An overview of environmental impacts of lighting products at the end of life stage through life cycle impact assessment

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Abstract. Life Cycle Impact Assessment (LCIA) of lighting products is a methodology that analyses and evaluates environmental impacts throughout their total life cycle, from the extraction and processing of raw materials, design, construction, transportation, distribution, use, recycling and re-use of materials, and last their final disposal. According to the results of a large number of LCIA, lighting products have a substantial environmental impact in multiple areas, as for example in primary energy, toxicological effects, the effect on global warming, the level of environmental acidification, etc. All of those impacts could result in more efficient products by enhancing the product design process (using Ecodesign). At the initial design stage of lighting products, the manufacturer should also take into consideration circular economy aspects at the End of Life stage (EoL) such as repair, reuse, remanufacturing, retrofitting, recycling, and upcycling and not only the energy savings from the use stage or the selection of raw materials. The scope of this paper is to collect and present an overview of all environmental impacts of LCIA analyses focusing at EoL stage of lighting products. Those impacts could be used as data input into a future model that determines which lighting products are more environmentally friendly.

1. Introduction
Sustainability and viability are dynamically entering the research, development, and design phase of lighting products by integrating life cycle analysis (LCA) into the overall context of environmental management. Sustainability should be a crucial factor in the decision making process, in order to choose which lighting products should be used when performing a lighting system upgrade or an initial placement [1-5]. The main problem is that lighting products are mainly studied during their use and not during their total life cycle. Sustainable Lighting Design (SLD) is a process that could change not only the selection process of lighting products, but also the criteria of lighting design itself. The Life Cycle Impact Assessment (LCIA) of lighting products is a method that converts inventory data from a life cycle assessment (LCA) into an environmental impact of their total life cycle. The outcomes of LCIA can be used to make decisions about which products can be chosen as being more environmentally friendly and also which of them contribute most to the sustainability of our society.
The results of many LCIA analysis have shown that lighting products have serious environmental impacts, particularly at the EoL [6-8]. For example, high and low pressure discharge lamps such as fluorescent lamps use mercury for their operation. Mercury is toxic to humans and to the environment. Therefore, proper recycling should be encouraged through certified recycling systems where proper collection and management of mercury and other toxic materials made up of the lamps is done. Recycling reduces the total cost of production of lighting products by taking into account the cost of dealing with the environmental impacts they cause and also the reusing of recovered materials.

The impacts of the analysis are given as categories of environmental impact such as primary energy, toxicological effects, the effect on global warming, the level of environmental acidification, etc. Also, the total environmental impacts of a product can be described as an indicator (i.e. EDIP97, CML2001 and Eco-indicator 99) [9-11]. Furthermore, these can be calculated using simulation tools, such as Sima Pro, Gabi, etc., where the result can be given in different categories of impacts, such as Resources, Ecosystems, and Human Health [12]. The most effective approach to deal with them is during the design phase of lighting products, so that these impacts can be identified and addressed by emphasizing real effective solutions. This can be done by choosing the proper materials (using Ecolabel), by changing the product design process (using Ecodesign), and participate circular economy by re-using materials that are recovered during the recycling process [13-16]. The first two steps are identified already by EU directives but the last one is gaining attention only in the last decade. Eco-design products have approximately 60% less environmental impact than non-eco design products, in decreasing order at the stages of use, manufacturing, end of life, and transporting [17-20]. The scope of this paper is to collect through literature all the LCIA analyses, focusing on the EoL of lighting products in the last decade, and present an overview of their environmental impacts. The outcome data of this overview can be organized and used as indicators in a future model which will take into account these impacts in order to recognize the products with the lower environmental impacts and thus being more environmentally friendly.

2. Methodology

The standard methodology used to review and evaluate the LCIA analyses of lighting products in the international literature was STARR-LCA for the last decade [21]. The checklist used by STARR-LCA relies heavily on the PRISMA checklist which is widely used for medical review. The proposed criteria that LCIA must meet in order to select and create a list of life cycle impact analysis (LCIA) characteristics are the following according to STARR-LCA:

1. Literature review by using abstract title and keywords. The literature search was done as a first step, based on keywords such as: life cycle analysis, light bulbs, light sources, luminaires, lighting products, environmental impact, energy, carbon emissions. To verify the results, independent studies were found for cross-referencing data and results, where the results are based on scientific standards

2. The selection of the LCA was based on the following International Standards: ISO 14040: 2006 [22], ISO 14044: 2006 [23], ISO / TR 14047: [24].

3. Environmental impacts. The environmental impact at the End of Life (EoL) of the lighting products were analyzed, specifically on their impacts on Resources - Air - Water – Soil – Human health – Ecosystem quality and Resource consumption.

4. The selected LCA must refer to a well-documented process database for thousands of lighting products such as Ecoinvent 3, Chinese Life Cycle Database CLCD, etc. Thus, the results could be safe to be used.

5. The selected LCA must refer to the methodology or software which could be used to calculate the environmental impact as for example Ecoindicator 99, CML2001, EDIP97, SimaPro, Gabi etc.

6. The selected LCA must have used a function unit such as megalumen, hour of light, lux hour etc.
3. Results and Discussions
A large number of LCAs have been performed in the last 10 years. The first analyses focused more on incandescent lamps and Compact Fluorescent Lamps (CFL). More recent analyses included more contemporary technologies in lighting products such as LED lamps. The LCAs of the last decade are presented in the below Table 1.

Table 1: Overview of Environmental Impacts of LCA analysis of Lighting products at the EoL Stage

| Reference Pub. Year | Lamps a | Function Unit b | Software c | Database d | Method End Point e | Environmental Impacts and Categories f |
|---------------------|---------|-----------------|------------|------------|-------------------|----------------------------------------|
| Witoon Apisitpuvakul et al.[18] | LFL | | Simapro 6.0 | Simapro | Eco-Indicator99 | Ecosystem quality, human health and resource depletion |
| Welz et al. [25] | IL, HL, FL, CFL and LED | one hour of lighting | ISO 14040:2006 ISO 14044:2006 | Ecoinvent 2.01 | Eco-Indicator99 | Ecosystem quality, human health and resource consumption |
| Dale et al.[26] | HPS, MH, LED | 100,000 h of light | No access to paper in order to have more information | | | GWP, respiratory effects, ecotoxicity |
| U.S. DOE [27] | IL, CFL, LED | 20 Mlmh | ISO 14040:2006 ISO 14044:2006 | Ecoinvent 2.2 | CML 2001 | ADP, AP, EP, GWP, ODP, POCP |
| Elijošiutė et al. [28] | IL, CFL | 10,000 h | Gabi 4.2 internal database | | CML 2001 | Ecosystem quality, human health and resource consumption |
| Abdul Hadi et al., [29] | CMH and LED | | SimaPro V.7.3 | Ecoinvent | Eco-Indicator99 | Ecosystem quality, human health and resource consumption |
| Tähkämo et al., [30] | LED | lm-h | SimaPro 7.3.2 | Ecoinvent 2.2 and European Reference Life Cycle | CML 2001 | AP, ADP, AiP, EP, GWP, HW, IW, NHW, NRE, ODP, PE, POC, RE, RW, WaC, WaP |
| Principi and Fioretti [31] | LED, CFL | lm-h | SimaPro 7.3.0 | Ecoinvent 2.1 | | AP, CED, FEP, FETP, GWP, HTPe HTPnce, LUP, MEP, ODP, POP, TEP |
| Kuldip Singh Sangwan et al. [32] | ICL, LFL, CFL and LED | lumen–hours, FLL:36375, CFL:14400, LED:6000, ICL:720 | Umberto | Ecoinvent 2.2 | Eco-Indicator99 | Ecosystem quality, human health and resource consumption |
| Reference Pub. Year | Lamps \(^a\) | Function Unit \(^b\) | Software \(^c\) | Database \(^d\) | Method End Point \(^e\) | Environmental Impacts and Categories \(^f\) |
|---------------------|----------------|---------------------|-----------------|-----------------|---------------------|-----------------------------------------------|
| Tähkämo and Halonen, [33] | HPS and LED Streetlight | lumen hour and a kilometre of lit road | ISO 14040:2006 | ISO 14044:2006 | Ecoinvent 2.2 | CML-IA |
| Quanyin Tan et al. [34] | LFL, CFL | Operating time in the use stage | Simapro 8.0 | Ecoinvent v3.2 | Eco-Indicator99 | Ecosystem quality, human health and resource consumption |
| JL Casamayor et al. [19] | LED | | SimaPro V.8 | Ecoinvent V.3 | ReCiPe V1.12 | Human health, ecosystems and resources availability |
| Sha Chen et al. [20] | LFL, CFL | | EBalance | EcolInvent and CLCD | | GHG emissions |
| Heather E. Dillon et al. [7] | LED | | Heijungs and Suh | Ecoinvent 3.0 | | |
| Kévin Bertin et al. [35] | CFL, LED, LFL (T5 type). | megalumen hour | Simapro 9 | Ecoinvent 3.5 | Recipe 2016 | Resources, Ecosystems, and Human Health |
| Manuel Jesús Hermoso-Orzáez et al. [36] | LED Streetlight | | SIMAPRO 8.3 | Simapro internal database | EPS 2000 | Ecosystem Production Capacity, Human Health, Damage Recourses, Biodiversity depletion |
| Camila Vicente de Farias et al. [37] | Fluorescent | | RISC4® | IRIS – U.S. EPA | SES Method | Human health risk by soil contamination |
| José Adolfo Lozano-Miralles et al. [38] | LED streetlight LED Luminaire | | SimaPro 8.3 | Ecoinvent | EPS 2000 | Ecosystem production capacity Human health Damage recourses Biodiversity depletion |

\(^a\) IL Incandescent Lamp, HL Halogen Lamp, (C)FL (Compact) Fluorescent Lamp, (L)FL (Linear) Fluorescent Lamp, CMH Ceramic Metal Halide lamp, HPS High Pressure Sodium.

\(^b\) Function unit is the basic parameter in the LCIA and when we want to compare two or more products they must have the same function unit.

\(^c\) The software which was used in the corresponding Life Cycle Analysis.
4. Conclusions

Lighting products have many environmental impacts that are very crucial and often irreversible as highlighted in Table 1. The most common impact categories that have been used in LCA studies of lighting products were seven. These were 1) global warming, 2) acidification, 3) eutrophication, 4) abiotic depletion, 5) photochemical ozone creation, 6) ozone depletion, and 7) primary energy demand. The results of the analyses indicate that the environmental impact can be reduced if the lighting products at the EoL stage can be easily disassembled, in order to recover materials that can be reused. Also, many lighting products contain toxic substances such as mercury that require special treatment and should not be dispersed into the environment because they contaminate it irreparably. Also, it has been estimated that large quantities of materials can be recovered through recycling, and then can be reused in other sectors of industry, in order to save energy and reduce CO₂ emissions [39].

As future work the results of the LCIA analyses (Table 1) can be analyzed and organized in order to be used as indicators in a new model which will calculate the energy and the annual CO₂ emissions saved from a lighting project depending the equipment used in real-time. According to the amount of savings, a recycling identity will be given. The recycling identity will be based on the European policy, where it has been adopted and at a national level, of "zero-carbon across the lifecycle 2050" [40], which refers that by 2050, all buildings, new and existing, must have a clear zero carbon footprint throughout their life using the circular economy concept.

In the future, a regulation needs to be implemented, which will define and oblige manufacturers of lighting products to publish data in order to inform the public about the environmental impact of lighting products at all stages of their life, so, that consumers can make their choice, by knowing which product has the highest performance and which product has the smallest environmental impact throughout its life cycle (Eco Label). Also, the creation of eco-label (Eco Label) will help manufacturers to advertise and promote their lighting products as ecological and environmentally friendly.

5. Appendix

| Environmental Impacts and Categories |
|--------------------------------------|
| ADP  | abiotic depletion potential          | HTPce | human toxicity with cancer effects | OD   | stratospheric O₃ depletion |
| AiP  | air pollution                        | HTPnce | human toxicity with non-cancer effects | ODP  | ozone depleting potential |
| AP   | acidification potential              | HW    | hazardous waste                    | POCP | photochemical ozone creation potential |
| ARD  | abiotic resource depletion           | HWL   | hazardous waste landfilled          | POP  | photochemical oxidation potential |
| CC   | climate change                       | IR    | ionizing radiation                 | RESP | respiratory effects          |
| CED  | energy demand                        | IW    | inert waste                         | RW   | radioactive waste            |
| EDP  | ecosystem damage potential           | LU    | land use                            | RWL  | radioactive waste landfilled terrestrial |
| EP   | eutrophication potential             | LUP   | land use potential                  | TAETP| terrestrial ecotoxicity potential |
| ETX  | ecotoxicity                          | MA    | maladors air                        | TEP  | terrestrial eutrophication  |
Environmental Impacts and Categories

| Abbreviation | Description |
|--------------|-------------|
| FAETP        | freshwater aquatic ecotoxicity potential |
| MAET         | marine aquatic ecotoxicity potential |
| TET          | terrestrial ecotoxicity potential |
| FEP          | freshwater eutrophication potential |
| MEP          | marine eutrophication potential |
| WaC          | water consumption potential |
| FETP         | freshwater ecotoxicity potential |
| WaP          | water pollution potential |
| FSET         | freshwater sediment ecotoxicity |
| MOCVD        | metalorganic chemical vapor deposition |
| HT/HTP       | human toxicity potential |
| GHG          | greenhouse gas |
| MOVPE        | metal organic chemical vapor phase epitaxy |
| MSET         | marine sediment ecotoxicity |
| GWP          | global warming potential |

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