities of the electrical and electronic equipment, the assessments of their environmental impacts differ from each other [69]. The electronic products have generally short innovation time, their use patterns change, and they use highly special materials, while electrical products are innovated more slowly, their use patterns are more stable and well known, and they use common materials [69]. The difference in the LCA of electrical and electronic products is also visible in the comparison of an incandescent lamp and an LED lamp due to their differences in composition, rate of development and potential applications. Fluorescent and CFL lamps fall into between of the two product types with a mediocre innovation time, somewhat established use patterns and relatively special materials. In fluorescent lamp luminaires, there is always some electronics, since a ballast, either integrated or non-integrated, is needed.

The challenges in the LED product LCAs are mainly the same as in electronic products in general. Moreover, it has been disputed whether the LCA is an appropriate method for analysing the environmental impacts of electronic equipment in detail at all [69, 70]. The LCA of the electronic products are challenging to conduct thoroughly and in detail due to the complexity of the products, lack of specific data, data gaps in the LCIA, short innovation time and changing use patterns [71, 69]. However, the LCA is acknowledged to be used in screening the life cycle of electrical and electronic equipment in order to *identify* the environmental hot spots of the life cycle [69]. Some level of simplification is needed in the LCA of electrical and especially electronic products due to their complexity and lack of specific data.

The LED component is a semiconductor. The life cycle environmental impacts of semiconductors have recently been a topic of a book by Boyd [72]. The book does not consider the diode technology particularly, but the semiconductor technology was represented by complementary metal oxide semiconductor (CMOS) logic, flash memory, and dynamic random access memory (DRAM). They are the three most common semiconductors globally. Boyd concluded that the environmental impacts of semiconductors are dominated by the electricity consumption in the use stage. The second greatest environmental concern of the semiconductors is the energy use in the manufacturing stage, and the third greatest are the process emissions in wafer fabrication, such as perfluorinated compounds.

When comparing the inventory and the results by Boyd [72] and US DOE [44], it is found that the manufacturing process of the LED chip and transforming it to an LED package has inputs and outputs that are somewhat different from the ones of the CMOS, flash memory or DRAM devices. The use of chemicals differs greatly (e.g., different chemicals and amount). The wafer fabrication for an LED chip consumed 42.57 kWh per 3-inch wafer, i.e., approximately 0.93 kWh/cm^2 according to US DOE [44], while Boyd estimated the energy consumption of wafer fabrication range between 0.5 and 0.7 kWh/cm^2 of wafer area in 1999-2005. Another study estimated that the wafer production consumes approximately 1.5 kWh/cm^2 [73]. No further comparison is made between the LED chip manufacturing and the manufacturing of CMOS, flash memory and DRAM devices due to the apparent differences in the manufacturing processes to a final product and the applications.

3.3 Summary

A number of LCAs of lamps and luminaires have been conducted over the last two decades, most of which compared incandescent lamps to CFLs. Currently, there are increasingly LCAs of various light sources, especially LED lamps and luminaires. Several differences were found in the previous LCAs of light sources. First, it was impossible to create a unified model for the energy consumption in manufacturing, as the data varied so much in incandescent lamps, CFLs and LED lamps. In addition, the material contents of incandescent lamps, CFLs and LED lamps varied in the LCAs and other references. Due to this and the scarcity of material data for LED lamps, it was impossible to create a consistent model of the material contents. Second, the LCAs use a variety of functional units from megalumen-hours to one piece of a lamp or one hour. Third, the studied environmental impacts vary, as there is a number of potential environmental impact categories to choose from, such as global warming, acidification, eutrophication, ozone depletion, abiotic resource depletion and human toxicity.

Despite the apparent differences in the LCA methodologies, the LCAs of light sources generally conclude similar findings: The use stage accounts for the majority of the environmental impacts due to the energy consumption, while other stages, such as raw material acquisition, manufacturing and

EoL, cause only fairly marginal total life cycle impacts. Thus, the luminous efficacy of the light source determines the environmental performance of the light source for the most part. Lamps and luminaires having high luminous efficacies, such as CFLs, fluorescent lamps, LED lamps and luminaires, and induction luminaire, were found to be the most environmentally friendly compared to the lamps and luminaires of lower luminous efficacies, such as incandescent lamp, halogen lamp, high pressure sodium (HPS) luminaire and metal halide (MH) luminaire.

Many light sources, such as LED lamps and luminaires, fluorescent lamp luminaires and HID luminaires, contain electronic components. It is challenging to assess the environmental impacts of electronic products in detail, since there are no LCIA data available for every type of electronic component in a certain geographic location. Hence, it is necessary to use some level of simplification and approximations in the LCAs of electronics. It is stated that the use stage is a major cause for environmental impacts in semiconductors [72]. In addition, the LCA is accepted as a tool to identify the environmental hot spots of electrical and electronic products. Nevertheless, it must be noted that the LCA of such products always contains uncertainty due to the lack of product- or geographically specific data.

4 Methodology study of life cycle assessment of light sources

This chapter describes a methodology study of the LCA of light sources. Four lighting cases are introduced in the study: non-directional lamps used in households, LED downlight luminaire, fluorescent lamp luminaire, and street lighting luminaires. The cases differ from each other in the lighting application and the lighting criteria. In addition, they are common applications and thus were considered as appropriate cases for the analysis. Each of the case is analysed separately due to the apparent difference in the applications, but, as a result, the findings are summarized.

The cases introduce either environmental or economic perspective or both. The case on the non-directional lamps typically used in households considers both environmental and economic perspectives, while the LED and fluorescent lamp luminaire cases concentrate on the environmental impacts in the LCAs of the products. The street lighting case includes only the economic analysis and is the only case of only LCC analysis and not an LCA. Social aspects are excluded from the scope of the analyses.

The requirements for lighting differ by the application, and thus, different products are used in different applications. Incandescent lamps are typically used in general lighting in households, but, as they are being phased out in the EU, a comparison of incandescent lamp to its replacement options (CFL and LED lamp) is in order. The LCCs of the household lighting are calculated from the customer's point of view. The lighting criteria in households include generally only the luminous flux and the colour temperature. The LED downlight luminaire in question is usually installed in commercial applications and the fluorescent lamp luminaire in industry premises. The street lighting case compares the LCCs of luminaires used in street lighting. The LCCs of the street lighting are covered from the point of view of the municipality.

4.1 Study of non-directional lamps used in households

Regular incandescent lamps that have traditionally been widely used in general lighting are being phased out in several countries worldwide. In the EU, the Ecodesign regulations [21, 22] set the energy efficiency requirements, and as a result, the incandescent lamps are phased out. In addition, the Ecodesign regulations establish a set of functionality requirements, such as lamp survival factor, lumen maintenance, starting time and colour rendering index, for the remaining lamps.

4.1.1 Methods

The environmental impacts and LCCs of non-directional lamps used typically in households are studied in the following. The environmental impacts and costs are calculated regarding manufacturing and use. The manufacturing costs were modelled on the basis of purchase prices, even though it was acknowledged that the purchase price does not totally correspond to the manufacturing costs, but it is an estimation. The costs from the use were calculated on the basis of electricity price and consumption. The LCCs were calculated from the point of view of the consumer, who purchases, replaces and uses the lamp.

The environmental impacts of light sources are generally clearly dominated by the energy consumption in the use [29]. Thus, the potential environmental impacts of the light source are strongly dependent on the choice of the energy source. That is the reason for considering *primary energy* consumption as the parameter for the calculations of the environmental impacts. The primary energy analysis excluded the impact of a specific energy production, e.g., wind power or nuclear power, but included the amount of primary energy consumed the manufacturing process and in use. In addition, the lamp comparison included the primary energy embodied in the materials, as it has been recently estimated by US DOE [30]. However, the US DOE study reported a high uncertainty in the primary energy consumption of the manufacturing process of LED lamps: 0.1 to 27 % of total life cycle energy consumption.

The idea of the study is to vary the luminous intensity distribution curves and luminous fluxes of CFLs and LED lamps to see their effect on the environmental and economic aspects of the lamps. The study compared three lamp types: 60 W incandescent lamp (750 lm), 13 W CFL of three shapes (spiral, tubular, enveloped) (750 lm), and 13 W LED lamp (800 lm). Figure 5 illustrates the schemas of the lamp types. The study is based on a previous environmental and cost analysis of non-directional household by Tähkämö et al. [7] which is updated herein. The original analysis compared a 60 W incandescent lamp, three shapes of CFLs of equivalent luminous flux, and an LED lamp corresponding to a 40 W incandescent lamp. At the time of the original calculation, there was no LED lamps equivalent to 60 W incandescent lamps on the market. The updated analysis herein changed the LED lamp to a lamp corresponding to a 60 W incandescent lamp having an equivalent luminous flux (800 lm). The shape of the 60 W equivalent LED lamp was as in Figure 5e, while the 40 W equivalent LED lamp in [7] had a different shape, and thus slightly different luminous intensity distribution curve.

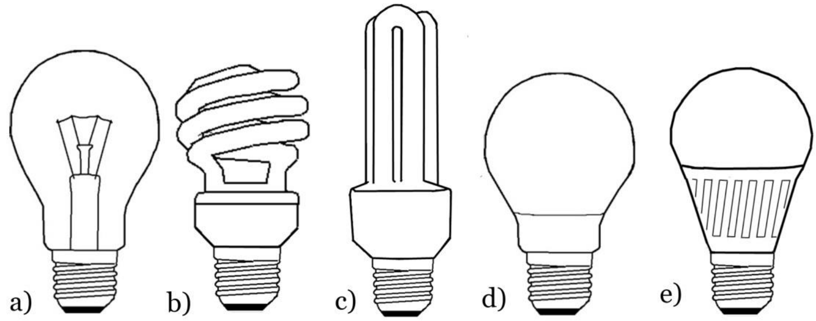


Figure 5. Schemas of the lamps: a) incandescent lamp, b) spiral CFL, c) tubular CFL, d) enveloped CFL, and e) enveloped pear-shaped LED lamp.

The functional unit is a key parameter in the LCA of light sources. The study used four functional units: a) a lamp, b) a megalumen-hour, c) an hour, and d) a direct illuminance at 1 m distance on a 1 m^2 square surface (marked with *E*) per hour. The megalumen-hour, an hour, and the illuminance per hour are related to the operating time of the lamp. All functional units and the analysis excluded the luminaire and other life cycle stages than manufacturing and use in order to simplify the study. The non-directional lamps are typically used in households in luminaires that are assumed not to direct or reflect the light significantly.

The LCC and energy analysis were calculated by taking the lamp variations into account by estimating *high-end* and *low-end* products of each lamp type. Table 5 provides the initial data on the high-end and low-end lamps. High-end products represented the products with high luminous flux, long life, high price, high illuminance (E) and high primary energy consumption in manufacturing. In contrast, low-end products possessed modest luminous flux, short life, low price, low illuminance (E) and low primary energy consumption in manufacturing. The primary energy consumption in manufacturing of low-end lamps was estimated at the lowest, and highest in high-end lamps, respectively, in the US DOE report part 1 [30]. Low-end lamps resulted in lower illuminance (lowest estimate based on different luminous intensity distributions). The luminous intensity distribution curves of the CFLs varied among the lamp shapes.

The shape of the luminous intensity distribution curve of the incandescent and LED lamps did not vary, but the luminous flux ranged from 600 to 900 lm and 700 to 1200 lm, respectively.

It is acknowledged that the high price does not necessarily result in high luminous efficacy or life of the lamp. However, the high- and low-end variance was supposed to illustrate the estimated highest and lowest prices, luminous efficacies, and lives of lamps, respectively. The dimmability may also increase the price, but it is excluded from the study.

Table 5. Data on the incandescent lamp (IL), compact fluorescent lamp (CFL) and LED lamp. "High" and "low" refer to the estimates on high- and low-end products (E=direct illuminance at 1 m distance on a 1 m² square surface).

Lamp type	Power	Luminous flux	Life of lamp	Luminous efficacy	Lumen-hours	Purchase price of lamp in 2012	Energy price	Primary energy consumption in lamp manufacturing [30]	E
unit	W	lm	h	lm/W	Mlmh	€/pcs	€/kWh	MJ/lamp	lx
IL	60	750	1000	12.5	0.75	0.8	0.1	1.9	47
high		900		15	0.9	1		4.77	56
low		600		10	0.6	0.5		0.455	37
CFL	13	750	8000	58	6	5	0.1	65	45
high		900	20000	69	18	15		199	50
low		700	6000	54	4.2	2.5		4.32	30
LED	13	800	15000	62	12	27	0.1	343	40
high		1200	25000	92	30	35		1490	60
low		700	10000	54	7	24		39.9	35

All of the lamps chosen for the comparison had an E27 cap, were non-directional and were intended for use in residential lighting. The colour characteristics were not compared, but all of the CFL and LED lamps possessed correlated colour temperature of approximately 2700 K according to the manufacturers, as the lamps were intended to replace incandescent lamps. The initial data was collected on the basis of measurements in the Aalto University Lighting Unit, manufacturers' data, and retailers' websites. The luminous intensity distribution curves of incandescent lamp and CFLs were measured in the Aalto University Lighting Unit, while the one of the LED lamp was retrieved from the manufacturer. The purchase prices were estimated on the basis of retailers catalogues in 2012. The energy price was estimated at 0.10 €/kWh. According to European Statistics [74], the electricity price was approximately 0.13 €/kWh (ranging between 0.07 and 0.17 €/kWh) in 2011 in medium-sized households.

4.1.2 Results

The results of the economic and environmental analyses, i.e., LCC analysis and the LCA, of non-directional lamps are presented in Figures 6 and 7, respectively. Four functional units were used: lamp (Figures 6a and 7a), megalumen-hour (Figures 6b and 7b), hour (Figures 6c and 7c), and illuminance (E) at 1 m distance on a 1 m^2 square surface per hour (Figures 6d and 7d).

Figures 6a and 7a show that the LED lamp causes the greatest costs and primary energy consumption per lamp. This is mainly due to the long life of the LED lamp, which results in high use-stage impacts, as they are expressed per lamp. In addition, the purchase price and primary energy consumption in manufacturing of the LED lamp was high. In Figures 6c and 7c, the results of lamp-based comparison are divided by the lives of the lamps, thus resulting in costs and primary energy consumption per hour. The hour-based comparison indicates that incandescent lamp causes clearly the greatest costs and primary energy consumption. Similar results are seen in Figures 6b, 6d, 7b and 7d, in which the incandescent lamp causes the greatest impacts. However, there was somewhat variation due to the high- and low-end products. According to Figures 6b-d and 7b-d, it seems that the megalumen-hour-based comparison results in similar results as in cases having an hour or illuminance as the functional unit.

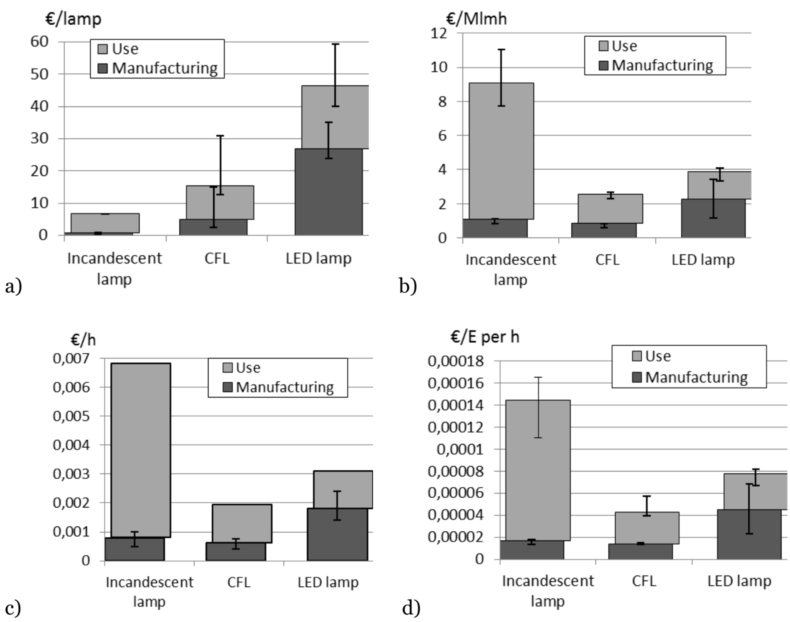


Figure 6. Life cycle costs of incandescent, compact fluorescent and LED lamps using four functional units: a) lamp, b) megalumen-hour (Mlmh), c) hour (h), and d) direct illuminance at 1 m distance on a 1 m^2 square surface (E) per hour. Life cycle includes here the manufacturing and use.

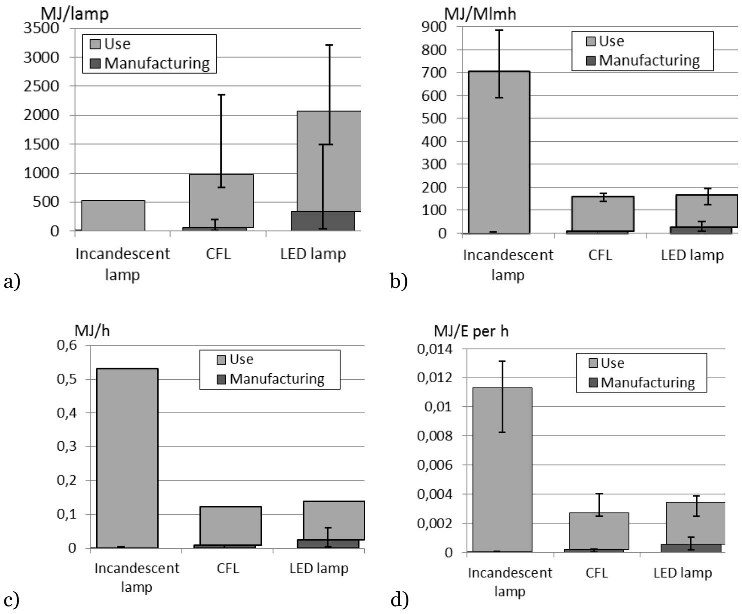


Figure 7. Life cycle primary energy of incandescent, compact fluorescent and LED lamps using four functional units: a) lamp, b) megalumen-hour (Mlmh), c) hour (h), and d) direct illuminance at 1 m distance on a 1 m² square surface (E) per hour. Life cycle includes here the manufacturing and use.

The manufacturing impacts remain very low in the primary energy analysis (Figure 7), while the manufacturing costs account for a significant share of the life cycle costs in CFLs (approximately 32 %) and in LED lamps (approximately 58 %).

4.2 Study of LED downlight luminaire

An LED downlight luminaire was the subject in a CITADEL (Caractérisation de l'Intégration et de la Durabilité des Dispositifs d'Eclairage à LED dans le Bâtiment; Characterisation of Integration and Durability of LED Lighting Devices in buildings) project lead by the French Scientific and Technical Centre for Building (CSTB) in Grenoble, France. The LCA was conducted by the author in collaboration with the researchers in CSTB. The LCA of the luminaire is published in Tähkämö et al. [4].

The LCA was a stand-alone LCA, not a comparative one. It was conducted in accordance with ISO 14040 [32] and ISO 14044 [33] standards with the addition of a French standard NF P01-010 [75].

4.2.1 Methods

The downlight luminaire in question was a 19 W LED downlight with a remote phosphor cover and a separate driver. It was a luminaire for the commercial and retail applications to replace CFL downlight luminaires.

The functional unit of the assessment was 50 000 hours use of the luminaire providing 1140 lm of luminous flux. The functional unit was equivalent to 57 Mlmh. The International Commission on Illumination (CIE) colour rendering index (CRI) R_a of the luminaire was approximately 80.

The assessment considered the manufacturing, transport, installation, use and EoL of the luminaire life cycle. It included all the inputs on which the data was obtained. A cut-off rule was used: inputs weighing less than 2 % of the total luminaire weight were excluded if there was no LCI available, as stated in the NF P01-010 [75]. The LED components were modelled as indicator LEDs (0.35 g/unit) available in the Ecoinvent database [76] multiplied the weight by a factor of five according to industry experts [4]. SimaPro [77] was used as the LCA software and Ecoinvent [76] and European Reference Life Cycle Database (ELCD) [78] as databases.

Table 6 lists the inventory data of the manufacturing of the LED downlight luminaire. The data was gathered from the disassembly of the luminaire by the author, from the luminaire manufacturer regarding electricity in assembly, and from a French Luminosurf project regarding the remote phosphor cover.

The LCA of the LED downlight luminaire considered a number of environmental impact categories presented in Table 7. Thus, the potential environmental impacts are included extensively. In addition, the primary energy was chosen as one impact category.

The base case of the LCA was modelled as 50 000 h life of the luminaire, French average electricity production in use stage, and the actual EoL (95 % landfill deposition, 5 % recycling treatment). In addition to the base case, the LCA contained several scenarios in order to analyse the sensitivity of the results to the life of the luminaire, use-stage electricity production and EoL scenario. The sensitivity analysis included three scenarios for the life of the luminaire (15 000 h, 36 000 h, 50 000 h), two electricity production mixes in use stage (European average, French average), and two EoL scenarios (actual; prospective 40 % landfill, 60 % recycling treatment). The average French electricity is mainly generated from nuclear power (77 %), while other energy sources account for a minority of the production (hydropower 12 %, coal 4 %, natural gas 3 %, oil 1 %, imported 2 %) [76]. The average European electricity is generated from nuclear power (30 %), coal (28 %), natural gas (19 %), hydropower (16 %), oil (4 %) and wind (2%) [76].

Table 6. Inventory data of manufacturing of an LED downlight luminaire. Adapted from Tähkämö et al. [4].

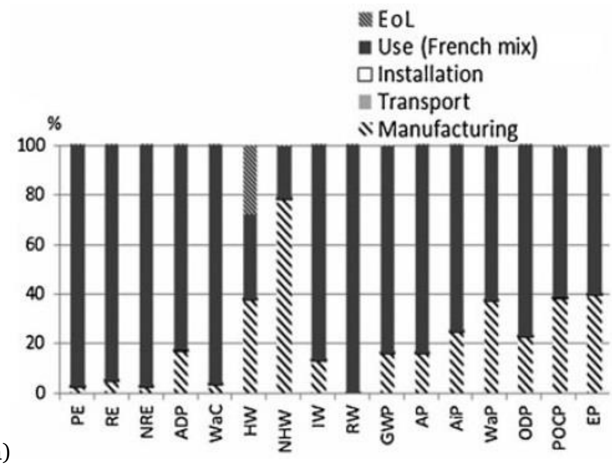
Raw material, product, or process input	Quantity and unit
Driver	
Printed circuit board	0.009 m^2
Capacitors	18 g
Diodes	0.6 g
Resistors	2 g
Transformers	48 g
Integrated circuits	0.1 g
Transistors	0.3 g
Other components (active, passive, or unspecified)	0.7 g
Steel	4 g
Plastics	130 g
Connectors	5 g
LED array	
Light-emitting diodes (16 units)	28 g
Silicone product	4 g
Aluminium	23 g
Aluminium parts	
Aluminium	700 g
Coating	0.17 m^2
Other parts	
Steel	17 g
Plastics	26 g
Cable	7 g
Paper	3 g
Remote phosphor cover	
Yttrium aluminium garnet (YAG) coating	0.2 g
Electricity, French	0.002 kWh
Aluminium oxide	0.1 g
Organic chemicals	0.1 g
Plastics	7 g
Assembly	
Electricity, French	0.029 kWh
Waste treatment (Packaging)	
Recycling intermediary cardboard packages	175 g

Table 7. Environmental impact categories used in the LCA of an LED downlight luminaire. CFC-11 refers to trichlorofluoromethane. Adapted from Tähkämö et al. [4].

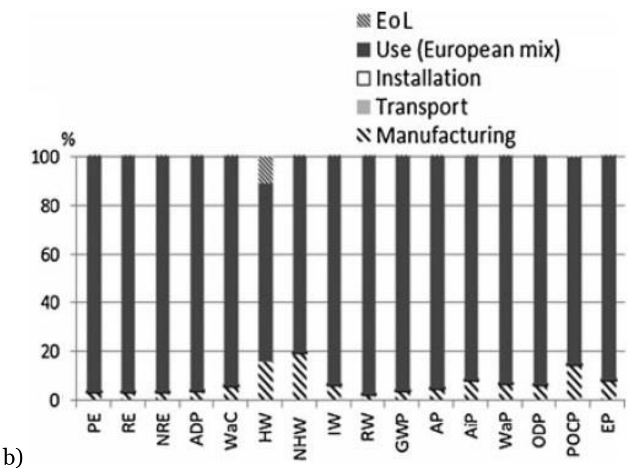
Environmental impact category	**Abbreviation**	**Unit (eq.=equivalent)**
Primary energy	PE	MJ
Renewable energy	RE	MJ
Non-renewable energy	NRE	MJ
Abiotic depletion potential	ADP	kg Sb-eq.
Water consumption	WaC	l
Hazardous waste	HW	kg
Non-hazardous waste	NHW	kg
Inert waste	IW	kg
Radioactive waste	RW	kg
Global warming potential	GWP	kg CO_2-eq.
Acidification potential	AP	kg SO_2-eq.
Air pollution	AiP	m^3
Water pollution	WaP	m^3
Ozone depletion potential	ODP	kg CFC-11-eq.
Photochemical ozone creation potential	POCP	kg C_2H_4-eq.
Eutrophication potential	EP	kg PO_4-eq.

4.2.2 Results

The results of the LCA of the LED downlight showed that the use-stage electricity consumption dominated the environmental impacts, as expected. Figure 8 presents the environmental impacts of the LED downlight luminaire in the sixteen impact categories. When the use was modelled by using the French electricity (Figure 8a), the manufacturing accounted for approximately 23 % and use 76 % of the total life cycle impacts. As seen in Figure 8a, the EoL caused insignificant impacts except for in the category of hazardous waste (28 %). Figure 8b shows the division of the environmental impacts when use was modelled as the European average electricity. In this case, the impacts were mainly divided between the manufacturing (7 %) and use (93 %). In both cases of electricity mixes, transport, installation and EoL caused very low impacts (average less than 1 %).



a)



b)

Figure 8. Division of environmental impacts of an LED downlight luminaire into life cycle stages when the energy consumption during use was modelled as a) average French, and b) average European electricity production. Adapted from Tähkämö et al. [4].

Figure 9 illustrates the division of the environmental impacts of the manufacturing of the LED downlight luminaire. As seen in Figure 9, the manufacturing environmental impacts were divided mainly (over 80 % in each category) between the driver (average 40 %), the LED array (average 28 %) and the aluminium parts (heatsink and reflector) (average 24 %). In the total life cycle scope, the LED array (LED components, aluminium board, silicone covering sheet) accounted for approximately 6 % or 2 % of the average environmental impacts when the luminaire was powered by French or European electricity, respectively.

There was uncertainty in the modelling of the LED component. The environmental impacts of the LED components were exaggerated by multiplying the weight of the component by five and using the data in the Ecoinvent database [76]. However, the US DOE part 2 report [44] indicated that the high-power LED component actually caused 94.5 % lower environmental impacts than the 5 mm indicator LED in the Ecoinvent database. The US DOE report was, however, based on the development of the luminous flux: the Ecoinvent data was for an LED through-hole technology (THT) component producing 4 lm, while the updated data by US DOE was for the high-brightness LED package producing 100 lm. Nevertheless, it was seen in the LCA of the LED downlight luminaire that the manufacturing of the LED components was not a major environmental concern.

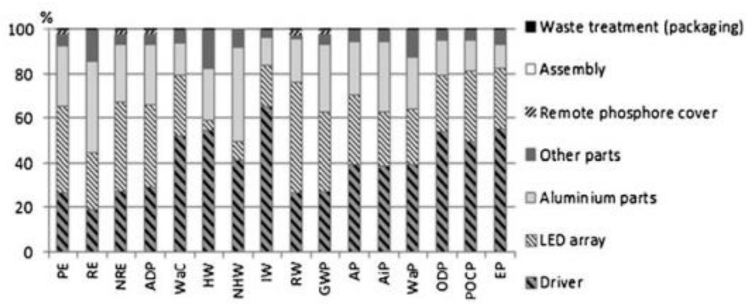


Figure 9. The division of the environmental impacts of manufacturing of an LED downlight luminaire. Adapted from Tähkämö et al. [4].

Figure 10 shows the total environmental impacts when the life of the luminaire is varied (15 000 h, 36 000 h, 50 000 h) and the EoL scenario changes (actual scenario 95 % landfill and 5 % recycling, prospective scenario 40 % landfill and 60 % recycling). The EoL scenario seemed to be practically insignificant in the total life cycle impacts, while the life of the luminaire had a notable effect on the environmental impacts (Figure 10).

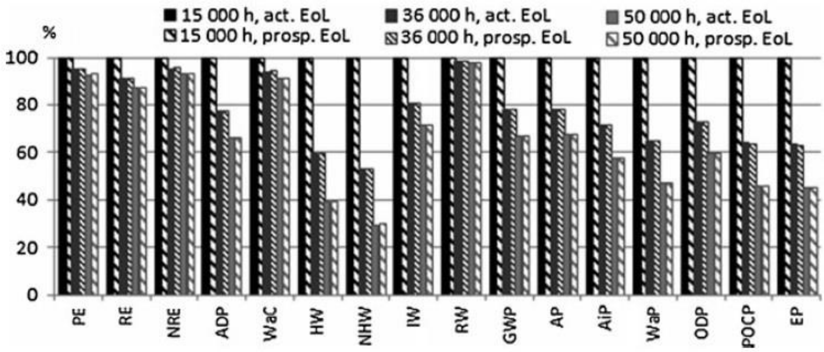


Figure 10. Life cycle environmental impacts of an LED downlight luminaire in three scenarios of product life (15 000 h, 36 000 h, 50 000 h) and two end-of-life scenarios (act. = actual scenario of 95 % landfill, 5 % recycling; prosp. = prospective scenario of 40 % landfill, 60 % recycling). Adapted from Tähkämö et al. [4].

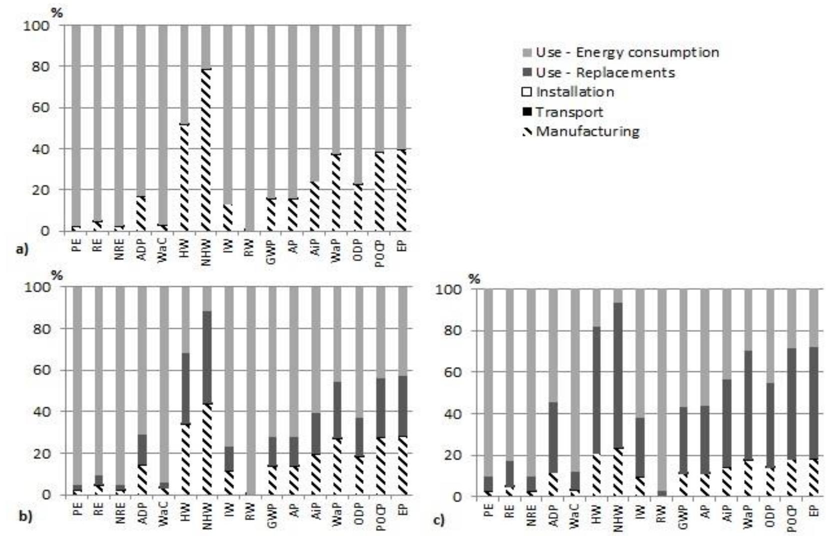


Figure 11. Division of environmental impacts into life cycle stages when the life of an LED downlight luminaire is a) 50 000 h, b) 36 000 h, and c) 15 000h. EoL is excluded. Adapted from Tähkämö et al. [4].

Figure 11 presents the division of the environmental impacts into life cycle stages (manufacturing, transport, installation, use) when the life of the luminaire is varied (15 000 h, 36 000 h, 50 000 h). Use was divided into two: the energy consumption during operation and the manufacturing of the replacement luminaires that are needed during operation. The life of the luminaire changed the division of the life cycle impacts: The lower the life was, the greater was the share of the manufacturing of luminaire (initial and replacements) of the total life cycle impacts. The energy consumption in use dominated the majority of the impact categories (Figure 11a).Taking the EoL into account, the manufacturing accounted for a major share in the hazardous waste (38 %) and non-hazardous waste (78 %) categories, and EoL caused 28 % of the hazardous waste. Thus, depending on the environmental impact category, it is *not* evident that in each case the use stage is the dominant one. This was somewhat due to the low energy consumption of the luminaire, since the luminous efficacy of the luminaire was approximately 60 lm/W.

Table 8 presents the environmental impacts of the LED luminaires published by the Department for environment, food and rural affairs (DEFRA) [47] and in this work. Table 8 addresses the environmental impact categories that were equivalent in the two LCAs, i.e., having similar calculation method (NF P01-010 is based on CML2001 method).

As seen in Table 8, the numeric life cycle impacts per Mlmh are similar in the two LCAs of an LED luminaire: 0.070 and 0.071 kg Sb equivalent in abiotic depletion, 0.040 and 0.032 kg SO_2 equivalent in acidification, 0.0029 and 0.0024 kg PO_4 equivalent in eutrophication, and 9.4 and 9.2 CO_2 equivalent (CO_2-eq.) in global warming in case of European or UK electricity, respectively. The numeric life cycle impacts of the two LCAs were similar even though the LCAs differed in methods and the LED luminaires were different. In contrast, the use of French electricity reduced the life cycle impacts notably. This shows that the results of the LED luminaire LCA are greatly dependent on the energy production mix used in the use stage.

Table 8. Comparison of LED luminaire LCA total life cycle impacts and their division into life cycle stages in LCAs using French (FR), European (EUR), and UK electricity in the use stage [4], [47].

			Impact category (unit)			
	Ref.	Electricity in use	Abiotic (resource) depletion (kg Sb-eq.)	Acidification (kg SO_2-eq.)	Eutrophi-cation (kg PO_4-eq.)	Global warming (kg CO_2-eq.)
Total life cycle impacts per Mlmh	[4]	FR	0.013	0.011	0.00056	2.0
		EUR	0.070	0.040	0.0029	9.4
	[47]	UK	0.071	0.032	0.0024	9.2
Manufacturing and raw materials	[4]	FR	17 %	16 %	39 %	16 %
		EUR	3 %	4 %	8 %	3 %
	[47]	UK	2 %	5 %	5 %	2 %
Transport / Distribution	[4]	FR	0 %	0 %	0 %	0 %
		EUR	0 %	0 %	0 %	0 %
	[47]	UK	0 %	0 %	1 %	0 %
Use	[4]	FR	83 %	84 %	59 %	83 %
		EUR	97 %	96 %	92 %	97 %
	[47]	UK	98 %	95 %	94 %	97 %
EoL	[4]	FR	0 %	0 %	1 %	1 %
		EUR	0 %	0 %	0 %	0 %
	[47]	UK	0 %	0 %	0 %	0 %

The energy production of lower emissions increased the relative significance of manufacturing and raw material acquisition. Table 8 shows the divisions of the impacts into life cycle stages: in case of UK or European electricity in use, manufacturing accounted for 2-8 % and use 92-98 %, and the rest of the life cycle stages (transport, EoL) caused 1 % or less of the environmental impacts in the four categories.

The LCA of the LED downlight luminaire in this work estimated that the luminaire would consume 230 MJ of primary energy and cause 2.0 kg CO_2-eq. per Mlmh over the total life cycle when using French average electricity in use. The total life cycle GWP impacts were approximately 9.4 kg CO_2-eq./Mlmh when using European average electricity in use. In comparison, the DEFRA LED luminaire LCA resulted in the total GWP impacts of 9.2 kg CO_2-eq./Mlmh by using UK electricity in use. The GWP100a factors for the electricity production are 0.087 kg CO_2-eq. for the French, 0.488 kg CO_2-eq. for the European, and 0.598 kg CO_2-eq. for the UK electricity production according to Ecoinvent database [76]. This indicates that the GWP factor of the electricity production in use partially explains the GWP impacts of the total life cycle.

4.3 Study of fluorescent lamp luminaire

4.3.1 Methods

A study on the LCA of a fluorescent lamp luminaire was conducted in 2011-2012 by the author [5]. It analysed a fluorescent lamp luminaire equipped with two linear double-capped fluorescent lamps of 16 mm diameter, an electronic ballast, and a metallic reflector and cover. The geographic location of the LCA was Finland, as the luminaire and the ballast were manufactured by Finnish companies. The LCA was a stand-alone assessment, but the results are compared to the previous LCA by DEFRA [47].

The luminaire accommodated two 49 W fluorescent lamps and provided 8600 lm according to the luminaire manufacturer. The functional unit was the use of the luminaire for 20 years, 4000 hours per year. This is equal to 688 Mlmh per functional unit. The luminaire consumed a total of 104 W electrical power. The life of a fluorescent lamp was estimated 20 000 h and the one of the ballast 50 000 h.

The luminaire is intended for industrial applications, such as manufacturing premises and warehouses. It is a very basic structure containing an aluminium body, an anodized aluminium reflector, plastic end caps, and the ballast and the lamps.

The LCA included the manufacturing, transport, use and end-of-life of the luminaire. The LCA was conducted according to the standards ISO 14040 [32] and ISO 14044 [33]. In addition, the ETSI specification for ICT products was used [31]. All the life cycle stages identified as mandatory in ETSI specification were included in the LCA.

The strength of the LCA is the amount of detailed initial data regarding the manufacturing of the ballast and luminaire cover. Table 9 presents the inventory data of the manufacturing of the fluorescent lamp luminaire. The initial data was gathered from the industry and literature. SimaPro [77] was used as the LCA software with the access to Ecoinvent [76] and ELCD [78] databases.

Table 10 lists a multitude of environmental impact categories considered in the LCA of the fluorescent lamp luminaire. Several impact categories were chosen so that the potential environmental impacts would be widely taken into account.

Table 9. Inventory data of manufacturing of a fluorescent lamp luminaire. Adapted from Tähkämö et al**.** [5]**.**

Raw material, product, or process input	Quantity and unit
Ballast (1 piece)	
Capacitors	18 g
Transformers	54 g
Diodes	1 g
Resistors	4 g
Transistors	1 g
Integrated circuits	0.16 g
Printed circuit board	21 g
Steel	140 g
Plastic parts	12 g
Transport, container ship ocean	5.6 tkm
Transport, lorry	0.2 tkm
Electricity, European	3 kWh
Luminaire (1 piece)	
Electronic ballast	1 piece
Aluminium profile	1352 g
Aluminium, cast alloy	254 g
Steel	32 g
Copper	3 g
Cable	65 g
Plastic parts	116 g
Silicone	7 g
Corrugated board	400 g
Paper	5 g
Packaging film	5 g
Heat, Finnish	33 kWh
Electricity, Finnish	24 kWh
Lamp (1 piece)	
Glass	115 g
Aluminium	3 g
Mercury, liquid	0.005 g
Argon, liquid	0.5 g
Triphosphor	2.5 g
Corrugated board	25 g

Table 10. Environmental impact categories used in the LCA of a fluorescent lamp luminaire. CFC11 stands for trichlorofluoromethane and 1,4-DB 1,4-dichlorobenzene. Adapted from Tähkämö et al. [5].

Environmental impact category	Time interval (years)	Unit (eq.=equivalent)
Abiotic depletion potential	-	kg Sb-eq.
Acidification potential	-	kg SO_2-eq.
Eutrophication potential	-	kg PO_4-eq.
Global warming potential	100	kg CO_2-eq.
Photochemical oxidation potential	-	kg C_2H_4-eq.
Ozone layer depletion potential	40	kg CFC11-eq.
Freshwater aquatic ecotoxicity potential	100	kg 1,4-DB-eq.
Freshwater sediment ecotoxicity potential	100	kg 1,4-DB-eq.
Marine aquatic ecotoxicity potential	100	kg 1,4-DB-eq.
Marine sediment ecotoxicity potential	100	kg 1,4-DB-eq.
Terrestrial ecotoxicity potential	100	kg 1,4-DB-eq.
Human toxicity potential	100	kg 1,4-DB-eq.

The LCA was modelled by using Finnish average electricity in the use stage. The average Finnish electricity is generated from nuclear power (27 %), coal (19 %), hydropower (18 %), natural gas (15 %), wood-based fuels (12 %), peat (8%), and oil and others (1 %) [76]. In addition, a sensitivity analysis was conducted regarding the electricity in use: The use stage was additionally modelled by using Nordic peat and Finnish hydropower. The sensitivity analysis addresses the range of the environmental impacts, as low- and high-emission electricity mixes are used (hydropower and peat).

4.3.2 Results

The study compared the environmental impacts of the luminaire parts: lamps, ballasts and luminaire. Figure 12 illustrates the division of the environmental impacts of the manufacturing of the fluorescent lamp luminaire. The lamps represented approximately 11 % of the average environmental impacts of manufacturing, while the ballast accounted for approximately 43 % and the luminaire cover 46 % of the impacts. However, the lamps caused a notable share (70 %) in the terrestrial ecotoxicity potential impacts (Figure 12). It is frequently claimed that the energy consumption in the use of the light source, or an energy-using product for that matter, is the most significant environmental factor in the LCA. The fluorescent lamp luminaire LCA attested the claim regarding the case study: the environmental impacts were mainly due to use (93 %), while manufacturing accounted for approximately 7 % and EoL and transport less than 1 % on the average [5].

The energy source affected the importance of the use-stage energy consumption: the less-polluting the energy production was, the lower the use-stage impacts and the total impacts were. Figure 13 presents the impact of the three electricity choices (Finnish average, Nordic peat, Finnish hydropower) on the relative environmental impacts of the fluorescent lamp luminaire. As presumed, the hydropower case had clearly the lowest environmental impacts in each category (Figure 13).

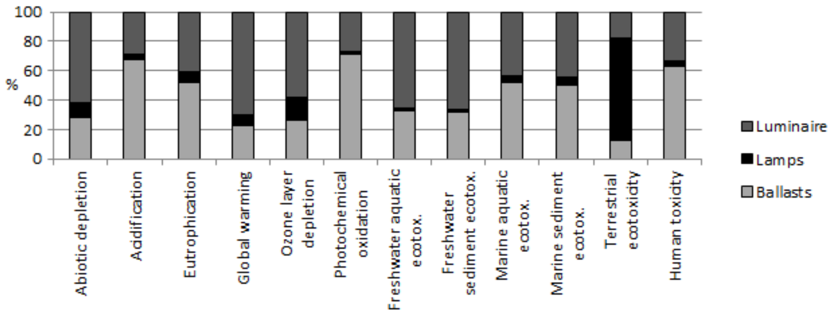


Figure 12. Environmental impacts of the manufacturing of fluorescent lamp luminaire divided into lamps (total eight pieces), ballasts (total 1.6 pieces) and the luminaire cover (one piece) during 80 000 h of operation. Adapted from Tähkämö et al. [5].

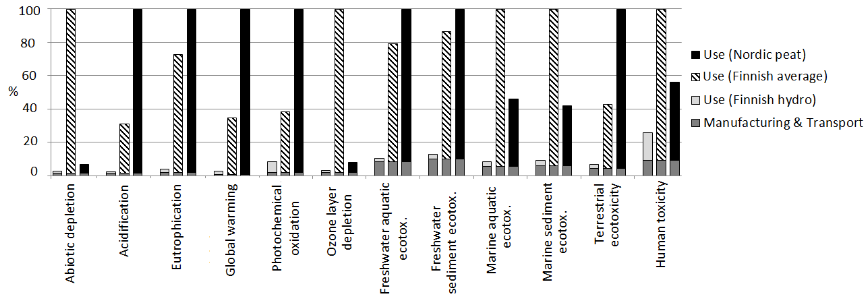


Figure 13. Relative environmental impacts of fluorescent lamp luminaire using three electricity production mixes in use stage: Nordic peat, Finnish average and Finnish hydropower. Adapted from Tähkämö et al. [5].

The fluorescent lamp luminaire LCA in this work was compared to the LCA by DEFRA (Table 11). It should be noted that the lamp powers are different: two 28 W fluorescent lamps in the DEFRA study and two 49 W fluorescent lamps in this work. The power consumptions of the luminaires were 59W and 104 W, respectively. Lamp lives were 24 000 h and 20 000 h, and luminaire lives 48 000 h and 50 000 h, respectively. The fluorescent lamp luminaire in DEFRA study provided approximately 5500 lm and the one in this work 8600 lm. The weights of the luminaires differed (3.79 kg and 2.73 kg) due to the different luminaire structures and materials.

The luminaires may be equipped with lamps of different powers but of the same length. If the amount of megalumen-hours was the same in both systems, the total GWP kg CO_2-eq. per system weight was found to be within 0.4 % in the two LCAs. Another finding was that the total life cycle GWP impact (kg CO_2-eq.) per system weight (kg) was approximately 1.7 times the amount of megalumen-hours: if the fluorescent lamp luminaire provided 688 Mlmh in either of the assessments, the GWP resulted to approximately 1200 kg CO_2-eq. per kg of system.

Table 11. Comparison of parameters and GWP impacts of fluorescent lamp luminaire LCA in this and the DEFRA study. GWP of electricity production retrieved from Ecoinvent [76].

	Mlmh per system	Weight of system	System weight per Mlmh	Total GWP	Total GWP	Manufacturing and distribution GWP	Manufacturing and distribution GWP	GWP factor of electricity production
Ref.	Mlmh/ system	kg	kg/ Mlmh	$kgCO_2$-eq./ Mlmh	$kgCO_2$-eq./kg system	$kgCO_2$-eq./ Mlmh	$kgCO_2$-eq./kg system	$kgCO_2$-eq./kWh
[5]	688	2.73	0.004	4.60	1200	0.066	17	0.384 (Finnish)
[47]	263	3.79	0.014	6.41	440	0.137	10	0.598 (UK)

4.4 Study of street lighting luminaires

The outdoor lighting sector in the EU is facing a major challenge in 2015 after which the HPM lamps cannot be sold, since they do not fulfil the luminous efficacy requirements for the lamps set in the Ecodesign regulation [20]. In 2010, there were approximately 660 000 HPM luminaires in use in Finland [79]. Due to the Ecodesign legislation, a notable effort is needed in the replacement work from HPM lamps to other outdoor lighting technologies.

The LCC study presented in the following was part of SolarLED research project [80] in the Lighting Unit of Aalto University School of Electrical Engineering. The life cycle approach and LCC analysis were the responsibilities of the author in the SolarLED project.

4.4.1 Methods

An LCC analysis of street lighting luminaires compared ten renewed street lighting cases in Finland. The environmental assessment of the street lighting technologies was excluded. The cases were located in Southern Finland in the municipality of Kotka (cases A and B), Kerava (case C) and Espoo (cases D to J). The LCCs were calculated from the point of view of the users, which were the respective municipalities in this case. The functional unit of the LCC analysis was a kilometre of illuminated street.

Street and road lighting are designed in Finland according to national guidelines [38] based on the European standards EN 13201:2-4 [81, 82, 83] and the technical report EN 13201:1 [84]. The design criteria for roads with motorised traffic are based on six lighting classes: AL1, AL2, AL3, AL4a, AL4b, and AL5. Photometric criteria are set for each lighting class in order for the road lighting to fulfil the visual needs of road users. The recommendations for road lighting apply to average road surface luminance (L_{ave}), overall and longitudinal uniformities of road surface luminance (U_o, U_l), surround ratio (SR), and threshold increment (TI). The road lighting shall be designed so that the recommendations and design criteria are fulfilled according to the lighting class. Table 12 presents the design criteria for the six lighting classes.

Table 12. Design criteria for luminance, disability glare and lighting of surroundings in Finnish road lighting classes AL1-AL5 for motorized vehicles on traffic roads [38].

Class	Luminance of road surface of carriageway for dry and wet road surface condition				Disability glare	Lighting of surroundings
	Dry condition			Wet condition		
	L_m	U_o	U_l	U_o	TI	SR
	[cd/m2], minimum	minimum	minimum	minimum	[%], maximum	minimum
AL1	2	0.4	0.6	0.15	10	0.5
AL2	1.5	0.4	0.6	0.15	10	0.5
AL3	1	0.4	0.6	0.15	15	0.5
AL4a	1	0.4	0.4	0.15	15	0.5
AL4b	0.75	0.4	0.4	0.15	15	0.5
AL5	0.5	0.4	0.4	0.15	15	0.5

The goal of the LCC analysis was to compare the costs occurring during the life cycle of the renovated street lighting cases, including purchase costs, operating costs and residual value. Purchase costs included the price of the luminaire, including the lamp and freight, and the costs of installation. The luminaire price excluded value added tax in the street lighting cases. Operating costs included the energy and maintenance costs, i.e., the electricity costs and replacement costs of the lamps and luminaires. Replacement costs contained group replacement costs, as spot replacement costs were excluded. The residual value represents the return or cost of the investment after the service time. In Equation 2, the residual value is negative if there is a profit in the end-of-life of the product, and positive if the end-of-life creates costs, such as recycling costs. As the service period of street lighting is long, approximately 30 years, the present value of the residual value remains low.

Base cases

Table 13 introduces the ten renewed street lighting cases in the LCC analysis in Finland. These ten cases were considered as the *base cases* in contrast to *variant cases* introduced in the next subchapter. Cases A to C have been presented in Tähkämö et al. [6], and cases D to J represent the additional cases conducted in this work.

The luminaire replacements took place in 2009-2010. In cases A to C, the old luminaires were equipped with HPM lamps. In cases D to J, the previous lamps were retrofit HPS lamps (110 W) that were installed to replace the original HPM lamps in the same luminaires in 1996-2000. The luminaires were replaced by HPS luminaires (cases A, B, I), LED luminaires (cases C to H), or induction luminaires (case J). It should be noted that, in the new installation of the case I, the HPS lamp had an especially long life (48 000 h) due to the special type of the lamp. HPS lamps normally have a life of 16 000-24 000 h. The new luminaires were installed in the existing poles except for case C. The case C was modelled here only by considering the purchase price and installing costs of the LED luminaires. In reality, there was additional costs of approximately 1 000 €/pole from the purchase and installing of the poles, cables and bases in the case C.

The LCC analysis was modelled to represent the actual cases in Finland. The electricity prices, including the electricity and the transmission, were the actual ones of the municipalities. In Espoo (cases D to J), the electricity price was calculated combining the day- and nighttime tariffs of both the electricity and the transmission. The purchase costs and the group replacement costs included the installing costs and the purchase prices of the luminaires. In cases D to J, it was possible to obtain data as detailed as separated into lamp price, luminaire price, cost of the worker, cost of the assembly truck and driving to and from the place of installation.

The nominal discount rate was estimated to be 6 % and inflation 3 % [38]. Thus, the real discount rate is approximately 2.91 %. The time scale of the calculation was 30 years. No fixed costs were included. The residual value is calculated to represent 25 % of the investment cost according to the Finnish Road Administration [38]. The costs of cleaning of the luminaires and other maintenance were excluded from the LCC analysis due to the high uncertainty in the need of such operations and in estimating their duration and costs.

The development of the LED technology was taken into account in the LCC analysis. The group replacement cost and luminaire power were changed in the cases C to H on the basis of an estimate of the technology development in terms of luminous efficacy and purchase price. The development of LED luminaires was cautiously estimated. Figure 14 illustrates the predictions of the price development and luminous efficacy of LED package and luminous efficacy of LED luminaire. The references used in Figure 14 are from year 2010 [85] and 2012 [86]. As seen in Figure 14, the 2012 estimates are somewhat more cautious compared to the 2010 estimates of LED package luminous efficacies. In contrast, the price reduction of the LED packages is estimated to be even more rapid than in 2010.

Table 13. Information on the street lighting cases A to J.

Quantity	Unit	case A	case B	case C	case D	case E	case F	case G	case H	case I	case J
Pole spacing, average	m	26	32	30	27	27	27	27	28	28	29
Number of lamps/luminaires	pcs	400	60	14	4	4	4	4	4	4	4
Operating time	h/a	4000	4000	4000	3900	3900	3900	3900	3900	3900	3900
Electricity price (electricity + transmission)	€/kWh	0.082	0.083	0.045	0.061	0.061	0.061	0.061	0.061	0.061	0.061
Old installation Lamp type		HPM 125W	HPM 250W	HPM 125W	HPS 110W	HPS 110W	HPS 110W	HPS 110W	HPS 110W	HPS 110W	HPS 110W
Measured luminaire power	W	140	284	140	143	143	143	143	143	143	143
Lamp group replacement period	a	3	3	3	6	6	6	6	6	6	6
Lamp life	h	12000	12000	12000	24000	24000	24000	24000	24000	24000	24000
Group replacement cost	€/pcs	13.13	15.9	-	27.86	27.86	27.86	27.86	27.86	27.86	27.86
Spot replacement cost, additional cost	€/pcs	33	36	-	-	-	-	-	-	-	-
Amount of spot replacements	%	2 %	2 %	-	-	-	-	-	-	-	-
Maintenance costs, overall	€/pcs,a	-	-	13.68	-	-	-	-	-	-	-
New installation Lamp/Luminaire type		HPS 50W	HPS 100W	LED 59W	LED 84W	LED	LED	LED	LED 86W	HPS 100W	Induction 85W
Measured luminaire power	W	63	114	60	110	140	134	108	95	114	77
Luminaire power in 2020 (+75% in efficacy)	W	-	-	34	63	80	77	62	54	-	-
Life of the lamp/luminaire according to manufacturer	h	16000	16000	75000	65000	50000	50000	100000	50000	48000	100000
Lamp/luminaire group replacement period, assumption	a	4	4	18	16	12	12	25	12	12	25
Purchase cost of the luminaire incl. installation costs	€/pcs	192	294	791.3	881.7	670.7	625.7	857.7	969.6	256.4	745.7
Group replacement cost	€/pcs	18.5	19.5	178.2	196.6	164.9	158.2	193.0	209.7	33.1	-
Spot replacement cost, additional cost	€/pcs	40	43	-	-	-	-	-	-	-	-
Amount of spot replacements	%	2 %	2 %	-	-	-	-	-	-	-	-

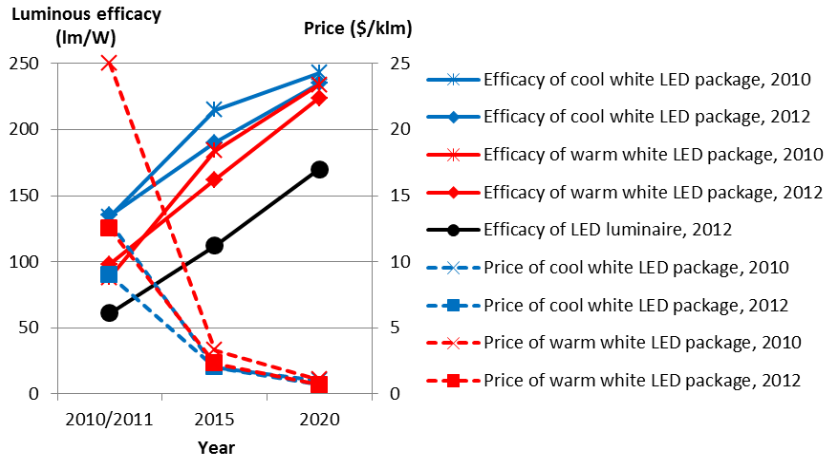


Figure 14. Predictions of cool and warm white LED package price development and luminous efficacy and LED luminaire efficacy. Year 2010 estimate from [85] and year 2012 [86].

In the base cases C to H (LED luminaires), the group replacement of the LED luminaires took the price and luminous flux development into account. The luminous efficacy of the LED luminaire was estimated to increase by 75 % by the time of replacement. Since the calculations did not address the luminous efficacy, the increase in the luminous efficacy affected the luminaire power by reducing it accordingly. The price of the LED luminaire was estimated to decrease by 85 % by the time of group replacement. The estimates for the future LED luminaires were cautious. The prediction of the LED package was assumed only partially to translate into the development of an LED luminaire, as the luminaire contained other parts having different development prospects.

The luminous properties of the ten base cases, including old and new luminaires, were measured by Aalto University Lighting Unit in the frame of SolarLED [80] and EkoValo [87] projects. Table 14 presents the measured characteristics of the street lighting: L_{ave}, U_o, U_l, and TI. Table 14 indicates with green and red colour whether the case fulfils the design criteria of the respective lighting class according to the national recommendations (Table 12). It was not possible to measure the case C before the renewal of the luminaires. In addition, at the time of measurement of the new luminaires, the road surface was not asphalt but gravel in case C. TI values were not measured in cases A, B and C and in new luminaires in cases I and J.

Table 14. Lighting classes and measured luminous properties of street lighting cases (IND=induction luminaire). Green cells indicate that the design criteria of the respective lighting class are fulfilled, while the values not fulfilling the criteria are marked with red cells.

Quantity	Unit	case A	case B	case C	case D	case E	case F	case G	case H	case I	case J
Luminaire replacement		HPM 125W to HPS 50W	HPM 250W to HPS 100W	HPM 125W to LED 59W	HPS 110W to LED 84W	HPS 110W to LED	HPS 110W to LED	HPS 110W to LED	HPS 110W to LED 86W	HPS 110W to HPS 100W	HPS 110W to IND 85W
Lighting class		AL4b	AL3	AL5	AL4b	AL4b	AL4b	AL4b	AL4b	AL4b	AL5
Old installation											
Luminous flux	lm	1020	6980	-	5010						
Correlated colour temperature CCT	K	2600	3600	-	1800						
Colour rendering index CRI (Ra)		60	47	-	25						
Luminous efficacy of luminaire	lm/W	7	25	-	35						
L_{ave}	cd/m²	0.06	0.35	0.3	0.64				0.89	0.91	0.4
U_o		0.48	0.47	0.22	0.5				0.5	0.51	0.6
U_l		0.38	0.4	0.15	0.6				0.6	0.58	0.5
TI	%	-	-	-	12				12		
New installation											
Luminous flux	lm	2940	8380	3410	6320	7880	5280	6320	5600	6880	4380
Correlated colour temperature CCT	K	1900	2000	6500	6200	6700	3200	3500	4600	2000	3100
Colour rendering index CRI (Ra)		15	31	76	71	83	71	84	80	27	78
Luminous efficacy of luminaire	lm/W	47	74	57	57	56	39	59	59	60	56
L_{ave}	cd/m²	1.1	1,6	0.62	1.84	1.2	0.88	0.78	1.3	0.62	0.4
U_o		0.15	0.36	0.51	0.5	0.2	0.3	0.5	0.2	0.59	0.6
U_l		0.32	0.69	0.5	0.5	0.6	0.3	0.5	0.52	0.47	0.5
TI	%	-	-	-	10	7	8	13	6	-	-

The luminous characteristics, such as luminous flux, colour rendering index, and correlated colour temperature, were excluded from the scope of the LCC analysis. In addition, the lighting design criteria were not included in the functional unit, as there is no method for it. The results of the measurements in Table 14 were not exactly comparable to each others, since there were differences in the environment: diffused light from other light sources, trees partially shading the luminaires, different curving and geometry of the streets, and gravel instead of asphalt (case C). As seen in Table 14, all design criteria are not fulfilled in most old installations and in several new installations. The new installations do not fulfil all the criteria due to their installation on the existing poles that are not at optimal distance.

Variant cases

The variant cases were based on the estimates of the development in the LED luminaire price and luminous flux [85, 86]. Two types of variants were introduced: 1 and 2. Variants 1 (cases C1, D1, E1, F1, G1 and H1) describe the situation in which the LED luminaire was purchased in 2015 and no spot or group replacements were taken into account. This is based on an assumption that the life of the LED luminaire is increased so that replacements during 30 years of operation are not needed. Variants 2 (cases C2, D2, E2, F2, G2 and H2) were likewise installed in 2015 but, in contrast to variants 1, they took the group replacement into account on the basis of the lives of the luminaire indicated by the manufacturers.

In the variant cases, the luminaires were first installed in 2015. The luminous efficacy of the LED luminaire was estimated to increase by 50 % in 2015 and by 75 % in 2020, and the purchase price reduced by 65 % and 85 %, respectively, compared to 2010. The luminous efficacy affected only the luminaire power in the LCC analysis, as the luminous fluxes were assumed to remain constant. The luminaire prices at the time of group replacement were estimated on the basis of 2020 estimates due to the lack of reliable estimates for a later point in time.

Table 15 illustrates the variant cases regarding the data that differs from the respective base cases. The variant cases used average electricity price for Finnish municipalities (0.095 €/kWh), as in Tähkämö et al. [6]. The purchase costs were reduced on the basis of the estimated luminaire price reduction, while the installation costs were assumed to remain unchanged. The costs of labour and equipment may rise, but the new luminaires may be easier to install.

Table 15. Information on the variant cases of LED cases C1 to H2 regarding the data that differs from the one of the base cases. Each variant case (1 and 2) corresponds to respective base case, e.g., C1 and C2 are based on case C in Table 13. Variant cases 1 (C1 to H1) are installed in 2015 and no group replacements are taken into account, while variant cases 2 (C2 to H2) are likewise installed in 2015 but consider also the group replacements according to the life of the luminaire.

Quantity	Unit	C1	C2	D1	D2	E1	E2	F1	F2	G1	G2	H1	H2
Luminaire replacement		HPM 125W to LED		HPS 110W to LED		HPS 110W to LED		HPS 110W to LED		HPS 110W to LED		HPS 110W to LED	
Electricity price (electricity + transmission)	€/kWh	0.095		0.095		0.095		0.095		0.095		0.095	
New installation													
Luminaire power in 2015 (+50% in efficacy)	W	40		73		93		89		72		63	
Luminaire power in 2020 (+75% in efficacy)	W	34		63		80		77		62		54	
Life of the lamp/luminaire according to manufacturer	kh	>75	75	>65	65	>50	50	>50	50	>100	100	>50	50
Lamp/luminaire group replacement period, assumption	a	30	18	30	16	30	12	30	12	30	25	30	12
Purchase cost of the luminaire incl. installation	€/pcs	322.5		357.8		283.9		268.2		349.4		388.5	
Group replacement cost	€/pcs	178.2		196.6		164.9		158.2		193.0		209.7	

4.4.2 Results

The LCC analysis results of the cases A to J are collected in Table 16. The investment costs of the cases C to H, in which LED luminaires were installed, were clearly greater (23 170 – 34 630 €/km) than the ones with HPS (7 380 – 9 160 €/km) and similar with induction (25 710 €/km) luminaires. The savings from the operating costs were low (7 – 260 €/km) in cases D to H due to the modest reduction in luminaire power from the old luminaire to the LED luminaires (reduction in power 3 – 48 W). The savings in operating costs in cases D to H were low also because of the installation of the luminaires in existing poles and not optimizing the pole distance.

The payback times of cases A and B were viable (5 – 9 a), while the rest of the cases had payback times approximately 30 years or more, which exceeds the 30 year time scale of the calculation. The payback times should remain as low as possible in order for the renewal to be profitable in monetary terms.

The LCCs of the cases A, B and I (new installation of HPS luminaire) were divided into discounted energy costs (56 %, 62 %, 62 %), investment costs (26 %, 25 %, 29 %), discounted maintenance costs (15 %, 10 %, 6 %) and discounted residual value (3 %). The LCCs of the cases C to H with LED luminaires were mainly caused by the investment costs, approximately 44 % to 63 % of the LCCs (average 53 %). Discounted energy costs accounted for approximately 14-33 % (average 26 %), maintenance costs 10-20 % (average 16 %) and residual value 5-7 % (average 6 %) of the LCCs of LED luminaires. The case J (induction luminaire) divided the LCCs between investment costs (63 %), energy costs (30 %) and residual value (7 %). Case J excluded the group replacement during 30 years of operation. The operating time of an induction lamp was estimated at 100 000 h. No lamp price data was available, since the induction luminaire was sold as one entity (670 €/piece).

The savings in operating costs from the renewal varied significantly in the studied cases (Table 16). The savings from operating costs depended on the differences in the luminaire power of the old and new installation and in the maintenance costs. The greatest savings in operating costs (1750 €/km, a) were achieved in case B due to the significant reduction in the luminaire power (from 284 W to 114 W measured luminaire power). Case A saved approximately 950 €/km per year and case C 670 €/km per year. Cases D to H created savings ranging from only 7 to 260 €/km per year in operating costs. In addition, the group replacement cost of the LED luminaires was higher compared to the conventional luminaires having only a lamp to replace, not the whole luminaire as in case of LED luminaires.

The variant cases considered the development of LED luminaire luminous efficacy and price reduction. Table 17 presents the results of the LCC analysis regarding the variant cases. As seen in Table 17, the savings in operating costs in the variant cases (C1 to H2) were highly increased from the ones in base cases C to H. It must be noted that the variant cases use 0.095 €/kWh as the electricity price, which increases the savings in operating costs. The savings resulted in payback times under 30 years in most variant cases.

The luminous efficacies of the luminaires in this case study do not represent all luminaires of the technology but are only cases of real-life luminaires. The old HPS luminaires with a retrofit lamp in cases C to J had luminous efficacy of only approximately 35 lm/W, which is considered quite low. The new HPS luminaire in cases A, B and I had the luminous efficacies of 47 lm/W, 74 lm/W and 60 lm/W, respectively. The luminous efficacy of the LED luminaires in cases C to H ranged between 39 and 59 lm/W at the time of installation, between 59 and 89 lm/W in 2015, and between 68 and 103 lm/W in 2020. There is always difference between the luminous efficacies of certain types of luminaires and the above mentioned values represent only the measured luminaires. Currently, the LED luminaire luminous efficacy is approximately 80 lm/W [88] but greater efficacies are possible, approximately 100 lm/W and above.

Figure 15 presents the division of LCCs of the cases into investment costs, operating costs (energy, maintenance) and residual value. The total LCCs of the cases were on an average 32 200 €/km in cases A, B and I (HPS cases); 55 200 €/km in cases C, D, E, F, G and H (LED cases); 32 400 €/km in LED variant cases 1 (installation in 2015, no group replacement); 40 000 €/km in LED variant cases 2 (installation in 2015, group replacement according to luminaire life); and 41 000 €/km in induction luminaire.

Figure 15 shows that the LED base cases (C to H) had high investment costs due to the high purchase price of LED luminaires in 2009-2010. Similarly, the induction luminaire case had also high investment costs. In contrast, the LED variant cases C1-H2 showed that the LCCs are reduced, as the investment costs were reduced in the foreseen 2015 installation. Most LED cases (cases D to H) had total LCCs greater than 50 000 €/km except for case C that provided a significant reduction in luminaire power from old to new luminaire. The HPS lamp in case I (life of 48 000 h) had low maintenance costs but a high share of energy costs.

Table 16. Results of the LCCs of street lighting renovation cases: change from HPM to HPS (cases A, B and I), from HPM to LED (case C), from retrofit HPS to LED (cases D to H) and from retrofit HPS to induction (case J) technologies.

Quantity	Unit	case A	case B	case C	case D	case E	case F	case G	case H	case I	case J
Investment costs (luminaires)	€/km	7380	9190	26380	32650	24840	23170	31760	34630	9160	25710
Operating costs, old	€/km, a	1970	3110	1300	1430	1430	1430	1430	1380	1380	1330
Operating costs, new	€/km, a	1020	1360	630	1230	1430	1370	1170	1220	1070	630
Residual value, calculatory	€/km	1850	2300	6590	8160	6210	5790	7940	8660	2290	6430
Present value of life cycle costs	€/km	28300	37100	41600	60500	55700	52700	58300	62500	31300	41000
Simple payback time	a	8	5	-	-	-	-	-	-	29	-
(Discounted) Payback time	a	9	6	-	-	-	-	-	-	-	-

Table 17. Results of the LCCs of variant cases of street lighting. Retrofit HPS lamp luminaires (110 W lamp) are replaced by various LED luminaires. Variant cases 1 (C1 to H1) are installed in 2015 and no group replacements are taken into account, while variant cases 2 (C2 to H2) are likewise installed in 2015 but consider also the group replacements according to the life of the luminaire.

Quantity	Unit	case C1	case C2	case D1	case D2	case E1	case E2	case F1	case F2	case G1	case G2	case H1	case H2
Investment costs (luminaires)	€/km	10750		13250		10510		9930		12940		13880	
Operating costs, old	€/km, a	2230		2130		2130		2130		2130		2060	
Operating costs, new	€/km, a	510	810	1010	1390	1280	1680	1230	1610	990	1250	840	1390
Residual value, calculatory	€/km	2690		3310		2630		2480		3230		3470	
Present value of life cycle costs	€/km	21900	27900	34600	42300	37000	44900	35300	42900	33900	39100	32000	42900
Simple payback time	a	6	8	12	18	12	23	11	19	11	15	11	21
(Discounted) Payback time	a	7	9	15	26	15	-	13	28	14	19	14	-

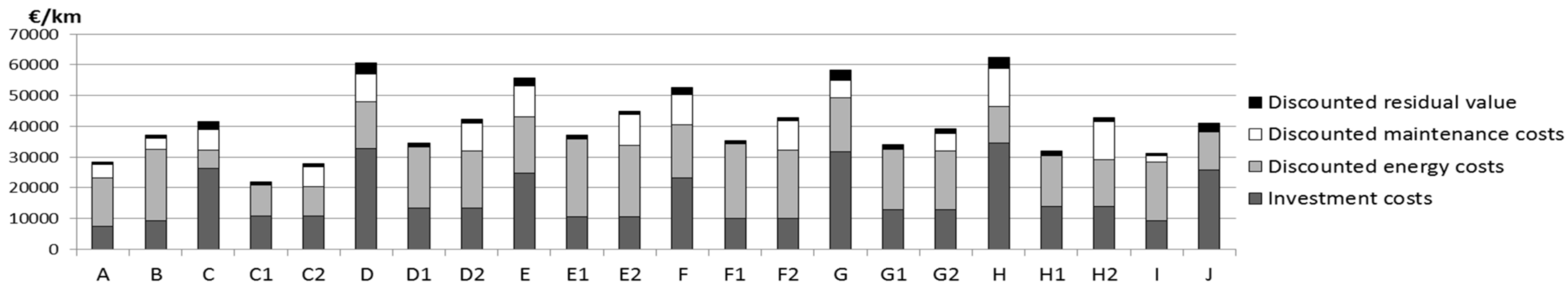


Figure 15. Life cycle costs (€/km) of street lighting cases A to J and variants of LED cases C1 to H2. Variants 1 consider only the initial installation in 2015, while variants 2 take also the group replacements into account according to the lives of the luminaire indicated by the manufacturers.

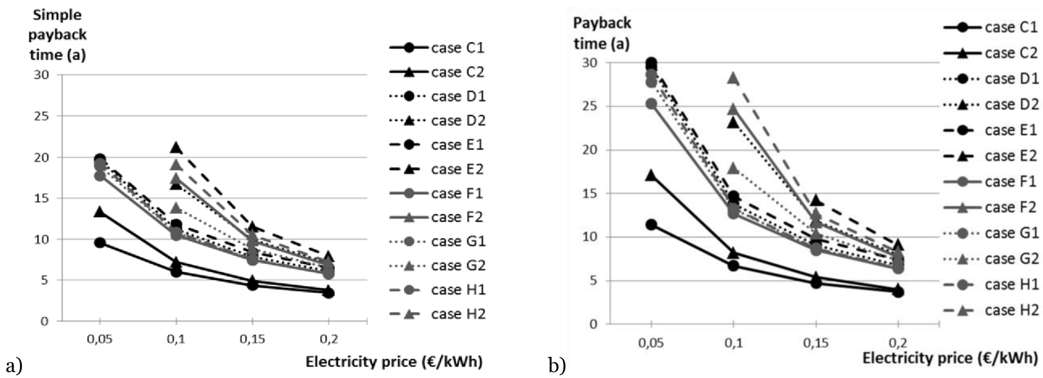


Figure 16. Simple payback time (a) and payback time (b) of the variant cases C1 to H2 when the electricity price is 0.05€/kWh, 0.10 €/kWh, 0.15 €/kWh and 0.20 €/kWh. Payback time takes the time value of the money into account. Payback times greater than 30 years are excluded, since the time scale of the calculation is 30 years.

The payback times of the variant cases (from C1 to H2) of LED luminaires are illustrated in Figure 16. It shows that as the electricity price increases, the payback times will become shorter. The payback times using average European electricity (0.10 €/kWh in 2012 [74]) were similar to the ones of the variant cases. Figure 16 indicates also that the variants 2 (group replacement included) had greater payback times compared to respective variants 1 (no group replacements). The difference between the two variants was reduced as the electricity price increases. It should be noted that the variants 1 included only the initial installation, and the luminaire power remained the same over the 30-year time scale. In contrast, variants 2 took the initial installation and the group replacement into account, and the luminaire power was reduced after the group replacement, since the luminous efficacy of the LED luminaire was estimated to increase.

All the LED cases (cases C to J) contained only a small number of luminaires (4 to 14 pieces). Thus, the luminaire prices were higher than they would be in case of an installation of hundreds of luminaires. In addition, the price of LED luminaires is predicted to decrease due to the price reduction of the manufacturing costs and intensified competition on the market [86].

4.5 Summary

This chapter presented four LCAs and/or LCC analyses: a simplified LCA and LCC analysis of non-directional lamps used in households, LCA of an LED downlight luminaire, LCA of a fluorescent lamp luminaire, and LCC analysis of street lighting luminaires. All of the assessment methods differed from each other.

The simplified assessment of the non-directional lamps compared the primary energy consumption and the costs from the user's point of view regarding the manufacturing and use. The simplified assessment used four functional units. The choice of the functional unit affected the results of the assessment, but no significant differences were found whether the functional unit was an hour, megalumen-hour, or illuminance on 1 m distance on a 1 m^2 surface. The primary energy consumption of manufacturing was fairly insignificant. In contrast, the manufacturing cost (modelled as purchase price) was found to account for a notable share of the LCCs in case of CFL (approximately 32 %) and LED lamp (58 %).

The LCA of the LED downlight luminaire concluded that the manufacturing stage caused approximately 23 % of the life cycle impacts, while the use accounted for 76 % when average French electricity was used in the use stage. In contrast, if European average electricity production was used during operation, the life cycle impacts would be divided between the manufacturing (7 %) and use (93 %). Manufacturing impacts were mainly (over 80 %) due to the driver, LED array and aluminium parts (reflector, heatsink). Other life cycle stages, such as transport, installation and EoL, were found to be insignificant in the total life cycle scope. The choice of the EoL scenario did not affect the total life cycle results. The study indicated that the life cycle results are sensitive to the life of the product and the electricity mix in use.

The environmental impacts of the fluorescent lamp luminaire were divided into manufacturing (7 %) and use (93 %) when use was modelled as Finnish average electricity production. Other life cycle stages (transport, EoL) accounted for less than 1 %. Manufacturing impacts were divided between the luminaire cover (46 %), ballast (43 %) and lamps (11 %) on the average. The study showed that the life cycle results are sensitive to the electricity mix in use, and the relative impact of other life cycle stages, notably manufacturing, is increased when the energy production is shifted towards low-emission energy sources, such as hydropower.

As a conclusion in the LCC analysis of street lighting cases, the LED luminaires were not economically profitable solution in small-scale installations in 2009-2010. However, the profitability of LED luminaires is significantly improved in large-scale installations lowering the purchase price, by using optimised pole spacing to utilise the LED luminaire optics, and by the increase in electricity price. The LED luminaire prices are reduced also due to the mass-production and reduction in component prices.

The LCC analysis showed that in case of HPS luminaires, the energy costs account for approximately 60 %, investment costs 27 %, maintenance costs 11 % and residual value 3 % of the LCCs. In contrast, the LCCs of the LED luminaire are divided into energy costs (average 26 %), investment costs (53 %), maintenance costs (16 %) and residual value (6 %). In the induction luminaire case, the energy costs covered 31 %, investment costs 63 % and residual value 7 % of the LCCs. It is seen in the LCC analysis of the street lighting luminaires that the energy and investment costs cause the majority of the LCCs.

On the basis of the four cases carried out in this work in Chapter 4 and the analysis of previous LCAs from 1991 to 2012 in Chapter 3, two models are created for conducting the LCA of light sources: a simple model and an extensive model. Table 18 describes the two models. The simple model is intended to be used when the resources are very limited and the results are needed rapidly. The simple model is created so that the presumed major environmental aspects are taken into account. The extensive model is intended for a more detailed assessment, but it also simplifies the method from a detailed LCA. The models are created for LCAs of lamps and luminaires.

The functional unit is recommended to be lumen-hours in the simple model. Lumen-hours depend on the luminous flux and the operating hours of the light source. Lumen-hour fulfils the criteria for the functional unit established in the standard ISO 14044 [33]: it is clearly defined, measurable and relates to the function of the product, i.e., lamp or luminaire. In the extensive model, the functional unit shall take the application of the light source into account. For instance, in indoor applications, the recommended functional unit is a direct illuminance at a distance on a surface per hour. The distance and the surface area should be specified according to the application. In outdoor applications, the recommended functional unit should take the design criteria into account, as the lighting is designed to fulfil the criteria. However, the case-specific functional unit shall be applied especially in the comparative LCAs. In the stand-alone LCAs, the functional unit may be lumen-hours so that the results are comparable to other LCAs. At least, the stand-alone LCA of light sources is strongly recommended to provide the luminous flux and the life of the light source.

Table 18. Models for a simple and extensive method of LCA of light sources.

Parameter	Simple model	Extensive model
Functional unit	Lumen-hours (e.g., Mlmh)	Case-specific, related to the function of the light source in a specific application In indoor applications: illuminance at a distance on a surface per hour In outdoor applications: related to the lighting design criteria, relative to road metre or surface illuminated
Life cycle stages	Manufacturing Use	Raw material acquisition and manufacturing Use EoL
Environmental impacts	Limited number of impact categories, e.g., only primary energy consumption or GWP	Several impact categories, e.g., GWP, AP, EP, POCP, ODP, toxicity categories (human, eco-), waste categories (hazardous, non-hazardous)
Energy source in use stage	Primary energy	Actual energy production, and high- and low-emission energy production

The simple model shall consider the manufacturing and use. Manufacturing shall include the materials of the light source or the energy embodied in the materials. The extensive model shall consider raw material acquisition and manufacturing (raw materials and manufacturing processes), use, and EoL.

The LCA of light sources may be a stand-alone or a comparative assessment. In case of a comparative LCA, the comparison should be lamp to lamp, or luminaire to luminaire, and any identical parts or processes of the compared products may be excluded. In contrast, in a stand-alone LCA, the exclusion of parts or processes is not recommended. Cut-off rules may be applied according to a specification or a PCR applied.

5 Discussion

Four LCA and/or LCC analyses of lamps and luminaires are conducted in this work. In addition, the author analysed the previous LCAs of lamps and luminaires found in the literature. The work showed that there is a variety of LCA methodologies (e.g., functional unit and life cycle stages) and initial data. Despite these differences, it was found out that the LCAs of light sources typically conclude the use stage to cause the majority of the life cycle environmental impacts. Consequently, the energy-efficient light sources, such as the CFL and LED lamp or luminaire, cause lower total life cycle environmental impacts compared to the conventional light sources, such as the incandescent lamp.

The dominance of the use stage in the life cycle impacts generally applies to the LCAs of light sources. However, the impact of other life cycle stages is likely to increase, especially the manufacturing. This is partially due to the shift towards more energy-efficient light sources but also due to the more detailed analyses of the manufacturing stage.

The LCA and LCC studies of light sources in this work were used as the basis for creating two models for the LCA method. The two models were created in order to simplify the LCA method without ignoring major environmental aspects of light sources. The models enable simplified and rapid conduction of the LCA, which is needed in the constantly evolving market of light sources. Especially the renewal rate of LED lamps and luminaires is very rapid, and there are countless LED products on the market. In order to analyse the environmental impacts of the constantly changing products, rapid methods are needed.

There is an analogy between the comparison of the LCA of electrical and electronic products and the LCA of an incandescent lamp and LED lamp. The electrical product (incandescent lamp) has typically stable manufacturing processes, uses common materials, has established use patterns, develops slowly and has a simple structure, while the electronic product (LED lamp) is developed fast with a short innovation time, has unestablished use patterns, contains special materials and has a complex structure. Therefore, it is challenging to compare the light sources of very different structures and to analyse the environmental impacts of LED light sources in detail.

The LED downlight LCA in Chapter 4.2 and its comparison to the LED luminaire LCA [47] showed that the use stage of the LED luminaire accounts for over 92 % of the four environmental impact categories (ADP, AP, EP, GWP). The energy production of the use stage determines the results: if the average French energy was used, the environmental impacts differed greatly from the ones of the average European energy, when the LCA method was otherwise the same.

The LED component in the downlight luminaire was modelled in the LCA as an indicator LED from the Ecoinvent database by multiplying its weight by a factor of five. Even with the somewhat exaggerated estimate, it was found out that the LED component caused only a marginal share of the total life cycle impacts of the LED luminaire in this work. In addition, the US DOE part 2 report [44] indicated that a high-power LED component actually caused 94.5 % lower environmental impacts than the indicator LED in the Ecoinvent database. The US DOE report was, however, based on the increase in the luminous flux.

It is difficult to establish an appropriate basis for the assessment of the environmental impacts of an LED, since the application of the LED differs from the one of the electronic components in general, such as a resistor or a capacitor. An update in the LCIA database is needed in order to evaluate the environmental impacts of the LED component more precisely. It is recommended that an LCIA database would provide data for a high-power LED component and would state both the luminous flux and the weight of the LED component. This would enable the future LCAs to analyse and compare LED light sources in an in-depth manner.

The objectives of the research work have been achieved, as the work introduces two models for the simplified conduction of the LCA of light sources and analyses the previous LCAs of light sources. However, the models are on a very gerenal level, so that they can be applied on any type of a light source. Despite this work, a need for detailed guidelines remains regarding different lighting applications, since the work suggests no detailed rules, i.e., PCRs, for the light sources of certain applications. The models created in the work may assist in the creation of the PCRs of light sources. A set of PCRs would complete the LCA method for light sources.

The work concentrates on the environmental point of view but analyses additionally the economic aspects in a simplified analysis of non-directional household lamps and conducts an LCC analysis of street lighting luminaires. The methods for LCAs and LCC analyses are similar, and both are part of the total sustainability assessment. Thus, a method for combining the environmental and economic analyses is needed in the future in order to make the combined assessment reliable and easy to use. Currently, the environmental LCA and the economic LCC analysis are mainly conducted either separately or considering the costs as one impact category in the LCA.

The LCA enables the identification of the environmental hot spots and, if used as a tool in the product development, the reduction of the environmental impacts. The LCC analysis evaluates the economic performance over the life cycle and provides the estimate of future costs. However, both types of analyses are in this work used from the point of view of a product and product comparison. The amount of luminaires or the effect to the whole lighting market is not considered. In order to analyse the total impact, the changes in the market need to be analysed. The current lighting market needs to be mapped in addition to the estimated market in the future. The lighting market is suspected to experience a rebound effect in which the energy efficiency of the light sources is increased but the energy saving potential is not fully achieved because of the simultaneous increase of the amount of light sources in use [89, 90]. The reduction in the purchase price of the light sources is one driver for the rebound effect and the increased wealth enables it. The work can be completed with a study of the whole lighting market and the estimated environmental and economic impacts of the market changes in the future. The lighting design has a role in the prevention of the rebound effect.

The LCAs of light sources do not consider the environmental impacts of light. The artificial light affects the living organisms directly and indirectly in many ways; e.g., birds may suffer from disorientation, birds and reptiles may start extending their hunting and eating period to the night time, birds and insects are attracted by the artificial light making it easier for the predators to detect them, and plant growth and flowering are affected by the colour, amount, timing and duration of the light [91]. It is evident that there is no method for combining the conventional LCA results, e.g., in unit of kg CO_2-eq., with the environmental impacts of light. Lighting design has a notable role also in the reduction of negative environmental impacts of artificial light.

6 Conclusions and recommendations

The primary aim of the work was to create a model for a method for conducting the LCA of light sources. The work established two models for the method for conducting an LCA of light sources on the basis of the LCAs conducted in Chapters 4.1-4.3 and the analysis of the previous LCAs in Chapter 3. The two models, the simple and the extensive one, act as guidelines for the LCAs of lamps and luminaires. The simple model offers guidelines for a rapid, highly simplified LCA to be conducted with limited resources. The extensive model provides a method for a more detailed LCA, yet it also simplifies the LCA. Despite the simplifications, the models are designed to consider the major environmental aspects of light sources. The models enable rapid LCAs which are needed in the constantly evolving market of light sources, especially LED lamps and luminaires.

The functional unit is a key parameter in the LCA. In case of light sources, the functional unit is recommended to be lumen-hours in the simple LCA model. Lumen-hour is clearly defined, measurable and relates to the function of the light source: luminous flux and operating time. The extensive LCA model recommends the use of a case-specific functional unit, e.g., illuminance at a distance on a surface per hour. This applies especially to the comparative LCAs, while the stand-alone LCAs should indicate the luminous flux and the life of the light source so that further comparison is possible.

It is noted that the case-specific functional unit is difficult to define in outdoor lighting. For instance in street lighting, there are five parameters in the lighting design criteria: average road surface luminance (L_{ave}), overall and longitudinal uniformities of road surface luminance (U_o, U_l), surround ratio (SR), and threshold increment (TI). The purpose is to fulfil all five parameters. However, actual street lighting cases do not always fulfil all the parameters mainly due to cost reasons in a number of limitations, such as in the pole spacing, pole height, and luminaire placing. The fulfilment of the criteria is recommended to be addressed in the choice of the functional unit. In the LCC analysis in Chapter 4.4, the functional unit was a kilometre of street, but no lighting design criteria were included.

The secondary aim was to analyse the previous LCAs of light sources found in the literature and the three LCAs conducted in this work in order to increase the knowledge on the environmental aspects of light sources. Several findings were concluded on the basis of the LCAs. First, the use stage dominates the life cycle impacts of light sources. This was found in all LCAs, even though the LCAs varied in the method and in the products they evaluated. Second, the manufacturing is typically the second most significant stage of the life cycle. In case of a fluorescent lamp luminaire, the average environmental impacts of manufacturing were caused by the luminaire cover and ballast, while in an LED downlight luminaire, the manufacturing impacts were mainly caused by the driver, LED array and aluminium reflector and heatsink. This indicates that the driver or ballast cannot be excluded in an LCA of a luminaire. Third, other life cycle stages, such as transport or EoL, are practically insignificant in the total life cycle scope. However, the EoL may cause significant share of certain environmental impact categories, e.g., hazardous waste, even if the average environmental impacts remained low.

In the LCAs of light sources, the dominance of the use stage depends on the used energy source and the life of the light source. The importance of the life cycle stages other than the use, especially the manufacturing, is increased in case of low-emission energy production. The importance of the manufacturing is also increased in case of a life of a lamp or luminaire shorter than the expected life, when more light sources are needed to provide light over the same period of time. This is especially acknowledged in the assessment of LED light sources. The life of the LED lamps and luminaires is based on extrapolations of measurements of part of the life, as their life is so long that it is not practical to measure it in full. This causes uncertainty in the life of LED light sources and further in the LCAs of LED light sources.

The LCC point of view of the light sources was addressed in Chapter 4.1 (non-directional lamps) and 4.4 (street lighting luminaires). The reason for the LCC aspect is the inclusion of the economic aspects in a total sustainability assessment. A product cannot be fully sustainable if it is not an economic solution in the scope of the total life cycle. The two LCC analyses in this work concluded that the investment costs are notable in the LCCs (32 % in CFL, 58 % LED lamp; 53 % LED luminaire, 27 % HPS luminaire, 63 % induction luminaire). The LCCs of the LED lamps and luminaires will be reduced in the future, as the luminous efficacy and life of the luminaire are improved and the luminaire price is reduced. At the time of installation in 2009-2010, the LED street lighting luminaires were not an economically viable solution due to the high purchase prices of the luminaires, low electricity price in the municipalities, and the modest reduction in the luminaire power compared to the preceding HPS luminaire. The LED street lighting cases contained only 4-14 luminaires. In case of hundreds of LED luminaires, the purchase price per luminaire will be reduced.

Future LCA and LCC studies of light sources should aim at detailed definition of the functional unit in lighting applications, e.g., in road and area lighting. The functional unit shall be applicable also in LCC analysis, so that a combined environmental and economic analysis would be possible. More LCA of various light sources are needed to better establish the environmental hot spots of light sources. In case of LED lamps and luminaires, especially the electronics (driver, LED array) needs to be analysed in various products. In addition, the heatsink is an interesting topic for the LCA research: it affects the environmental impacts of manufacturing and the life of the LED light source.

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Appendix I: Résumé en français

1 Introduction

Il est nécessaire d'agir immédiatement et efficacement pour réduire la consommation d'énergie et les émissions de gaz à effet de serre. Le domaine de l'éclairage est un gros consommateur mondial d'électricité (19 % d'énergie électrique [3]*). Les mesures pour réduire la consommation d'énergie de l'éclairage sont efficaces et appropriées [18, 19]. Cependant, certains aspects environnementaux des sources lumineuses sont disputés, tels que le contenu matériel et la fin de vie.

Les impacts environnementaux d'un produit ou d'un service sont évalués par une analyse du cycle de vie (ACV). L'analyse du cycle de vie est normalisée à un niveau général dans les normes ISO 14040 [32] et ISO 14044 [33]. Le problème de recherche de la thèse est l'absence de règles établies pour la conduite de l'ACV des sources lumineuses. L'absence de ces règles rend difficile d'évaluer systématiquement la performance environnementale des sources lumineuses.

L'objectif principal de la thèse est d'établir un modèle pour effectuer une ACV des sources lumineuses. Le modèle est nécessaire pour systématiquement et simplement évaluer les impacts environnementaux des sources lumineuses, surtout parce que ces dernières connaissent actuellement des changements en raison des mesures législatives et volontaires qui ont été prises. Les sources lumineuses sont en train de changer. Les sources lumineuses conventionnelles, telles que les lampes à incandescence ou les lampes à mercure haute pression sont remplacées par des sources lumineuses modernes à haute efficacité énergétique, telles que les lampes et luminaires à LED. La méthode d'ACV devrait par conséquent être simplifiée en considérant tous les aspects environnementaux.

Le modèle est développé sur la base de quatre études de cas d'analyses environnementales et/ou économiques des sources lumineuses réalisées dans le cadre de la thèse: deux ACVs d'un luminaire encastré à LED et d'un luminaire à lampe à fluorescence, une analyse combinant à la fois l'ACV et l'analyse de coût du cycle de vie (CCV) des lampes non-dirigées, et une analyse de CCV des luminaires d'éclairage public. Trois des études de cas

**) Numéros de référence se réfèrent à références respectives originales dans la thèse en anglais.*

sont basées sur des articles scientifiques publiés [4, 5, 6] et une est basée sur une communication dans une conférence [7].

L'objectif secondaire de la thèse est d'analyser les ACVs précédents trouvés dans la littérature pour accroître la connaissance sur les aspects environnementaux des sources lumineuses. L'analyse de CCV dans le cadre de la thèse est destinée à étendre le champ à la durabilité et ne pas se concentrer seulement sur les aspects environnementaux.

2 Analyse du cycle de vie

L'analyse du cycle de vie est un outil pour évaluer les impacts potentiels sur l'environnement d'un produit ou d'un service durant le cycle de vie. L'ACV compile les entrants, sortants et les impacts potentiels sur l'environnement du système analysé. L'ACV est un outil d'aide à la décision en marché publique, à l'élaboration des lois, et à la décision d'achat des consommateurs conscients de l'environnement.

L'ACV évalue le cycle de vie entier, de l'acquisition des matières premières à la fin de vie, à savoir du berceau à la tombe, ou une partie du cycle de vie. Un exemple du cycle de vie est présenté sur la Figure A. Il n'existe pas de règles absolues qui dictent quelles étapes du cycle de vie doit être considérée pour l'ACV, cela dépend du produit analysé.

Les normes ISO 14040 et 14044 établissent une méthode générale à l'ACV. Toutefois, les normes de l'ACV sont suffisamment vagues pour que les normes soient utilisées pour tous les produits et services. L'ACV conventionnelle (ACV par processus, « process LCA») contient quatre phases: définition des objectifs et du champ de l'étude, analyse de l'inventaire, évaluation de l'impact et interprétation. L'étape de la définition des objectifs et du champ de l'étude définit le système de produits à étudier, la frontière du système, l'unité fonctionnelle, et les hypothèses et critères de coupures utilisées dans l'analyse. On peut utiliser plusieurs critères de coupure des entrants et sortants du système considéré, tels que la masse, l'énergie et la portée environnementale [33]. L'analyse de l'inventaire du cycle de vie (ICV) comprend le recueil des données, le calcul des données, et l'affectation. L'évaluation de l'impact du cycle de vie (ACVI) inclut la sélection des catégories d'impact, les indicateurs de catégories et les modèles de caractérisation. L'ACVI affecte les résultats de l'ICV aux catégories d'impact environnementaux. Plusieurs catégories d'impact existent, telles que le changement climatique, l'acidification, la destruction de la couche d'ozone et la toxicité humaine. L'interprétation combine les résultats et la conclusion de l'ICV et de l'ACVI, conformément à l'objectif et au champ de l'étude, et les présente clairement et de façon cohérente.

L'ACV est une approche relative en raison de l'*unité fonctionnelle*. L'unité fonctionnelle fournit une référence par rapport à laquelle l'ACV est quantifiée et normalisée. L'unité fonctionnelle est un paramètre clé à l'ACV, surtout à l'ACV comparative où on compare plusieurs produits. Il est important que l'unité fonctionnelle soit cohérente avec les objectifs et le champ de l'étude, clairement définie et mesurable [33].

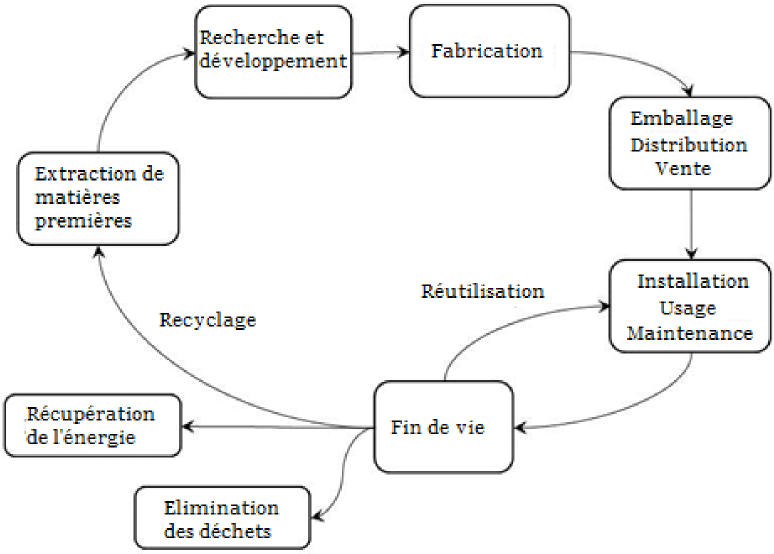

Figure A. Exemple des étapes du cycle de vie.

2.1 Coût de cycle de vie

Il y a plusieurs méthodes pour calculer les CCVs cela dépend du champ d'étude choisi. La valeur actuelle et la période de récupération sont les indices les plus complets de critères financiers du budget de décision [37]. L'analyse du CCV de l'éclairage public inclut ces deux indices.

Il est recommandé d'inclure la valeur temps de l'argent si la période de calcul dépasse deux ans [11]. Dans le domaine de l'éclairage, la valeur temps de l'argent peut être ignorée en cas de vie courte de la source lumineuse, comme la lampe à incandescence. Au contraire, en cas d'éclairage public, la période de calcul est longue, typiquement 30 ans, et il est donc nécessaire de considérer la valeur temps de l'argent.

3 Examen des analyses de cycle de vie précédentes

Plusieurs ACVs de lampes et luminaires ont été réalisées au cours de deux dernières décennies. Typiquement elles sont réalisées en comparant les lampes à incandescence avec les fluocompactes, mais également avec les autres sources lumineuses, en particulier les sources lumineuses à LED [30, 40-48, 51-55]. De nombreuses différences ont été identifiées dans les ACVs précédentes. Il s'est avéré impossible, dans un premier temps, de créer un modèle uniforme de consommation de l'énergie pour la fabrication, de part des données variées, notamment pour les lampes à incandescence, lampes fluocompactes et lampes à LED. De plus, le contenu matériel des lampes à incandescence, fluocompactes et à LED était différent entre les ACVs et les autres références. En second temps, un modèle uniforme pour le contenu matériel n'a pas été trouvé. Troisième point, les ACVs utilisaient les unités fonctionnelles différentes: megalumen heures, une heure, une lampe. En outre, les impacts environnementaux variaient, alors qu'il y a un nombre des catégories d'impacts environnementaux potentiels à choisir.

Malgré les différences dans les méthodes de l'ACV, les ACVs des sources lumineuses ont généralement abouti à des résultats similaires: l'utilisation est majoritairement responsable des impacts environnementaux en raison de la consommation d'énergie. Les autres étapes du cycle de vie, telles que l'acquisition des matières premières, la fabrication et la fin de vie, ne causent que des impacts mineurs. L'efficacité lumineuse de la source de lumière détermine donc, pour la plupart, la performance environnementale. Il a été constaté que les lampes et luminaires à haute efficacités lumineuses, tels que lampes à fluorescence, lampes et luminaires à LED, et luminaire à lampe à induction, sont les sources lumineuses les plus favorables à l'environnement.

Les ACVs des sources lumineuses utilisent de nombreuses unités fonctionnelles, typiquement le lumen heure, ou le flux lumineux pendant quelques heures, par exemple 500 ou 900 lm pendant 10 000 h. Dans ce dernier cas l'unité fonctionnelle n'est pas équivalente (500 lm comparés à 900 lm). L'unité fonctionnelle devrait être clairement définie [33]. Ceci n'est pas respecté dans trois des ACVs [42, 45, 54], où les unités fonctionnelles sont respectivement 345-420 lm pendant 25 000 h, 500-900 lm pendant 10 000 h, et une quantité de lumière équivalente pendant 8 000 h (supposé comme flux lumineux équivalent).

Les sources lumineuses comportent souvent des pièces électroniques. Il y a eu beaucoup de discussions concernant l'ACV pour déterminer s'il s'agit d'une méthode appropriée pour l'évaluation des impacts environnementaux du détail des équipements électroniques [69, 70]. Il est difficile de réaliser l'ACV des produits électroniques à cause de la complexité des produits, de l'absence de données spécifiques, des écarts de données dans l'ACVI, et des changements dans le mode d'utilisation [69, 71]. Pourtant, il est possible d'utiliser l'ACV pour identifier les points environnementaux majeurs du cycle de vie [69].

4 Etude de méthodologie de l'analyse du cycle de vie des sources lumineuses

Quatre études de cas sont présentées: une analyse simplifiée de l'ACV et CCV des sources lumineuses utilisées par les ménages, une ACV d'un luminaire encastré à LED, une ACV d'un luminaire à lampe à fluorescence, et une analyse de CCV des luminaires d'éclairage public. Les cas représentent les applications communes et ils varient sur les méthodes d'évaluation, l'application de l'éclairage et le critère d'éclairage.

4.1 Etude de cas des lampes non-dirigées utilisées par le ménages

Les impacts environnementaux et les CCVs des lampes non-dirigées sont étudiés en considérant la fabrication et l'utilisation. Les coûts de la fabrication sont modélisés sur la base du prix d'achat qui est estimé pour correspondre aux coûts de la fabrication. Les coûts d'exploitation sont calculés sur la base de prix d'électricité (0.10 €/kWh). Les coûts sont calculés du point de vue du consommateur qui achète, remplace et utilise la lampe. L'impact de la source d'énergie est éliminé en utilisant l'énergie primaire de fabrication des lampes [30] et d'utilisation.

L'idée de cette étude de cas est de modifier les courbes de répartition de l'intensité lumineuse et le flux lumineux des lampes. L'étude compare trois types de lampes: lampe à incandescence de 60 W (750 lm), lampe fluocompacte de 13 W et de trois formes (spirale, tubulaire, enveloppée) (750 lm), et lampe à LED de 13 W (800 lm). Les courbes de la répartition de l'intensité lumineuse de la lampe à incandescence et des lampes fluocompactes ont été mesurées à Aalto University Lighting Unit, alors que les courbes pour la lampe à LED sont obtenues par le fabricant.

Quatre unités fonctionnelles sont utilisées: a) une lampe, b) un megalumen-heure, c) une heure, et d) l'éclairement lumineux direct à une distance d'une mètre sur une surface de 1 m^2 par heure. Toutes les unités fonctionnelles excluent le luminaire afin de simplifier l'étude.

Résultats

Les résultats montrent que, dans la comparaison de lampes, c'est la lampe à LED qui cause les coûts et la consommation d'énergie les plus hautes principalement à cause de sa longue durée de vie. De plus, le prix d'achat et la consommation d'énergie de fabrication de lampe à LED sont élevés. Dans la comparaison sur une heure, la lampe à incandescence cause clairement les coûts et la consommation d'énergie les plus hautes. Il semble que les résultats de la comparaison basée sur le lumen heure soient similaires aux résultats obtenus pour des comparaisons basées sur une heure ou l'éclairement lumineux.

Le choix de l'unité fonctionnelle affecte les résultats de l'analyse. Pourtant, il n'existe pas de différences significatives dans les résultats si l'unité fonctionnelle est une heure, le lumen heure ou l'éclairement à une distance d'une mètre sur une surface de 1 m^2. Il a été constaté que l'énergie primaire de la fabrication était plutôt insignifiante. Au contraire, le coût de la fabrication (modelé comme prix d'achat) représente une part notable de CCVs dans le cas de la lampe fluocompacte (approximativement 32 %) et de la lampe à LED (58 %).

4.2 Etude de cas du luminaire encastré à LED

Le luminaire en question est un luminaire encastré à LED de 19 W avec un driver et un diffuseur au phosphore déporté. C'est un luminaire appliqué dans des bâtiments de commerce et peut servir pour remplacer un luminaire encastré à lampe fluocompacte. L'unité fonctionnelle est la production de flux lumineux de 1140 lm pendant une durée de 50 000 heures, équivalent avec 57 Mlmh. L'ACV a été réalisée selon des normes ISO 14040 [32], ISO 14044 [33] et norme française NF P01-010 [75].

L'analyse couvre la fabrication, le transport, l'installation, l'utilisation et la fin de vie. L'ACV inclue tous les entrants sur lesquels il était possible d'obtenir des données. Une règle de coupure a été utilisée et permet d'ignorer les entrants dont la somme totale était inférieure à 2 % de la masse du total de tous les entrants s'il n'y avait pas l'ICV disponible [75]. SimaPro [77] a été utilisé comme logiciel et Ecoinvent [76] et European Reference Life Cycle Database (ELCD) [78] comme bases de données.

Pour étudier largement les impacts environnementaux potentiels, seize catégories d'impact ont été choisis dans l'ACV du luminaire à LED: l'énergie (primaire, renouvelable, non-renouvelable), l'épuisement de ressources, la consommation d'eau, les déchets (dangereux, non-dangereux, inertes, radioactifs), le changement climatique, l'acidification atmosphérique, la pollution de l'air et de l'eau, la destruction de la couche d'ozone, la formation d'ozone photochimique, et l'eutrophisation.

Le scénario de base de l'ACV incluait la durée de vie du luminaire de 50 000 h, le moyen de production d'électricité française, et le scénario actuel de fin de vie (95 % de mise en décharge, 5 % de retraitement pour recyclage). En plus du scénario de base, l'ACV contenait plusieurs scénarii pour effectuer l'analyse de sensibilité de la durée de vie du luminaire (15 000 h, 36 000 h, 50 000 h), les moyens de production d'électricité à l'étape de l'utilisation (moyen européen, moyen français), et le scénario de fin de vie (actuel; prospectif 40 % de mise en décharge, 60 % de retraitement pour recyclage).

Résultats

C'est la consommation d'énergie durant la phase d'utilisation qui prédomine sur les impacts environnementaux du luminaire à LED comme prévu. Cependant, les impacts étaient affectés par la durée de vie du luminaire et les moyens de production électrique pendant l'utilisation. Quand on modélise les moyens de production électrique française, la fabrication représente environ 23 % et l'utilisation 76 % des impacts environnementaux totaux moyens. Quand on modélise les moyens de production électrique européenne, les impacts sont divisés entre la fabrication (7 %) et l'utilisation (93%). Dans les deux cas de moyens de production électriques, les autres étapes du cycle de vie, telles que les transports, l'installation et la fin de vie, sont insignifiants (moins de 1 % moyen) dans le cadre du cycle de vie entier. Pourtant, la fin de vie causait 28 % des impacts en catégorie de déchets dangereux quand l'utilisation a été modélisée pour l'électricité française.

Les impacts environnementaux de la fabrication du luminaire encastré à LED sont principalement causés (plus de 80 % dans chaque catégorie) par le driver (40 % moyen), le porte LED (28 % en moyenne) et les pièces en aluminium (échangeur thermique et réflecteur) (24 % en moyenne). Le porte LED (les LEDs, l'aluminium, le joint thermique en silicone) est responsable d'environ 6 % ou 2 % des impacts environnementaux moyens du cycle de vie entier en utilisant respectivement les différents moyen de production électrique français ou européen.

La consommation d'énergie pendant l'utilisation prédomine sur les impacts environnementaux en cas de durée de vie du luminaire de 50 000 h. La fin de vie était pratiquement insignifiante dans le cadre du cycle de vie entier, alors que la durée de vie du luminaire affectait notablement les impacts environnementaux. La fabrication prend en compte d'une part notable de deux catégories: les déchets dangereux (38 %) et les déchets non-dangereux (78 %). La fin de vie représentait 28 % de déchets dangereux. Ainsi, si l'utilisation est l'étape dominante du cycle de vie, alors elle dépend de la catégorie d'impact en question.

4.3 Etude de cas du luminaire à lampe à fluorescence

L'ACV d'un luminaire à lampe à fluorescence pour les applications industrielles a été réalisée en 2011-2012 [5]. Cette analyse évalue un luminaire à lampe à fluorescence équipé avec deux lampes à fluorescence linéaire de diamètre de 16 mm, un ballast électronique, et un réflecteur métallique. Le luminaire accommodait deux lampes de puissance de 49 W qui produisent ensemble un flux lumineux de 8600 lm selon le fabricant du luminaire. L'unité fonctionnelle est l'utilisation du luminaire pendant 20 ans 4000 heures par ans, ce qui correspondait à 688 Mlmh. Le luminaire consommait 104 W au total. La durée de vie de la lampe à fluorescence était estimé à 20 000 h et pour le ballast à 50 000 h.

L'ACV incluait la fabrication, le transport, l'utilisation et la fin de vie du luminaire. L'ACV a été conduit en accordance avec les normes ISO 14040 [32] et ISO 14044 [33] et la spécification pour les produits de technologies de l'information et de la communication [31]. Toutes les étapes du cycle de vie identifiées comme obligatoires selon la spécification [31] sont inclues dans l'ACV. Cette ACV utilisait Ecoinvent [76] et ELCD [78] comme bases de données et SimaPro [77] comme logiciel. Les impacts environnementaux sont largement pris en considération dans douze catégories d'impact: l'épuisement de ressources, l'acidification, l'eutrophisation, le changement climatique, la formation d'ozone photochimique, la destruction de la couche d'ozone, l'écotoxicités (terrestre; aquatique d'eau douce, marine ; des sédiments d'eau douce, marine), et la toxicité humaine.

L'ACV a été modélisée utilisant le moyen de production électrique finlandaise. De plus, l'impact du moyen de production électrique a été analysé par l'utilisation d'électricité de tourbe nordique et hydro-électricité finlandaise.

Résultats

Les impacts environnementaux du luminaire à lampe à fluorescence sont divisés entre fabrication (7 %) et utilisation (93 %) en cas du moyen de production d'électricité finlandaise. Les autres étapes du cycle de vie, (transport, fin de vie) tenait compte moins de 1 % en moyenne. Les impacts de la fabrication sont divisés entre le luminaire (46 %), ballast (43 %) et lampes (11 %) en moyenne. Pourtant, il doit être noté que les lampes à fluorescences causent une part notable de la catégorie d'écotoxicité terrestre (70 %).

L'étude de cas a indiqué que les résultats de l'ACV du luminaire à lampe à fluorescence sont affectés par le moyen de production électrique utilisée pendant le fonctionnement. Les impacts relatifs des autres étapes du cycle de vie, notablement la fabrication, seraient augmentés quand la production d'énergie changerait vers la production d'électricité à faible taux d'émission. Comme prévu dans la comparaison de trois productions d'électricité (finlandaise moyenne, tourbe nordique, hydro-électricité finlandaise), le cas de l'hydro-électricité causait les impacts environnementaux les plus bas dans tous les catégories d'impact.

4.4 Etude de cas des luminaires à l'éclairage public

L'analyse de CCV des luminaires d'éclairage public contenait dix cas où les luminaires sont rénovés en Finlande. Les cas A, B et C sont présentés dans l'article par Tähkämö et al. [6]. Les cas supplémentaires de D à J sont réalisés dans la thèse. Les cas sont situées dans la sud de la Finlande dans la municipalité de Kotka (cas A et B), Kerava (cas C) et Espoo (cas de D à J). Les CCVs sont calculées du point de vue de l'utilisateur, des municipalités. L'unité fonctionnelle est un kilomètre d'une route illuminée.

L'analyse de CCV compare les coûts: coûts d'investissement, coûts d'exploitation et la valeur résiduelle. Les coûts d'investissement contiennent le prix du luminaire et l'installation. Les coûts d'exploitation incluent les coûts d'électricité et les remplacements des lampes et luminaires. La valeur résiduelle exprime le coût ou le profit d'investissement après le temps de fonctionnement. Alors que le temps de fonctionnement est long dans le cas de l'éclairage public, typiquement 30 ans, la valeur résiduelle reste basse.

Dans les dix cas, les luminaires installés sont de trois technologies: luminaire à lampe à sodium haute pression, luminaire à LED, et luminaire à lampe à induction. Les luminaires précédents étaient équipés soit de lampes à mercure haute pression soit d'anciennes lampes à sodium haute pression.

Le développement de la technologie LED est pris en compte dans l'analyse de CCV. On estime une amélioration de 75 % par le développement de l'efficacité lumineuse, et une réduction de 85 % sur le prix d'achat du luminaire au moment du remplacement.

Résultats

Les coûts d'investissement des cas LED (C à H) étaient nettement plus hauts (23 170 – 34 630 €/km) que ceux des cas de lampes à sodium haute pression (7 380 – 9 160 €/km) et similaires à ceux des lampes à induction (25 710 €/km).

Les périodes de récupération n'étaient pas viables dans la plupart de cas (plus de 30 ans). Les luminaires à LED n'étaient pas des solutions profitables dans les installations à faible quantité de luminaires (4 à 14 luminaires dans une installation). La rentabilité des luminaires à LED sera accrue quand les installations deviendront plus larges en réduisant le prix d'achat d'un luminaire. La rentabilité sera augmentée également en utilisant l'espacement optimisé entre les pôles et en exploitant les possibilités des optiques du luminaire à LED.

L'analyse de CCV montait que les coûts d'énergie et d'investissement causent la majorité des CCVs. Dans les cas de l'installation de luminaire à lampe à sodium haute pression, les coûts sont divisés entre les coûts d'investissement (27 %), les coûts d'énergie (60 %), les coûts de maintien (11 %) et la valeur résiduelle (3 %). Dans les cas de l'installation de luminaire à LED, les coûts sont divisés entre les coûts d'investissement (53

%), les coûts d'énergie (26 %), les coûts de maintien (16 %) et la valeur résiduelle (6 %). Les coûts de luminaire à lampe à induction sont divisés entre les coûts d'énergie (30 %), les coûts d'investissement (63 %), et la valeur résiduelle (7 %).

Tous les cas de luminaire à LED ne contenaient qu'une faible quantité de luminaires (4 à 14 pièces). Le prix des luminaires est donc plus élevé qu'il ne le serait dans le cas d'une installation de cent luminaires. De plus, le prix des luminaires à LED sera réduit grâce à la réduction des coûts de la fabrication et concurrence intensifiée sur le marché [86].

4.5 Modèle proposé

Sur la base de quatre études de cas réalisés dans cadre de la thèse, deux modèles sont créés pour la conduite de l'ACV des sources lumineuses: un simple et l'autre étendu. Le tableau B présente les deux modèles qui sont dessinés afin que tous les impacts environnementaux présumés soient pris en compte. Le modèle simple peut être utilisé quand les ressources sont limitées et quand il est nécessaire de produire des résultats très rapidement. Le modèle étendu est destiné à une évaluation plus détaillée mais c'est également une simplification de l'ACV très détaillée.

Tableau B. Modèles simple et étendu pour la méthode de l'ACV des sources lumineuses.

Paramètre	Modèle simple	Modèle étendu
Unité fonctionnelle	Lumen heures (par exemple Mlmh)	Spécifique pour le cas, relié à la fonction des sources lumineuses dans une application particulière Applications en intérieur: éclairement à une distance sur une surface par heure Applications en extérieur: en rapport avec des critères pour l'éclairage
Étapes du cycle de vie	Fabrication Utilisation	Acquisition des matières premières Utilisation Fin de vie
Impacts environnementaux	Nombre limité de catégories d'impacts, par ex., seulement l'énergie primaire ou réchauffement climatique	Plusieurs catégories d'impacts divers
Source d'énergie de la phase d'utilisation	Énergie primaire	Moyen de production d'électricité actuel, et l'électricité à faible et haut taux d'émission

Il est recommeandé que l'unité fonctionnelle soit en lumen heures dans le modèle simple. Les lumens heures dépendent du flux lumineux et du temps de fonctionnement de la source lumineuse. Le lumen heure obéit au critère de l'unité fonctionnelle établi dans la norme ISO 14044 [33]. Dans le modèle étendu, l'unité fonctionnelle devra prendre l'application de l'éclairage en compte. Par exemple, les applications en intérieur peuvent utiliser l'unité fonctionnelle de l'éclairement direct à une distance sur une surface par heure. La distance et la largeur de la surface devront être spécifiées en accord avec l'application particulière. Dans les applications extérieures, il est recommandé d'utiliser l'unité fonctionnelle qui prend le critère pour l'éclairage en compte, alors que l'éclairage est dessiné à obéir à des critères. Il est pourtant recommandé d'utiliser l'unité fonctionnelle spécifique dans les ACVs comparatives. Les ACVs non-comparatives peuvent utiliser les lumens heures comme unité fonctionnelle pour que les résultats soient comparables aux autres ACVs des sources lumineuses. Au moins, il est fortement recommandé d'indiquer le flux lumineux et la durée de vie de la source lumineuse dans l'ACV de tous types (comparative ou non-comparative).

5 Discussion

Quatre analyses d'ACV et/ou CCV des lampes et luminaires sont réalisées dans le cadre de la thèse. De plus, les ACVs précédentes des lampes et luminaires trouvées dans la littérature ont été analysées. L'étude montrait qu'il y a des différences dans les méthodes de l'ACV (par exemple l'unité fonctionnelle, les étapes du cycle de vie) et données initiales. Malgré des différences, il a été constaté que toutes les ACVs des sources lumineuses concluent que l'étape de l'utilisation cause la plupart des impacts environnementaux. Par conséquent, les sources lumineuses de haute efficacité énergétique, telles que la lampe fluocompacte et la lampe et luminaire à LED, causent les impacts environnementaux les plus bas pour le cycle de vie entier, comparé avec les sources lumineuses conventionnelles telles que la lampe à incandescence. Il est probable que l'impact des autres étapes de cycle de vie accroisse, notamment par la fabrication, étant donné que le domaine de l'éclairage évolue vers des sources lumineuses plus efficaces énergétiquement. En même temps, la fabrication sera analysée plus en détail.

L'ACV du luminaire encastré à LED démontrait que l'étape de l'utilisation représente la majorité des impacts environnementaux. La source d'énergie détermine les résultats: si le moyen de production d'électricité française est utilisée, les impacts environnementaux sont notablement différents comparé aux moyens de production d'électricité européenne, quand la méthode ACV étaient autrement le même.

Les LEDs dans l'ACV du luminaire encastré à LED étaient modélisées comme LED de signalisation dans les données de l'ACVI trouvées dans la base de données Ecoinvent. Le poids des LED était multiplié par cinq selon les experts pour que les impacts des LED ne soient pas sous-estimés. Même si l'impact des LED était exagéré, il a constaté que les LEDs n'ont causé qu'une part insignifiante des impacts environnementaux du cycle de vie total.

Les ACVs des sources lumineuses ne prennent en compte que les impacts de la lumière sur l'environnement. L'éclairage artificiel affecte les organismes vivants directement et indirectement de façons multiples: par exemple, les oiseaux souffrent de désorientation, les oiseaux et les insectes sont attirées par la lumière ce qui rend facile leur détection par les prédateurs, et la croissance et la floraison des plantes est affectée par la couleur, la quantité, l'instant et la durée de la lumière [91]. Il n'y a pas une méthode pour combiner les résultats d'une ACV conventionnelle (par exemple la quantité de dioxyde de carbone) avec les impacts environnementaux de la lumière.

6 Conclusions et recommandations

L'objectif primaire de la thèse était de créer un modèle d'une méthode pour la réalisation d'ACV des sources lumineuses. La thèse a établi deux modèles pour l'ACV des sources lumineuses sur la base des ACVs réalisées dans la thèse et l'examen des ACVs précédentes. Les deux modèles rendent possible la conduite rapide de l'ACV des sources lumineuses ce qui est nécessaire en considérant le marché des sources lumineuses en perpétuelle évolution, surtout les lampes et luminaires à LED.

L'objectif secondaire de la thèse était d'analyser les ACVs trouvées dans la littérature et les trois ACVs présentées dans la thèse pour accroître la connaissance sur les aspects environnementaux des sources lumineuses. De nombreuses conclusions ont été trouvées dans les ACVs. Premièrement, l'étape d'utilisation prédomine sur les impacts du cycle de vie des sources lumineuses. Cela a été trouvé dans toutes les analyses même si les méthodes variaient. Deuxièmement, la fabrication était typiquement la deuxième étape du cycle de vie la plus impactant. Dans le cas d'un luminaire à lampe à fluorescence, les impacts environnementaux moyens sont causés par le luminaire (réflecteur) et le ballast. Quant au luminaire encastré à LED, les impacts de la fabrication sont générés majoritairement par le driver, le porte LED, le réflecteur en aluminium et l'échangeur thermique. Cela indique que le driver ou le ballast ne peut pas été ignoré dans une ACV du luminaire. Troisièmement, les autres étapes du cycle de vie, telles que le transport et la fin de vie, sont pratiquement insignifiants dans le cadre du cycle de vie entier. Pourtant, la fin de vie peut causer un impact notable dans une certaine catégorie d'impact, par exemple les déchets dangereux, même si les impacts moyens restent bas.

Dans les ACVs des sources lumineuses, la dominance de la phase de l'utilisation dépend de la source d'énergie utilisée et la durée de vie de la source lumineuse. L'importance des étapes du cycle de vie autres que l'utilisation, en particulier la fabrication, est augmentée dans le cas de la source d'énergie ou moyen de production d'électricité à faible taux d'émission. L'importance de la fabrication est accrue aussi dans le cas d'une durée de vie de la lampe ou du luminaire plus courte que prévue, quand il faut fabriquer plusieurs sources pour le même période de temps. En particulier dans l'ACV de luminaire à LED, la durée de vie des lampes et luminaires à LED est basée sur les extrapolations des mesures d'une partie de la vie, comme leur durée de vie est tellement longue, il n'est pas pratique de la mesurer en entier. Cela entraîne des incertitudes dans la durée de vie des sources lumineuses à LED et en outre dans les ACVs des sources lumineuses à LED.

L'analyse de CCV incluait les lampes non-dirigées et des luminaires de l'éclairage public. L'analyse de CCV était inclue dans la thèse parce que les aspects économiques font partie de l'évaluation de la durabilité totale. Il n'est pas possible pour un produit d'être durable s'il ne constitue pas une solution économique pendant le cycle de vie. Les deux analyses de CCV ont conclu que les coûts d'investissement sont notables (32 % lampe fluocompacte, 58 % lampe à LED; 53 % luminaire à LED, 27 % luminaire à lampe à sodium haute pression, 63 % luminaire à lampe à induction). Les coûts du cycle de vie des lampes et luminaires à LED sera réduits à l'avenir, comme l'efficacité lumineuse et la durée de vie sont améliorées et le prix du luminaire sera réduit.

Les études de l'ACV et CCV à l'avenir devraient viser à la définition en détail de l'unité fonctionnelle aux applications d'éclairage public. L'unité fonctionnelle sera applicable également dans les analyses CCV, afin qu'il soit possible de combiner les analyses environnementales et économiques. Plusieurs ACVs des sources lumineuses sont nécessaires pour mieux établir les points environnementaux majeurs des sources lumineuses. Quant aux lampes et luminaires à LED, surtout les pièces électroniques (driver, porte LED) devraient été analysées dans les produits divers. De plus, l'échangeur thermique serait un sujet très intéressant dans l'étude de l'ACV: il affecte les impacts environnementaux de la fabrication et la durée de vie des sources lumineuses à LED.

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The environmental impacts of light sources, i.e., lamps and luminaires, are studied by life cycle assessment. The life cycle assessments typically conclude that the environmental impacts of light sources are mainly caused by the energy consumption of the use. However, the dominance of the use strongly depends on which energy source is chosen. The use of renewable energy sources increases significantly the importance of other life cycle stages. In addition, the significance of the use depends on the life and the luminous efficacy of the light source. The life of the light source contributes to the importance of manufacturing, as more products are needed to be manufactured in case of a short life. Light sources of high luminous efficacy provide illumination in an energy-efficient way but they tend to be more complex to manufacture, which further increases the environmental impacts of manufacturing.

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