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Praca dyplomowa

Life Cycle Assessment (LCA) of Heliostat Dedicated to Daylighting in Comparison with Artificial Lighting Sources.

Środowiskowa analiza cyklu życia heliostatu przeznaczonego do doświetlania wnętrz światłem dziennym w porównaniu do źródeł światła sztucznego

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Abstract

This paper compares the environmental effects of current artificial lighting sources and a novel lighting system called Heliostat. The paper begins by describing the role of the heliostat and how it reflects solar light energy into buildings. There has been a study of the literature on life cycle analyses of lighting products. Numerous experts stated in the review that the use phase of artificial lighting items uses the most energy. The functional unit is another vital consideration. Because it would serve as the baseline for comparison for the lights under examination, a 20Mlm-hr functional unit was chosen. The results were split into three impact categories after creating the model in GABI and simulating the inventory analysis; Air, soil, and water, as well as climate change. Heliostat has the least negative environmental effects and uses no energy during the usage phase when compared to all other categories and phases of the Life Cycle Assessment. As a result, Heliostat is both a future-proof lighting solution and an environmentally friendly product.

Streszczenie

Celem niniejszego raportu jest porównanie wpływu na środowisko nowatorskiej technologii oświetleniowej o nazwie Heliostat z istniejącymi źródłami sztucznego oświetlenia. Po pierwsze, w raporcie opisano funkcję Heliostatu i sposób, w jaki odbija on energię świetlną ze słońca do budynków. Przeprowadzono przegląd istniejącej literatury dotyczącej oceny cyklu życia produktów oświetleniowych. Z przeglądu wynika, że wielu autorów podało, że faza użytkowania zużywa najwięcej energii dla produktów oświetlenia sztucznego. Innym ważnym czynnikiem do rozważenia jest jednostka funkcjonalna. Zastosowano jednostkę funkcjonalną 20Mlm-hr, ponieważ będzie ona służyć jako podstawa porównania dla badanych lamp. Po zbudowaniu modelu w GABI i przeprowadzeniu symulacji analizy inwentaryzacyjnej, wyniki podzielono na trzy kategorie wpływu: powietrze i zmiany klimatu, gleba i woda. We wszystkich kategoriach i fazach oceny cyklu życia, Heliostat ma najmniejszy wpływ na środowisko, a także ma zerowe zużycie energii w fazie użytkowania. To sprawia, że Heliostat jest produktem przyjaznym dla środowiska i produktem oświetleniowym przyszłości.

Abbreviations

CFL Compact Fluorescent Light

EPD Environmental Product Declarations

ESD Environmentally Sustainable Design

GWP Global Warming Potential

LCA Life Cycle Assessment

LCI Life Cycle Inventory

LED Light Emitting Diode

LCIA Life Cycle Inventory Analysis

ISO International Standard Organization

PDS Product Design Specification

SSL Solid State Lighting

US DOE United State Department of Energy

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1. Introduction

In this first section, the investigated product is described. Next, is the research motivation; the scope and limitations; and, as well as the goals of this Master's thesis, are presented. In the end, the structure and content of the thesis are also specified.

1.1 Heliostat

The Heliostat considered in this thesis is a product designed at the AGH Center of Renewable Energy and it is dedicated to daylighting. As shown in figure 1, the product is designed to provide efficient indoor illumination for buildings/spaces during daylighting. Pictures the parts and weight of the Heliostat are presented in Appendix B and C. The objective of the product is to use as much sunlight as possible for indoor lighting to reduce or even temporarily pause the use of artificial light sources for the same purpose [1]. The main goal of the heliostat is to reflect direct solar radiation from a sunny place to the shaded interior where daylight is available only temporary or unavailable at all times. In the opinion of the inventor, heliostat may play a significant part in the sustainable development of the lighting industry by reducing energy consumption, and positively improving the indoor environment [1]. More so, the heliostat can be categorized according to its geometry:

(i) small scale, with $Rh \in \langle 0.05; 0.15 \rangle$[m],

(ii) medium scale, with $Rh \in \langle 0.15; 0.35 \rangle$[m], and

(iii) large scale, with $Rh \in \langle 0.35; 1.00 \rangle$[m].

Where Rh is the radius of the mirror. Rh is important because it plays a major role in determining the luminous flux of the heliostat.

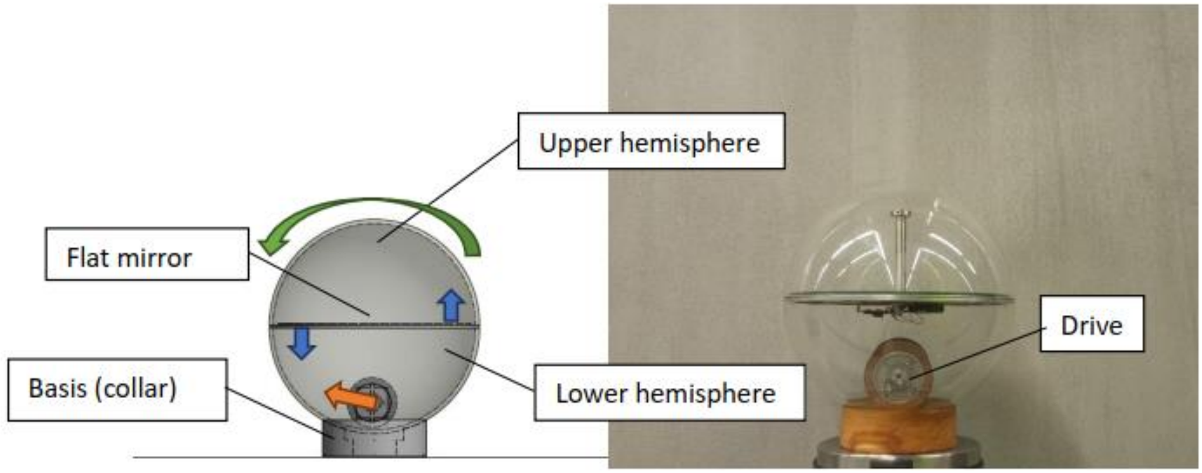

***Figure 1**: Heliostat Source: [1]*

1.2 Research Motivation

Lighting consumes a significant amount of electricity globally and has a significant negative influence on the environment, especially when it comes to energy utilization. Over 90% of a light source's overall life cycle environmental consequences are attributable to its electricity consumption during use [2]. But the environmental impact of light sources is not limited to the energy used during the "use" phase; the entire life cycle must be considered. One of the most crucial requirements for new product development projects is sustainable design in order for any product to remain competitive in today's marketplaces. Environmentally friendly items are becoming more and more significant [3]. Due to increased public knowledge of how the items we use influence the environment, consumers are now more likely to favor greener products. From a commercial standpoint, more environmentally friendly items will enhance a company's brand and boost its market share. This is what inspired me to evaluate Heliostat's effects on the environment. The Life Cycle Assessment (LCA) technique can help with this. The LCA makes it possible to pinpoint the root causes of environmental consequences throughout a product's life cycle [2], [4]. LCA is also used to assess the potential environmental effects of a process, system, or service over the course of its life cycle, from the extraction of raw materials to the point of no return (ISO, 2006a).

1.3 Thesis Outline

In Chapter 2, a thorough examination of the use of lighting technology is also covered in great detail. The LCA methodology's framework is described in Chapter 3. In Chapter 4, the outcomes of the inventory analysis would be examined. Chapter 5 provides the summary and conclusion and chapter 6 covers the Reference.

2. Literature Review

This chapter is an extensive literature review of Environmental Assessment of Lighting Products. The focus of **Chapter 2.1** is to introduce the concept of daylighting and artificial lighting; **Chapter 2.2** introduces the carbon footprint of artificial lighting. **Chapter 2.3** focuses on the Life cycle assessment of lighting product and finally, **Chapter 2.4** briefly outlined the economic impact of lighting industry.

2.1 Lighting

a. Daylighting

Man has always wanted to continue living his regular life after nightfall. Daylight, or solar radiation, is a free and effective source of illumination. Because of this, daylighting is essential to a person's daily activities. For survival, plants, animals, and other living things all rely on solar energy. Natural light is the best source of light since it has a high quality that corresponds to how human eyes perceive things. Daylight is greatly appreciated by people for their living and working places since it has a beneficial impact on individuals by making the environment feel lively and bright. As a result, daylighting is a crucial component of contemporary architecture [2], [6], and [7].

Instead of being proportionate to the horizontal illuminance of the outside, the amount of indoor light in a side-lit room is almost proportional to the amount of daylight falling on the window. In the following equations, [8] show how this idea has been expanded upon to relate the average indoor daylight illuminance to the illumination on an exterior vertical surface for the "average sky," where "average sky" refers to an estimate over all points in the space as well as a limit of sky conditions for a specific place:

Light flux entering windows = $\frac{1}{4} * E_v * V_T * A_w$ --------------------(1)

Light flux absorbed by indoor surfaces = $\frac{1}{4} * E_{in} * A_{in} (1-R)$ -------(2)

where R is the average reflectance of all interior surfaces, and Ain is the total area of indoor surfaces (m2) (m2), Window area (Aw) is measured in square meters (m2), window facade vertical illumination (Ev) is measured in lux, and average surface illumination (Ein) is measured (lux).

Daylight is seen as an alternate source of light to artificial lighting in sustainable building designs. By employing more energy-efficient lighting fixtures or boosting natural lighting in buildings, more lighting energy savings can be achieved. The quantity of power used and the related sensible cooling load brought on by artificial lights are reduced when there is daylight. Therefore, effective daylighting plans can aid in lowering a building's peak electricity usage. As a result, daylighting has the potential to reduce the size of High Voltage Air Conditioning (HVAC) systems and reduce cooling loads in addition to peak electricity demands and electric lighting [8], [9]. The health and productivity of the building's occupants as well as the interior environment will all be directly impacted by how well natural lighting is used. This impact also extends to the building's total energy efficiency. More importantly, it will contribute to lowering the energy sector's lighting industry's environmental effect [6].

Instead of relying solely on artificial light during daylighting, [10] stated that by successfully harnessing daylight as a renewable source and properly integrating daylighting systems into buildings, we can help to reduce energy usage. The authors also mentioned how this integration can aid in the creation of environmentally friendly, long-lasting, high-performing, and energy-efficient structures. The similar idea has also been advanced by many authors [11].

Several authors have improved daylighting technology. [10] introduced and implemented an approach for identifying the optimal set of integrated daylighting systems into building windows in order to maximize energy efficiency performance in industrial buildings in the blazing hot desert climate. [12] offered a condensed analysis approach to calculate how much energy may be saved by using daylighting instead of electric lights. The daylight factor, illuminance and brightness, and glare index were some of the essential components of daylighting and lighting control systems that [9] studied.

b. Artificial Lighting

Our daily lives have been profoundly altered by electrical lighting to the point where it is now impossible to function without it. Modern human inventions all rely on electricity as their power source. Everything that works, from tiny sensors to massive industrial machinery, depends on electricity. The lighting sector is no different. A total of 2,650 TWh, or nearly 19% of the total power produced globally, is consumed annually by the estimated 30 billion light bulbs that are in use worldwide [13]. As a result, artificial light sources are essential to a person's daily life. An estimated 1/5 to 1/6 of the electricity produced worldwide is used to power electrical light sources. The average amount of energy used for lighting in various parts of the world is depicted in figure 2 below. Although traditional lighting technologies are now in their mature stages, there is still room for innovation because the light sources' luminous efficiency and light quality have not yet reached their maximum levels. There are many opportunities today to improve the quality of light as perceived by the end user while also increasing the efficiency and dependability of lighting systems [7], [13]. Three main technologies—Light Emitting Diode (LED), Incandescent bulbs, and Electrical Discharge, often known as Compact Fluorescent Lights—dominate the market (CFL). In some nations, the last two are currently off the market. Solid State Lighting (SSL) is currently ushering in the next revolution in the lighting sector [7].

It is technically, commercially, and environmentally difficult to create, optimize, and mass produce new and more efficient light sources, but this approach appears to be the most viable one. The maximum efficiency of these systems has been increasing since the 1970s and is currently somewhere between 100 and 110 lm/W6, despite several scientific and technological improvements in the field of electrical light sources. The international society is moving toward a trend where lighting with new technology uses less than 10 kWh/m2 of electricity annually [14]–[16]. Utilizing daylight is the most essential approach to reduce energy consumption in the lighting sector. Other methods include using lighting control systems, lowering power density, and using light sources with high luminous efficacy [7].

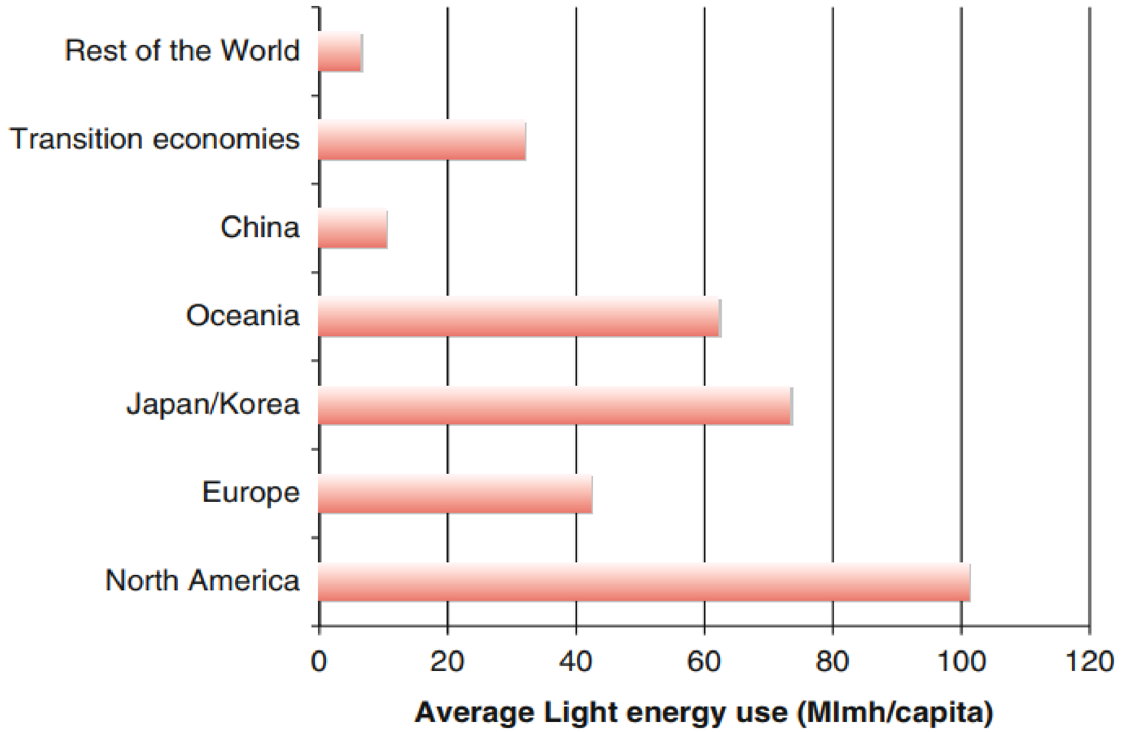

Figure 2: *Average light consumption per capita by country. Source [7]*

It is technically, commercially, and environmentally difficult to create, optimize, and mass produce new and more efficient light sources, but this approach appears to be the most viable one. Nevertheless, despite several scientific and technological advancements in the field of electrical discharge light sources, these systems' maximum efficiency has been rising since the 1970s and is now approximately 100–110 lm/W6. The international society is moving toward a trend where lighting with new technology uses less than 10 kWh/m2 of electricity annually [14]–[16]. Utilizing daylight is the most essential approach to reduce energy consumption in the lighting sector. Other methods include using lighting control systems, lowering power density, and using light sources with high luminous efficacy [7].

Looking at energy consumption by economic sector, as reported in [7] and shown in figure 3, tertiary buildings (43%) and residential sector (31%), are major contributors. The tertiary building's annual lighting electricity consumption per square meter ranges between 20 and 50 kWh/m2.

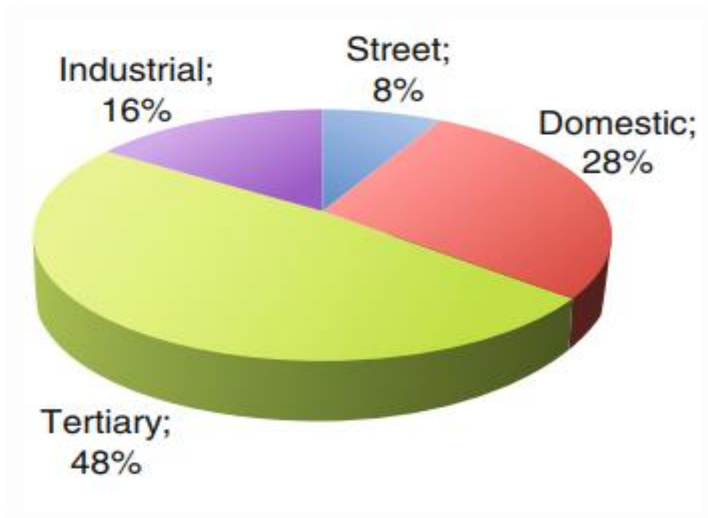

Figure 3: *Energy consumption by economic sector. Source [7]***.**

It should be noted that, in contrast to secondary building lighting, residential lighting as a very low average luminous efficacy of just 21.5 lm/W, as opposed to commercial buildings' 50 lm/W and industrial buildings' 79 lm/W. The global society has a trend toward lowering lighting's annual electricity use per square meter to under 10 kWh/m2. As was previously noted, using daylighting could aid in accomplishing this. Daylighting is a plentiful and cutting-edge technology that uses the optical principle to reflect sunlight into buildings, eliminating the need for artificial light sources when it is daylight [7], [17]–[21]. New technologies that can maximize the illuminating power of the sun cannot also be ruled out.

It is possible that future developments will enable us to optimize the sun's lighting potential. One of the least complicated strategies for increasing building energy efficiency is the integration of daylighting with artificial lighting systems, which has the potential to minimize reliance on artificial [22].

2.2 Carbon Footprint of Artificial Lighting.

The effects of artificial lighting on the environment depend on how much energy is used, what materials are used to make the lighting equipment, how much energy is consumed for transportation, and how old equipment is disposed of. An accurate assessment of the full impact of lighting can only be made through a comprehensive life cycle assessment using the ISO 14040 methodology. The ISO 14040 methodology is the subject of this thesis' third chapter. This part, however, focuses on the carbon footprint associated with energy use. Lighting actually has an environmental impact that is 85% to 90% accounted for by its carbon footprint, similar to the impact of many electrically powered items [16] .

Environmental contamination is a natural result of producing electric energy from non-renewable sources to meet human demand for illumination. We can determine the carbon footprint of lighting fixtures [2], [16] by assuming that energy consumption over the course of a lamp's lifetime accounts for about 90% of its environmental impact, while production, disposal, and recycling phases correspond to 4% and raw material use to 6%, respectively. In 2005, it was estimated that greenhouse gas (GHG) emissions from lighting fixtures totaled 1900 million tons (Mt), or roughly 7% of the total global CO2 emissions from burning and venting fossil fuels [2]. Seventy percent of the emissions from light passenger vehicles are represented by this global total. Of course, this percentage will decrease proportionally as the share of renewable energy sources in global electricity production increases. 244 Mt of greenhouse gases are annually released into the atmosphere as a result of the fuel-based illumination utilized in developing nations. The aforementioned figures, however, represent worldwide averages and cannot be generalized to a national or regional scale. The energy mix and energy technology of the nation have a significant impact on the greenhouse gas (GHG) emissions caused by lighting fixtures. The "total primary energy factor" can be used as a first approximation to define the energy mix. This quantity is calculated by dividing the delivered energy by the sum of the principal energy sources (renewable and non-renewable). The overall primary energy factor for electricity in Europe is 2.5. Additionally, each European nation has a different CO2 intensity in the power generating process. If an average electricity emission factor of

527 g/kWh is employed, Europe's yearly GHG emissions are in the range of 200 Mt [2], [7], [18], and [23].

Figure 4: *Lighting Products. Source. [18]*

2.3 Life Cycle Assessment of Lighting Products

Life cycle assessment, a methodology that considers the product's entire life cycle, is used to investigate the environmental impacts of lighting products. When deciding on a different type of technology based on environmental impacts, it is critical to examine the entire product life cycle to identify major environmental hotspots and to ensure that environmental impacts are not shifted from one stage to the next [24].

The goal of green design or sustainable design is to "completely eliminate negative environmental impact through skillful, sensitive design" [25]. In both literature and industry, terms such as "Environmental Design (ED)," "Environmentally Sustainable Design (ESD)," "Eco-design," and "Environmental Conscious Design" are being used in place of green design. Despite the fact that there are some real differences between them, the overall goal of each of them is the same [3].

A notable finding of a thorough LCA assessment of light sources is that the energy consumption during the light source's "use" phase has the biggest negative effects on the environment. However, this is sensitive to the source's energy-mix. In the context of the entire life cycle, other stages of the life cycle typically only have minimal effects on the environment. However, more thorough modeling is advised, particularly with relation to the product's manufacture and end of life. The dynamics of the LCA of light sources and, for the most part, all energy-using items will alter as a result of the global transition toward environmentally friendly power sources. As a result, manufacturing and end-of-life are probably going to start playing a bigger role in LCA in the future [18], [19].

Numerous LCA publications and reports have examined the environmental effects of light sources over the course of their lifetimes. Studies have unequivocally shown that the environmental effects of lighting are mostly a result of the electricity required during use, supporting the idea that, generally speaking, lighting with higher energy efficiency will have a less negative environmental impact [26].

Ming Hu conducted research on the life-cycle environmental effects of urban energy retrofit solutions. After comparing the three stages of energy retrofit to the current situation, the author described potential reductions in environmental effect. The author then identified the life-cycle weak points of the energy retrofit schemes and provided an illustration of how life cycle assessment (LCA) could be used as a quantitative assessment technique for energy retrofits carried out on a wide scale. Five categories had their life-cycle environmental impact determined. The findings showed that, overall, energy retrofits reduced life-cycle environmental consequences, with the exception of ozone-depletion potential, in all environmental categories [15]. TThe best-performing light source is the expected LED lamp 2017 (which takes into account numerous forecasted advancements in LED manufacture, LED performance, and driver electronics) [14]. The worst performer was the compact fluorescent lamp, which had much lower affects than incandescent but was somewhat more damaging than the 2012 integrally ballasted LED lamp. Of all the bulbs considered, incandescent lights had the most impact per unit of lighting service. This is accurate for all categories aside from hazardous waste landfills, where the impact of the LED bulb is slightly greater than that of the CFL due to the massive metal heat sink [14]. In order to support the creation of a sustainable energy policy, [27] examined the resource depletion and toxicity potentials from the metals in incandescent, CFL, and LED lights. Due to their high lead, copper, and zinc compositions, the authors concluded that CFL and LED bulbs had been classified as hazardous, whereas incandescent bulbs had not. Additionally, because of their higher levels of aluminum, copper, gold, lead, silver, and zinc than an incandescent bulb, CFLs and LEDs have larger potentials for resource depletion and toxicity.

Two lighting technologies based on compact fluorescent (CFL) and Light Emitting Diode (LED) luminaires were assessed from cradle to grave for the general illumination of the office by [23], [28]. The bulb, housing, and ballast are all taken into consideration throughout the life cycle assessments. According to life cycle analyses, LED luminaires enable the environment to be much less affected (reduction of 41–50% of greenhouse gas emissions and cumulative energy demand), mostly because of their excellent energy efficiency during operation. The results of the LCA models used by [29] offered eco-design solutions for the environmental sustainability of the new LED modular luminaire, along with a number of recommendations and reflections throughout its life cycle.

In their study, [30] developed an approach for integrating LCA into the eco-design of lighting products. The authors performed LCAs on five contemporary lighting products to validate this methodology. A sustainability request for lighting products was created and included in the product design specification based on the findings of these LCAs (PDS). This guarantees that the desired eco-design elements will be present in any product created in compliance with the PDS. The next step was to develop and produce a new sustainable lighting product in compliance with the PDS, and an LCA was then carried out on the new product. The newly designed product was shown to produce better results when the LCA results of the new product were compared to the LCA results of the current lighting products. The consumption of electricity during the use phase was found to be the most significant contributor to the environmental impact of each product, accounting for more than 90% of the total impact of each product on average. According to [17], resource scarcity, hazardous waste, and climate change are driving forces in the development of energy efficient and non-toxic lighting sources. The study gives an overview of the global lighting market and LED-lamp technologies before conducting a thorough review and comparison of life cycle assessment studies. The authors also considered environmental aspects which are relevant for the well-being of an end-user.

[23] evaluated and compared a luminaire with a Light Emitting Diode (LED) light source to a comparable compact fluorescent luminaire (CFL) used as general office lighting to offer a life cycle assessment of two lighting technologies. The evaluation examines all stages of the luminaire's life cycle, from cradle to grave. Utilizing LED luminaires, especially those of the most recent generation, it is feasible to obtain a substantial reduction in environmental impact (31% to 50%). The LED luminaire, in particular, provides a 41%-50% reduction in Global Warming Potential (GWP) and cumulative energy demand (CED). [31] evaluated and contrasted the environmental effects of two different LED lighting products, one of which was an eco-friendly new LED product. The system boundaries cover every stage of the product life cycle, with the exception of packaging production and luminaire maintenance. For the evaluation, a new functional unit that is better suited for LED lighting products was defined. The authors took into account six possibilities, including two end-of-life alternatives and three luminaires with usable lifetimes of 1000, 15,000, and 40,000 hours (domestic bin and recycling center). The results of the life cycle evaluation show that the new eco-lighting product has, in every case, a 60% lower environmental effect than the current lighting product.

In conclusion, all authors concurred that the use phase of an artificial lighting product has the greatest environmental impact. [2] contains a table summarizing other works that have been done in this area.

2.4 Lighting's Economic Impact

The value of the worldwide lighting market was estimated at $110 billion in March 2011 by the US Department of Energy (DoE). Figure 5 shows the expansion of the world lighting business since 1997 as well as the expected trajectory until 2031. The expansion of the electrical infrastructure, an increase in the demand for lighting in developing nations, and population growth are the main factors driving the graph's growth [7].

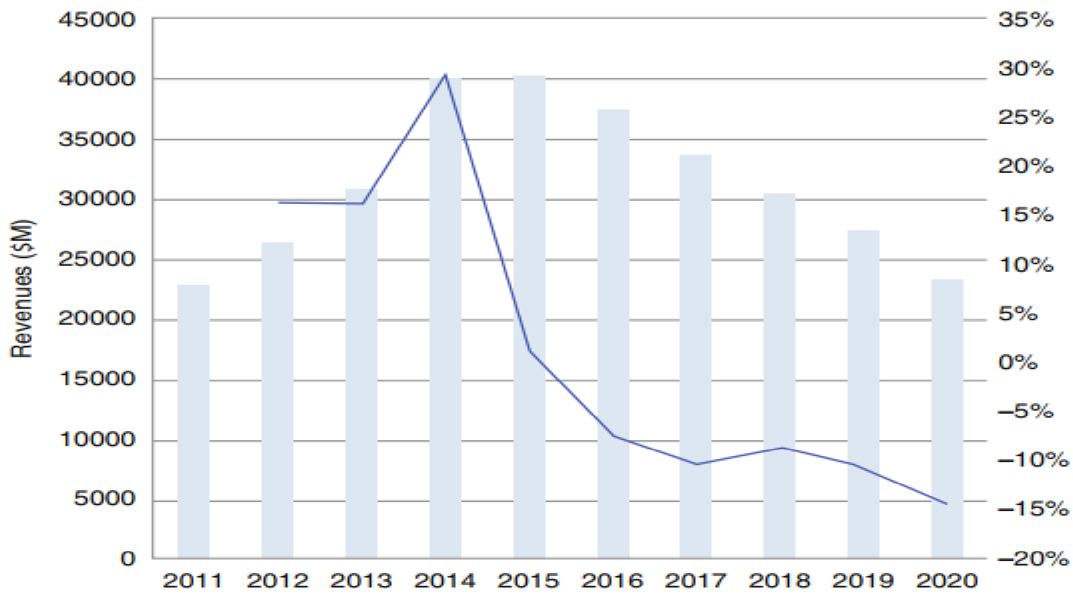

Figure 5*: Forecasts for the global lamp market revenue. Source [7]*

3 Proposed Methodology

A life cycle assessment is a methodical approach that enables researchers to quantitatively assess the environmental and sustainability effects of a product over the course of its life cycle across a number of impact categories. An LCA analyzes and describes the inputs, outputs, and environmental impacts of a system or product at every stage of its life cycle [32]. The ISO 14000 and 14040 document series outlines the general accepted guidelines for performing a life-cycle analysis. Goal, scope, and boundary definition; life-cycle inventory (LCI) analysis; life-cycle impact assessment; and interpretation are the four main stages of an LCA, according to ISO criteria [21], [32].

3.1 ISO LCA Framework Description

Through the ISO 14040 (Environmental Management - Life Cycle Assessment - Principles and Framework) and 14044 (Environmental Management - Life Cycle Assessment - Requirements and Guidelines) standards, the ISO documents provide a rigorous and generally agreed-upon framework. LCA studies are shaped by how these ideas are used generally or how standards are applied specifically. These will be discussed and used as the LCA model in this thesis. LCA is divided into four phases: Goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation of the life cycle are the first four steps.

i. Goal and Scope

The purpose of the LCA and the boundaries of the system under analysis are both described in the goal and scope defining step. This is the most fundamental and important stage in all LCA. Decisions on what to measure, how to assess it, and what sources of information to employ are varied for each study and must be the same for comparative studies. These decisions can result in significantly different results between LCA studies, and it is critical that it is made explicit what systemic factors or values contributed to that difference. Figure 6 depicts a life cycle assessment in general.

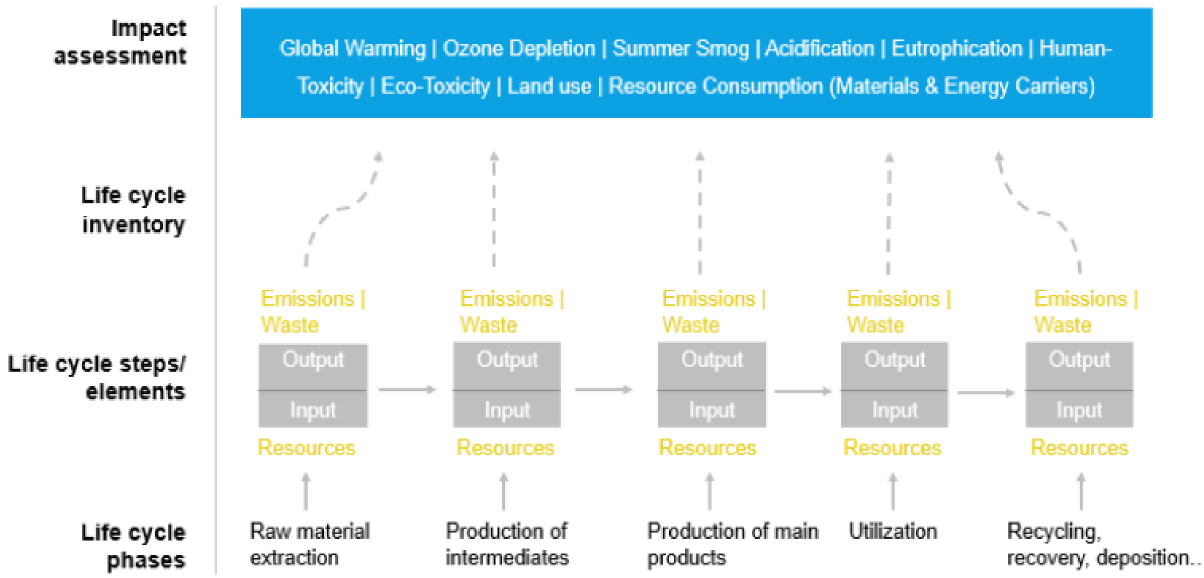

Figure 6: *Life Cycle Assessment Overview. Source:[32]*

The ISO 1400 and 14040 series require defining the goal to include the reason for the LCA, who will use it, how it will be used, and whether it will be used as a comparative analysis. Defining the scope, on the other hand, necessitates a description of the system. To serve as the foundation for any comparative study, the description of a functional unit, which is a way of measuring the product's performance, is required. Section 3.4 will go over the significance of functional units. Defining the scope also entails defining the system boundary, life-cycle impact categories, impact assessment methods, and subsequent interpretation to be used. Figure 7 depicts an example of a complete system boundaries definition for LCA.

Despite the fact that LCA can be used to evaluate a system's overall environmental impact, it is typically employed to respond to inquiries about a particular environmental impact (such as the consequences of factory plants on agricultural systems) using a subset of environmental impact categories (for example, land use). The type and format of the report that is required for the study are also typically decided upon when determining the LCA's scope, along with the data needed for the study, any and all hypotheses that are made, the study's limitations, the preliminary data quality requirements, proposals for a thorough analysis, and the nature of the data that will be used. The inclusion of all these details will aid readers in appropriately comprehending and contextualizing the study [32].

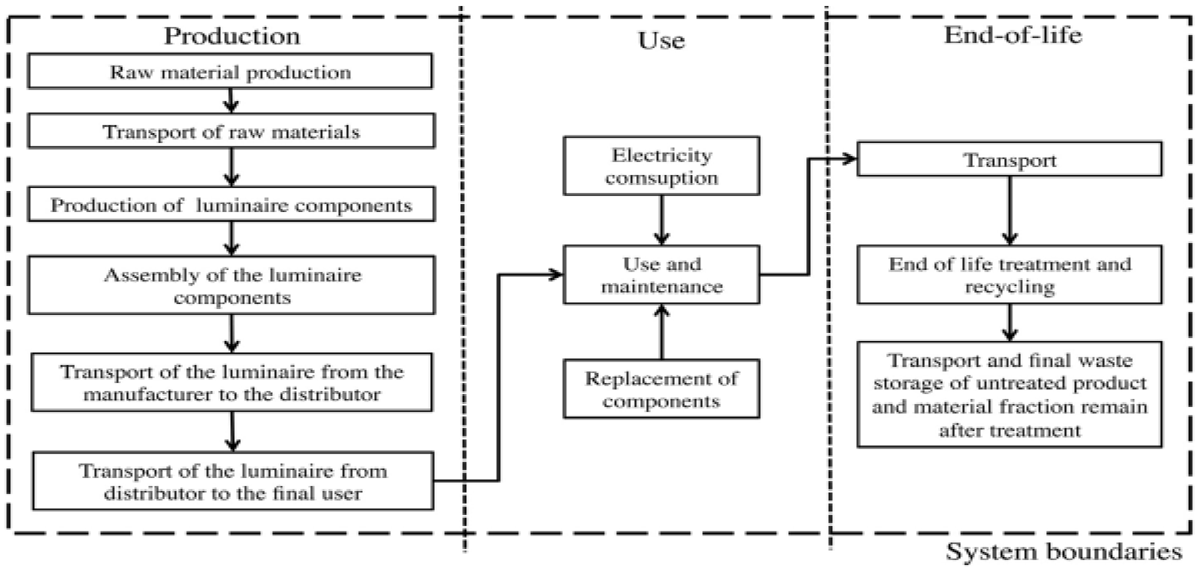

***Figure 7**: System Boundaries. Source.[32]*

ii. System Boundaries

Which processes are included and which are excluded from the system are specified by the system boundary. The boundaries of a system are defined by "cut-off" criteria. Cut-off criteria are utilized to identify which components and materials are included in the product system and which are not. To define system boundaries, one has four main choices:

a) **Cradle-to-grave**: encompasses all operations from raw material extraction to production/manufacturing, transportation, and consumption, all the way to the end of the product's useful life.
b) **Gate-to-Gate:** only includes manufacturing processes; it is used to evaluate the environmental impact of a single manufacturing stage or operation.
c) **Gate to Grave:** This method is employed to evaluate a product's environmental impact after it departs the factory. It covers all operations from the "use" phase to the end-of-life phase, or anything that occurs after production.
d) **Cradle-to-gate**: This refers to assessment of a portion of the product's life cycle from the factory to the consumer. This type of evaluation disregards the

use and disposal phases. Environmental product declarations are frequently based on cradle-to-grave assessments.

Other LCA system boundaries includes;

e. **Cradle-to-cradle:** is a type of assessment where the product's end-of-life disposal step is a recycling process. The recycling process can produce new, different, or brand-new products.
f. **Well-to-wheel**: this is a type of LCA used to evaluate the efficiency of road transportation fuels. The analysis is frequently divided into stages such as "well-to-station" and "station-to-wheel," as well as "well-to-tank" and "tank-to-wheel."
g. **Economic Input-Output LCA**: This assesses the environmental effects of each economic sector by using aggregate sector-level data. Additionally, it's utilized to calculate how much one sector buys from the others.

For this thesis, the goal has been defined in the first chapter. For the system boundary, the Cradle to Cradle evaluation would be the main focus, with recycling serving as the product's end-of-life disposal.

iii. Analysis of Life Cycle Inventory (LCI)

The gathering, computation, and distribution of data form the core of the life cycle inventory (LCI). The accuracy of the data is crucial while doing an LCA. The information gathered consists of information on energy (inputs and outputs), raw materials (often known as material flow), and supplementary inputs. The data is computed by linking it to the system using the functional unit. Since single-output industrial processes are uncommon, data allocation is necessary. Allocating resources makes guarantee that processes with many outputs are accurately represented by the amount of data required for the output under study[16].

iv. Life Cycle Impact Assessment (LCIA)

The purpose of the impact assessment stage is to comprehend the system's potential environmental impacts. After selecting impact categories, the data must be classified and characterized. This means that the effects are computed using normalized inputs and outputs. Normalization, grouping, and weighting are optional components of the assessment stage. The quantitative value of an impact category is generally recalculated to reflect its relative importance in terms of absolute regional, national, or global impacts. This may be helpful based on the objectives of the LCA. Sorting impacts to find more general areas of importance is what grouping entails. Weighting can also be used to produce more relevant results.

The LCA standard does not suggest a method of appraisal or an impact category to be taken into account. The estimated outcomes articulate potential environmental effects in relation to the reference unit. The following impact evaluation will be taken into account: Acidification, resource depletion, eutrophication, land usage, ozone depletion, production of photochemical ozone, potential for global warming, toxicity, water use, and waste [33], [34].

3.2 Categories of Environmental Impacts

An LCA study must consider a range of environmental impacts. The environmental impact category to choose is frequently informed by the scope and purpose of the LCA. LCA practitioners generally recommend that an LCA study must contain a number of impact categories so that environmental impacts are taken into account throughout a broad spectrum.

The following subchapters give a quick summary of the environmental impact categories that are most frequently used in LCAs.

i. **Global Warming Potential (GWP)-** measured in kg of CO2 equivalents
The term "greenhouse gas potential" (GWP) refers to the amount of heat that any greenhouse gas in the atmosphere can absorb. These figures relate to CO2. The concentration of these and additional heat-trapping gases will rise along with their heat-trapping capacity, which will ultimately cause global climate change and its related environmental effects.

ii. **Photochemical Ozone Creation Potential (POCP**) - measured in kg of O3 formed
POCP measures the photochemical smog produced during the product's life cycle. When these primary pollutants come into contact with sunlight, they

degrade into a variety of hazardous chemicals known as secondary pollutants. These secondary pollutants contribute to what is commonly known as "urban smog."

iii. **Ozone Depleting Potential (ODP)-** measured in kg of CFC-11 equivalents

This metric assesses the product's ozone-depleting potential over its entire life cycle. Though beneficial to the earth at the stratospheric level because it shields the earth from excessive ultraviolet light, it is a pollutant at the atmospheric level

iv. **Human Toxicity Potential (HTP)-** is expressed as a unit of 1,4-dichlorobenzene (DCB) equivalents per kilogram.

This indicator makes an effort to measure the air, water, and soil emissions connected to the life cycle of the product that could be detrimental to human health.

v. **Acidification Potential (AP)-** measured in kg SO2 equivalents.

This indicator measures the amount of air pollutants that cause ecosystem acidification, primarily ammonia, sulfur dioxide, and nitrogen oxides. It typically leads to "acid rain," which is most well-known for the harm it does to lakes and forests.

vi. **Marine Aquatic Eco-toxicity Potential (MAETP)-** is expressed as a unit of 1,4-dichlorobenzene (DCB) equivalents per kilogram.

This indicator is similar to FAETP, but it refers to marine aquatic organisms. It brings together additional factors related to the maximum tolerable concentrations of various toxic substances in marine water.

vii. **Eutrophication Potential (EP)**- measured in kilograms of phosphate (PO4) equivalents

The excessive growth of algae caused by over-fertilization of the ecosystem is known as eutrophication. This phenomenon is primarily caused by two compounds: nitrates and phosphates. EP assesses a product's ability to cause this phenomenon.

viii. **Freshwater Aquatic Eco-toxicity Potential (FAETP)-** is expressed as a unit of 1,4-dichlorobenzene (DCB) equivalents per kilogram.

This is quite similar to the potential for human toxicity, but it also takes into account aspects related to the highest concentrations of different harmful compounds that freshwater aquatic creatures can tolerate.

ix. **Ecosystem Damage Potential (EDP)**- measured in points

This indicator makes an effort to quantify how a product will impact forestry, agriculture, the growth of metropolitan areas, and infrastructure. It combines land use and land transformation to take the relative impact of the land usage into consideration (both from and to industrial uses).

x. **Terrestrial Eco-toxicity Potential (TAETP)**- is expressed as a unit of 1,4-dichlorobenzene (DCB) equivalents per kilogram.

This indicator, which instead refers to the maximum acceptable doses of various harmful chemicals by terrestrial species, is essentially comparable to the previous toxicity potentials.

xi. **Abiotic Resource Depletion (ARD)**- is calculated as the equivalent kilos of the rare element antimony (Sb)

The unsustainable nature of the present rates of global consumption of resources is well known. Abiotic resources are naturally occurring and, unlike renewable sources like biomass, are finite. Examples include natural gas, crude oil, and iron ore. To account for the consequences of ARD, the residual global inventory of antimony (Sb), a relatively rare element, is employed.

xii. **Land Use (LU)**- is calculated as square meters used annually (m2a)

The presence of any industrial facility prevents the land from being returned to a more natural state, which includes supporting animals. This indicator tracks the impact on the target region and how long it lasts.

xiii. Radioactive Waste Landfilled (RWL), and Hazardous Waste Landfilled (HWL), Non-Hazardous Waste Landfilled (NHWL)- are all expressed in kilograms (kg)

These metrics all aim to estimate the volume of waste products disposed of in landfills, broken down into three categories: non-hazardous waste, radioactive waste, and hazardous waste [34].

3.3 Life Cycle Interpretation

The interpretation stage's goal is to explain and present the assessment's findings. This needs to be accomplished by first identifying critical issues that emerge in the earlier stages [34, 35]. The interpretation stage also includes a re - evaluation of the data as well as an elaboration of how it meets the study's objectives. The information gleaned from evaluating the results must also be presented in a way that is appropriate for the intended audience, who may not be technically inclined, policy- or business-oriented [17]. For example, an LCA on agriculture in a region will need to be appropriately interpreted to various stakeholders in order to assist policymakers in developing water consumption policies or assist regional planners in making plans for areas that need more water [32].

3.4 Functional Unit

When it comes to light sources, most authors agreed that lumen-hours are an appropriate functional unit because they consider both luminous flux and operating hours. f the lightbulbs are meant for the same usage and have comparable qualities such as luminous intensity distribution curve, luminous flux, and color characteristics, the functional unit could be a single lamp piece. To account for actual illumination, a light source's functional unit may consider illumination on a surface, such as illumination on a 1 m2 square surface at 1 m distance. The definition of reference flow is an important part of defining a functional unit. The reference flow is a measurement of the number of product components and materials required to perform a specific function as defined by the functional unit. All information gathered during the inventory phase must be relevant to the reference flow [21Lighting technologies' environmental impacts, for example, can be quantified per lamp, per lamp lifetime hour(s), or per lamp lumen-hour (s). Alternatively, all data used in the LCA must be assessed or scaled in consonance with the reference flow. [2], [17], [23], [30], [31].

The lumen-hour appears to be a suitable functional unit for light sources, despite the fact that a number of functional units have been employed in the LCAs of light sources, as mentioned above. It does so because it takes into account both the luminous flux and the operating hours. It should be noted that an incandescent lamp's luminous flux remains constant during the course of its lifespan. In contrast, the luminous flux of LED and compact fluorescent lighting technologies depreciates over the course of operation [7]. It was discovered in a methodology study that utilizing Mlmh, hour, or illuminance as the functional unit did not significantly alter the comparison's findings for non-directional lamps (incandescent, CFL, and LED) [8].

3.5 Total Sustainability Assessment

The term "life cycle assessment" is frequently used to refer to the process of taking into account the economic, social, and environmental effects. Alternately, the evaluations might be improved so that Total Sustainability Assessment serves as the general phrase. The three components of a comprehensive sustainability assessment are represented in Figure 9 and are included in this definition. The goal of sustainability, also known as sustainable development, is to provide for the requirements of the present generation without endangering the capacity of future generations to provide for their own needs. These requirements address social, economic, and environmental needs. The total sustainability assessment, usually refer to as Life Cycle Sustainability Assessment (LCSA) is defined as

$$LCSA = SLCA + LCA + LCC \quad (3)$$

where SLCA represents Social Life Cycle Assessments (evaluates the social impact), LCC refers for Life Cycle Costing (economic impact), and LCA represents for the (environmental) life cycle assessment [36], [37].

Since monetary values have long been a source of interest, the life cycle cost analysis, often known as the economic effect, has the longest narrative of the three pillars. Even though life cycle costing as a sustainability indicator may not be the same as traditional cost analysis, there are some parallels between the two. The present value and temporal value of money, for instance, can both be calculated. For LCC, it might cover things like environmental protection costs.

The total sustainability assessment is a large and difficult entity to calculate across a product. Nonetheless, it provides a comprehensive overview of a product system's sustainability. These can be conducted from various perspectives, such as the manufacturer's, consumers, or municipality's [38]. The environmental and economic consequences are more developed than the social consequences. The reason for this is that social life cycle assessment faces challenges in developing a methodology as well as a data shortage. However, much research is currently being conducted on this topic, as general interest in it grows in sustainability discussions [32].

The social perspectives include organization-specific elements, and they can be categorized by stakeholders like employees, society, and customers or by effect categories like cultural heritage, health and safety, and human rights. SLCA currently lacks any international standards.

3.6 Assumptions

i. Manufacturing/Transportation phase

The datasets from the GABI Student Database 2016 for the production of plastics, rubber, aluminum, and paper were used to define the manufacturing parameters. The assessment also took into account the transportation of the material from the extraction site to the plant that produced it, as well as from the factory that produced it to the factory that assembled the product. The assumption was that Poland is where the raw materials are harvested, processed, and transported. The model was built using the Polish electricity mix.

ii. Use

Maintenance and repair of the luminaire during the 'use' stage were not considered in the assessment. It was assumed that the battery (12.5W) powering the Heliostat's electronics would be changed about five times during its lifetime. This may have an additional impact during the 'use' stage, but it is insignificant because we are not considering the LCA of a battery.

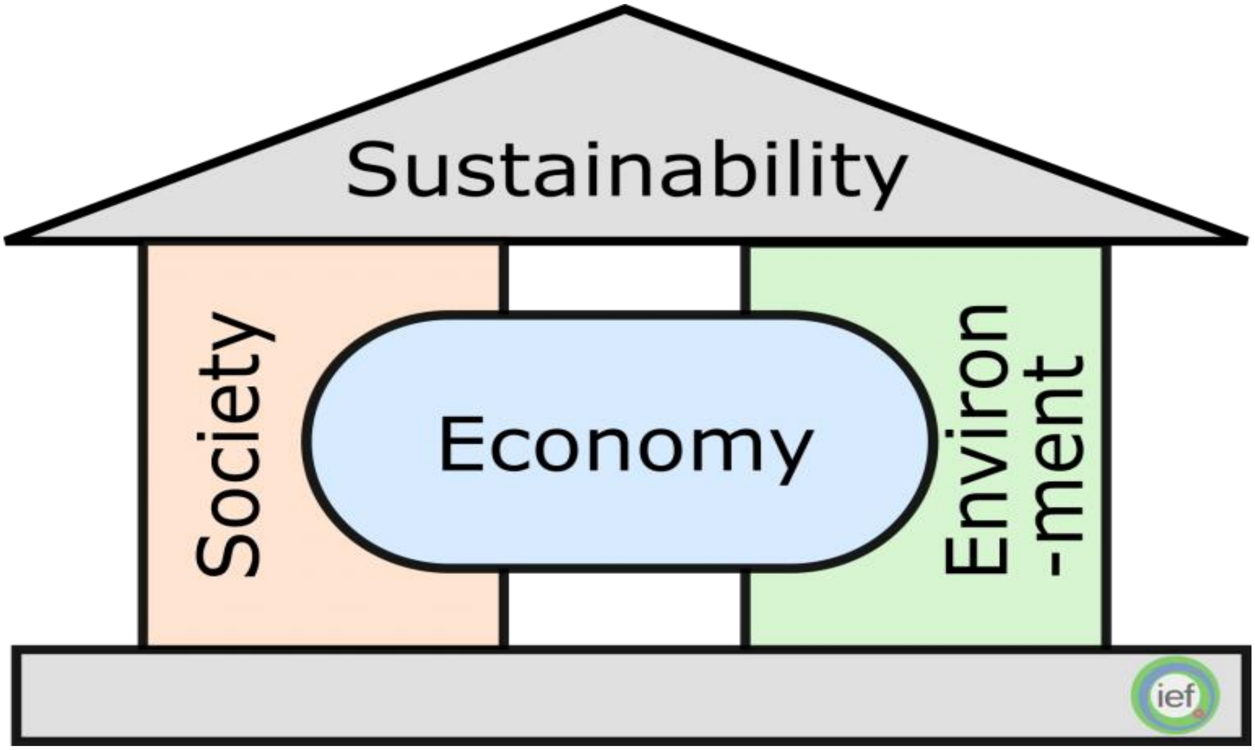

Figure 8: *Pillars of Sustainability. Source: [36]*

iii. **Functional Unit**

Following a review of the literature on functional units and US Department of Energy documentation on the LCA of three lamps, 20 million lumen-hours of lighting service were utilized as the functional unit, which roughly represents the total amount of light production of a 12.5W Philips Endura LED lamp throughout its entire life. Heliostats have different geometry, as discussed in section 1.1, and thus have different luminous fluxes. Figures 9a-9c depict the various luminous fluxes of heliostats and their relationship to the radius of the mirror.

iv. **Transportation Phase**

In this stage, the Heliostat is transported from a Polish manufacturing to the final consumer in a different Polish city. 263 kilometers is the expected total distance. The model utilized the Polish railroad system, and the fuel mixture originated there.

v. **End of life**

The Heliostat's end of life is difficult to predict because it has many parts and is also dependent on the consumer's disposal decisions. Nonetheless, there are two possible end-of-life scenarios: domestic bin and recycling center. In the model, we assume that paper is disposable, whereas plastics and metallic parts are recycled.

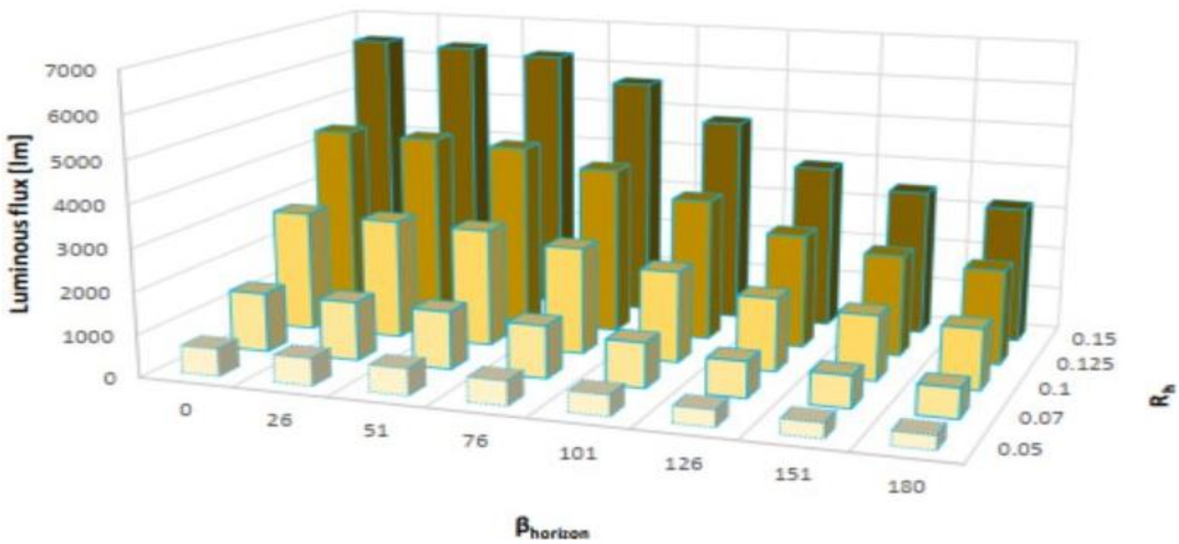

Figure 9a*: Luminous flux obtained from small scale spherical shaped heliostats*.

Source:[1]

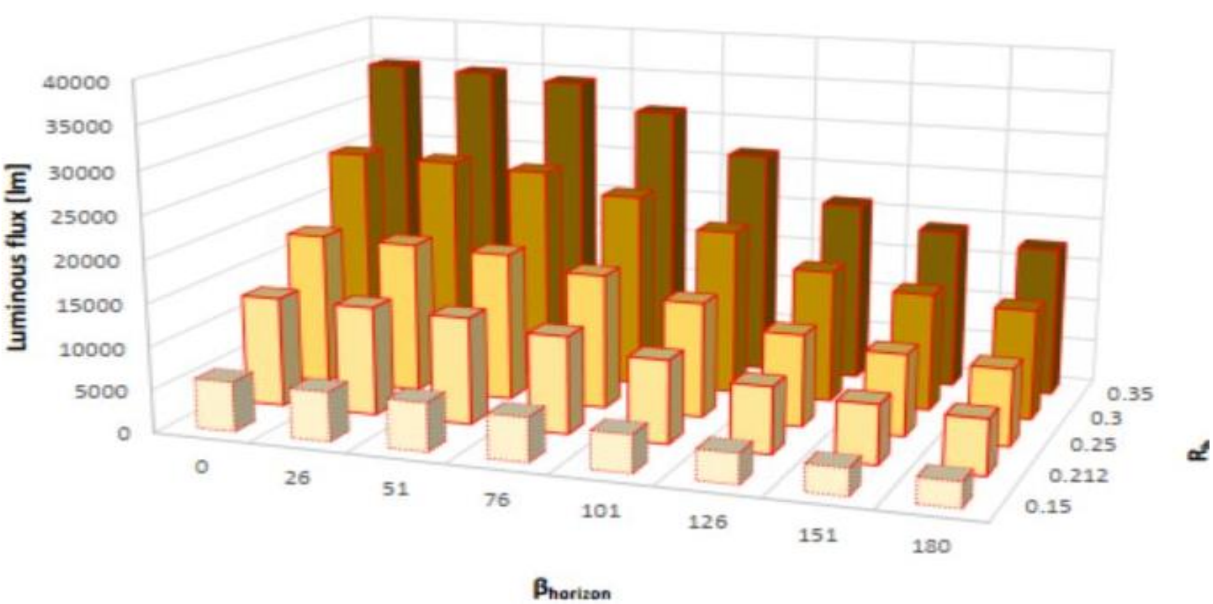

Figure 9b*: Luminous flux obtained from medium scale spherical shaped heliostats*

Source:[1]

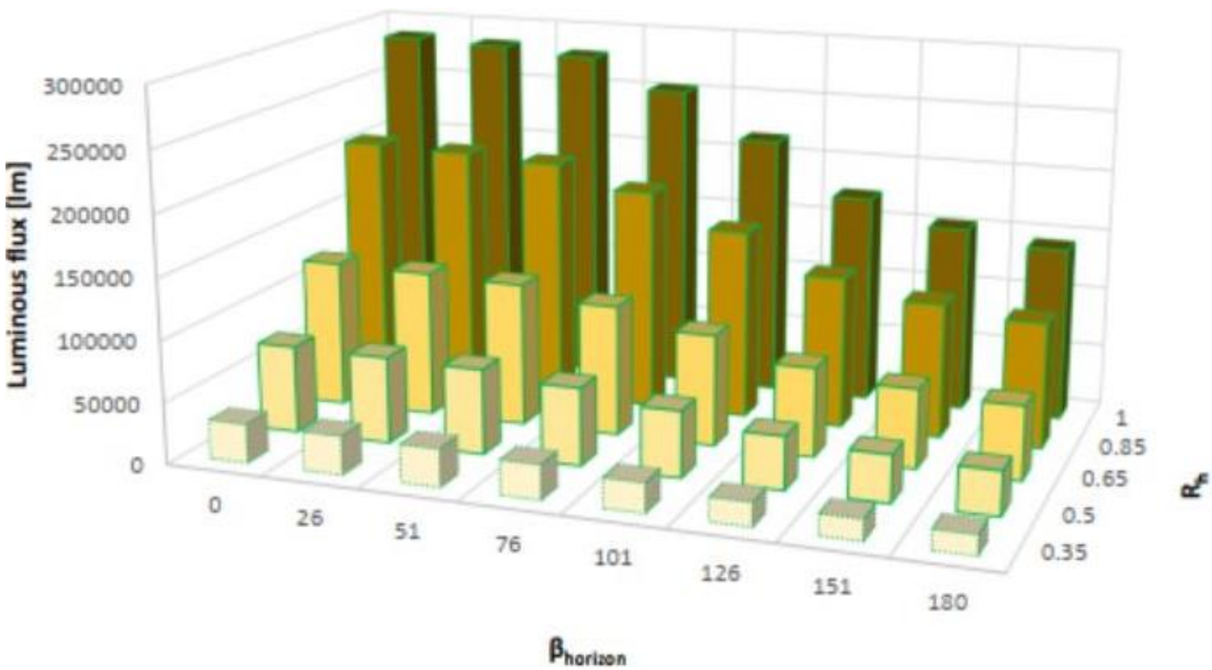

Figure 9c: Luminous flux obtained from large scale spherical shaped heliostats.

Source: [1]

According to the figures above, 10 huge heliostats with a radius of 0.65 and an angle of 101 degrees would create 20 million lumens per hour of illumination. The reference flow was then scaled to the power of 10.

3.7 About the Software

Gabi Software is a solution to carry out life cycle assessment of product, process and system. The software is used to support business decisions that involves developing products that meets environmental regulations, reducing material, energy and resource use and also enhancing the efficiency of the value chain. More so, it is used for Life cycle Costing, and Life Cycle Reporting. The software is provided by "Sphera" and it has different version. For these thesis, the GABI Education version was used and the Educational Databases accompanying the software. More about the product can be found on the official website of the software provider-www.sphera.com.

4. Result and Discussion

The LCA methodology's flexibility, as described in Chapter 3 of this work, permits a broad range of possible results. The results presented are based on the assumptions listed in section 3.8 of this report. The potential impacts of the assessment are characterized using the ReCiPe 2008 midpoint Life cycle Impact Assessment (LCIA) technique.

4.1 Results of Life Cycle Impact Assessment

This section introduces the Heliostat's life cycle result before comparing it to other results on Incandescent Lamps, LED, and CFL published by the US Department of Energy. The first step is to determine which phases of the life-cycle assessment have a significant environmental impact and which do not. Manufacturing and transportation processes are the most significant contributors to environmental impacts (because of the electricity mix). The manufacturing phase has the greatest amount of environmental impacts across all variables, as demonstrated in the series of charts below. All of the environmental indicators have no relevance during the use period. This is due to the fact that Heliostat doesn't require any energy when in operation. The only energy used is from the battery, and it exclusively reflects solar light energy. It was expected that the final items would be recycled after their useful lives. Since that is outside the purview of this study, we have no findings on it.

4.2 Discussion of Life Cycle Assessment Results

The manufacturing phase, which is represented in figures 10 and 11, is clearly the phase that controls the bulk of the environmental indicators taken into account. Almost 0% of the whole life cycle analysis's impact may be attributed to the usage phase. It is also possible to conduct a more thorough investigation into the role that each raw material plays in the impact evaluation. The scope of this study does not, however, extend to this. In the life cycle analysis, the transportation phase makes up about 10%. In the report, it is presumptively assumed that the rail transportation system uses the same electricity mix that the production facility does. By doing this, the influence of the electricity mix on the LCA as a whole will not be doubled.

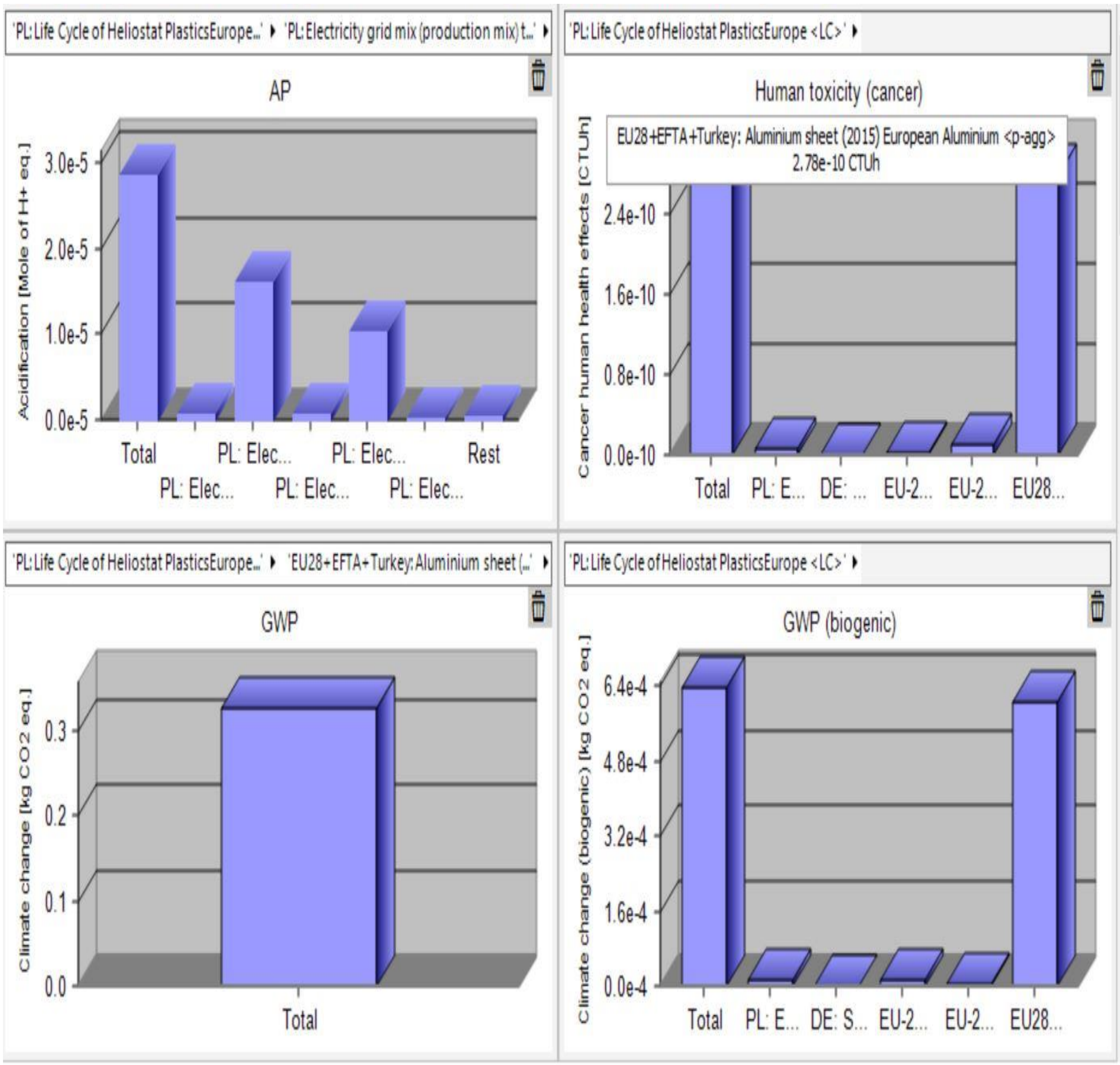

Figure 10*: Results of Life cycle manufacturing phase. Source: Own*

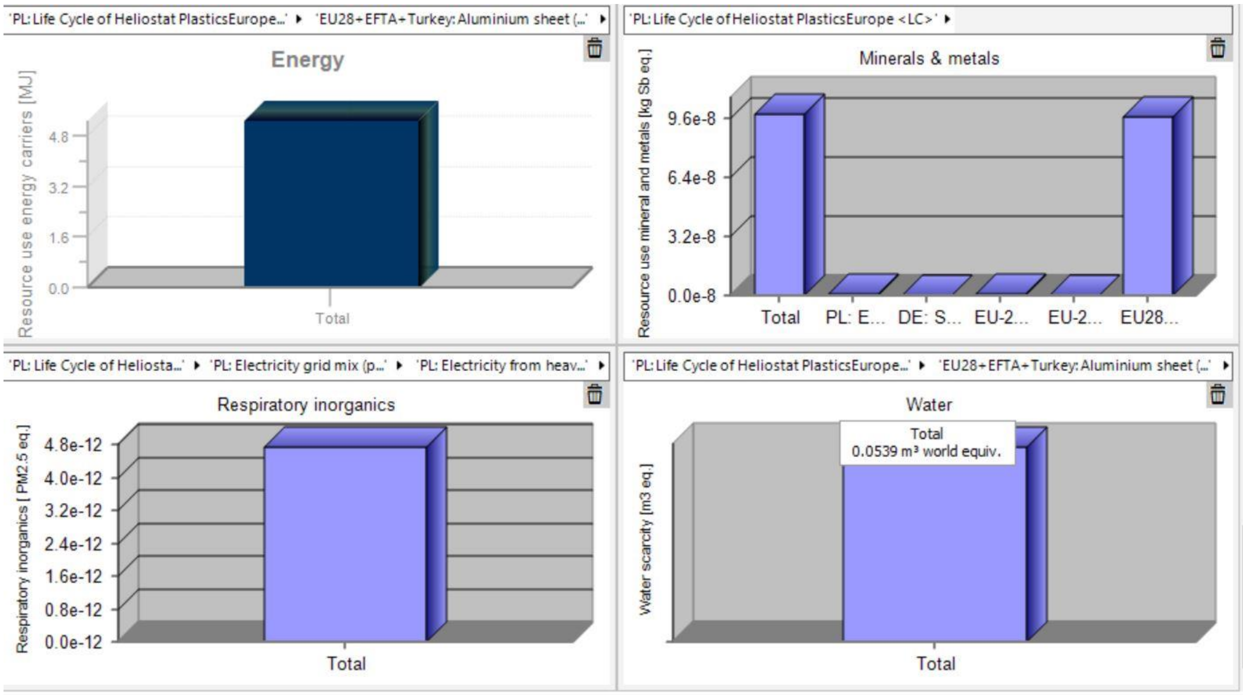

Figure 11*: Continuation of LCI results. Source: Own*

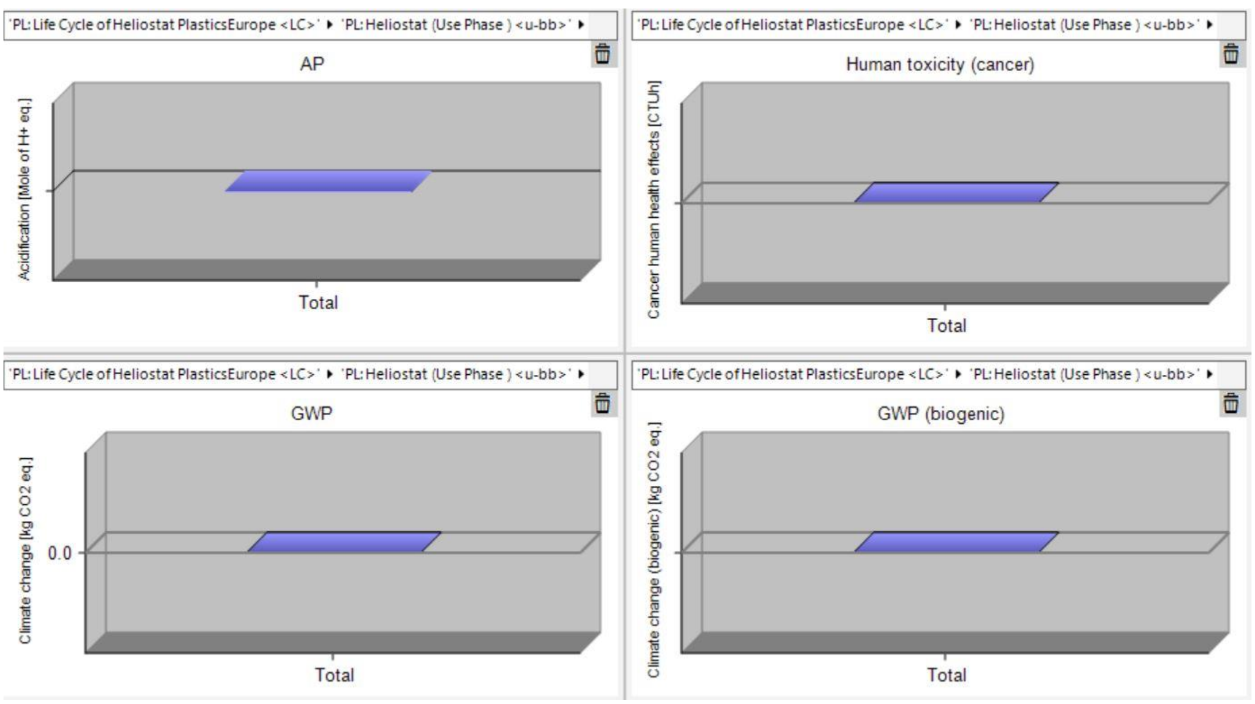

Figure 8*: Use Phase of heliostat. Source : Own*

4.3 Comparative Analysis of the Lighting Products

It is crucial to compare results to previous findings since it aids in eco-design and product improvement. Comparing the lamps is essential to figuring out which one has the biggest and least overall influence. The results from Heliostat are provided in the Tables below, coupled with a life cycle study for various artificial light sources that was previously published by the US Department of Energy [38]. Three categories of impacts have been established: air, climate change, soil, and land. The values shown in each table are similar within each of the impact indicators that belong to the category. The output has been normalized to 20 Mlm-hr of light output, which is our functional unit. As a result, we have a foundation for our comparison.

The table below shows the environmental impacts of each lamp type in terms of air and climate.

Table 4.1 Environmental Impacts of the Lamps Relating to Air and Climate Change.

Lamp Type	Acidification Potential (AP)	Stratospheric O3 depletion (ODP)	Human Toxicity Potential (HTP)	Global Warming Potential (GWP)	Photochemical Oxidation (POCP)
	kg SO2-Eq	**kg CFC-11-Eq**	**kg 1,4-DCB-Eq**	**kg CO2-Eq**	**kg formed O3**
Incandescent	7.90790	0.0000111	205.4860	1031.640	0.0458570
CFL	2.27035	0.0000052	67.6920	304.879	0.0162390
LED-2012	1.75115	0.0000038	60.4102	251.025	0.0125682
LED-2017	0.85335	0.0000020	30.4625	122.772	0.0061200
Heliostat	0.00766	3.2e-11	2.2e-11	6.5	0.000789

Source: compiled from [31] and own

In terms of acidification potential, incandescent lamps emit the most SO2-equivalent emissions, followed by CFL lamps and LED 2012-, LED-2017. The Heliostat has the lowest impact in this category, which is easily explained by the material component of this technology. The Heliostat is mostly made of plastic. There is no need for rare earth metals, and the plastics can be obtained from recycled plastics. In terms of global warming potential, the same pattern can be seen. The incandescent lamp has the greatest environmental impact, emitting 6.5 kilograms of CO2 equivalent for 20 mega lumen-hours of light, while the Heliostat reduces GWP by more than 94%. The similar pattern is seen in human toxicity potential, stratospheric ozone depletion, and photochemical oxidation. As a result, Heliostat is the least hazardous type of artificial lighting that was taken into account.

The following table shows the environmental effects associated with water-related indicators.

Table 4-2. Environmental Impacts of the Lamps for Water

Lamp Type	Marine Aquatic Eco-toxicity Potential (MAETP)	Eutrophication Potential (EP)	Freshwater Aquatic Eco-toxicity Potential (FAETP)
	kg 1,4-DCB-Eq	**kg PO4-Eq**	kg 1,4-DCB-Eq
Incandescent	111.6980	1.9465	21.5907
CFL	36.3825	0.6505	5.9298
LED-2012	29.7654	0.5292	4.6758
LED-2017	15.3707	0.2696	2.3312
Heliostat	0.000229	0.00246	8.28e-7

Source: compiled from [31] and own

The trend observed in the Air and Climate Change categories can also be seen in Water. In terms of kilograms of phosphate equivalents, the Heliostat has the lowest potential impact on eutrophication, which could cause unnecessary growth of algae in waterbodies, lowering oxygen content in the water and harming the biosphere. In 2017, incandescent lamps had more than 3 times the impact of CFLs, and ten times the impact of LEDs, and over 3000000 times the impact of the Heliostat. That's a significant difference. Overall, Heliostat has the least environmental impact in this category.

Finally, the table below shows the environmental impacts of soil-related indicators related with each one of the three lamp types and Heliostat.

Table 4-3. Environmental Impacts of the Lamps for Soil related Indicators.

Lamp Type	Terrestrial Ecotoxicity Potential (TAETP)	Ecosystem Damage Potential (EDP)	Land Use (LU)
	kg 1,4-DCB-Eq	points	m2a
Incandescent	0.1244	16.9970	22.7878
CFL	0.0486	5.4200	7.2909
LED-2012	0.0354	4.0701	5.4011
LED-2017	0.0182	2.0073	2.6661
Heliostat	0.0089	0.0034	0.48

Source: compiled from [31] and own

The incandescent light, out of the lamps taken into consideration, has the greatest effect on the soil-related indication, following a pattern seen in the previous two categories. For land use, incandescent is forty-seven (47) times more expensive than a heliostat and three (3) times more expensive than a CFL. The pattern is similar for potential ecosystem harm and terrestrial eco-toxicity. Incandescent light sources have the biggest environmental impact, while heliostats have the lowest..

4.4 Summary of the Environmental Impacts

The use phase of current artificial light sources uses the greatest energy, as noted in the literature review [38]. For the Heliostat, this is the opposite. There is no energy used during the use period. As a result, Heliostat is the most environmentally friendly product among all the effect categories and phases studied in this study. The energy consumption category of impacts is another important one. The energy usage for the artificial source is depicted in figure 13 below.

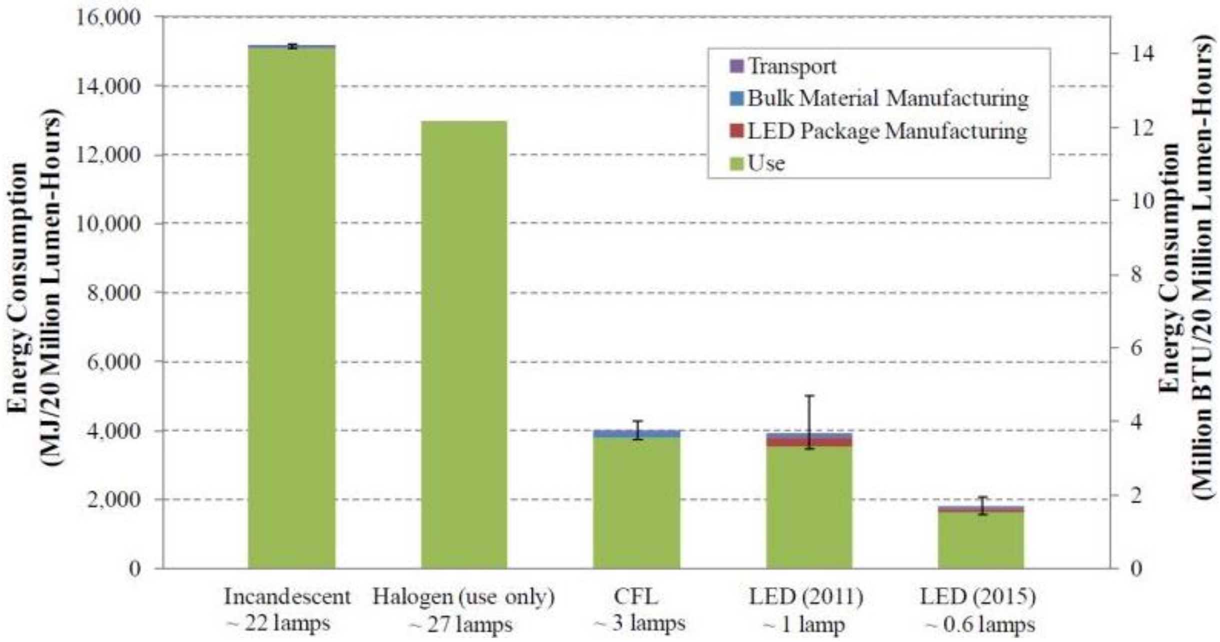

Figure 13: Life Cycle Energy of Incandescent Lamps, CFLs, and Led Lamps

Source [31]

However, for the Heliostat, energy the total energy (mostly used in the manufacturing phase) is 5.29J- the lowest among the lighting sources.

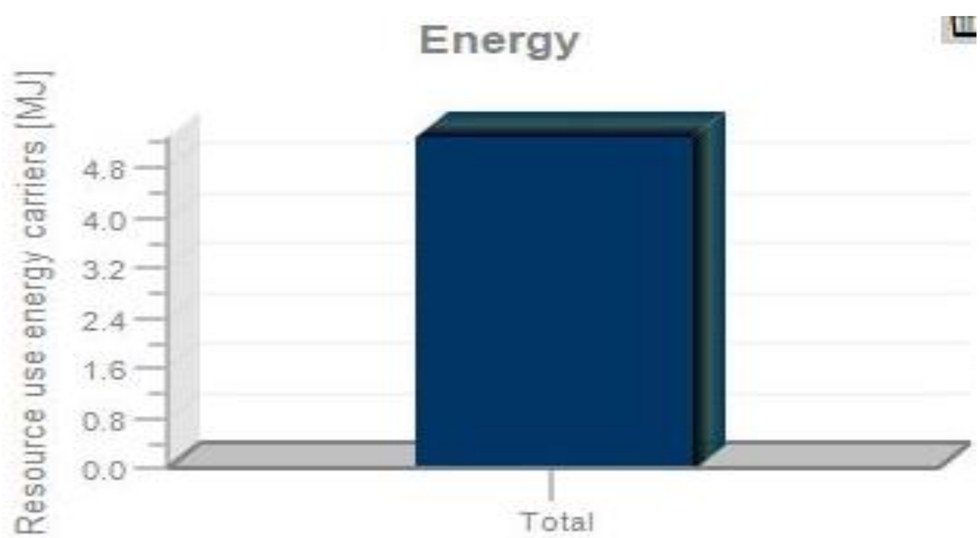

Figure 9: *Life Cycle Energy of Heliostat*

5. Conclusion

The heliostat has the least environmental impact of any lighting product tested. It has a greater potential to save energy during the use phase than other conventional lighting fixtures. The findings of this report are based on a comparative analysis of existing life-cycle assessment studies, particularly reports from the US Department of Energy on "Life-cycle assessment of energy and environmental impacts of led lighting products. Part I: Review of the life-cycle energy consumption of incandescent, compact fluorescent, and led lamps." Though this report was divided into three parts, the findings in the last two reports went beyond the scope of this study.

The key findings of this analysis show that Heliostat is the most environmentally friendly lighting product at the same functional unit (20 million lumen-hours). Furthermore, it outperforms every existing artificial lighting product in every life cycle phase and impact category. The heliostat demonstrated the inverse of the other artificial lighting source. It uses no energy during the use phase, whereas for other lighting sources, the use phase is the most energy-intensive, accounting for 90% of total life-cycle energy on average. Furthermore, it is important to note that the majority of the uncertainty in the Heliostat's life-cycle energy consumption is concentrated in the manufacturing and end-of-life phases.

5.1 Future Work.

The purpose of this report is not to develop a unique estimate for the life cycle energy use of Heliostats, as this is a new product, but rather to provide general conclusions based on current LCA data. This report, hopefully, will serve as a foundation for future environmental assessments and provide context for future work. As more Heliostat data becomes available, a more detailed LCA could be performed for more accurate results and more detailed product documentation.

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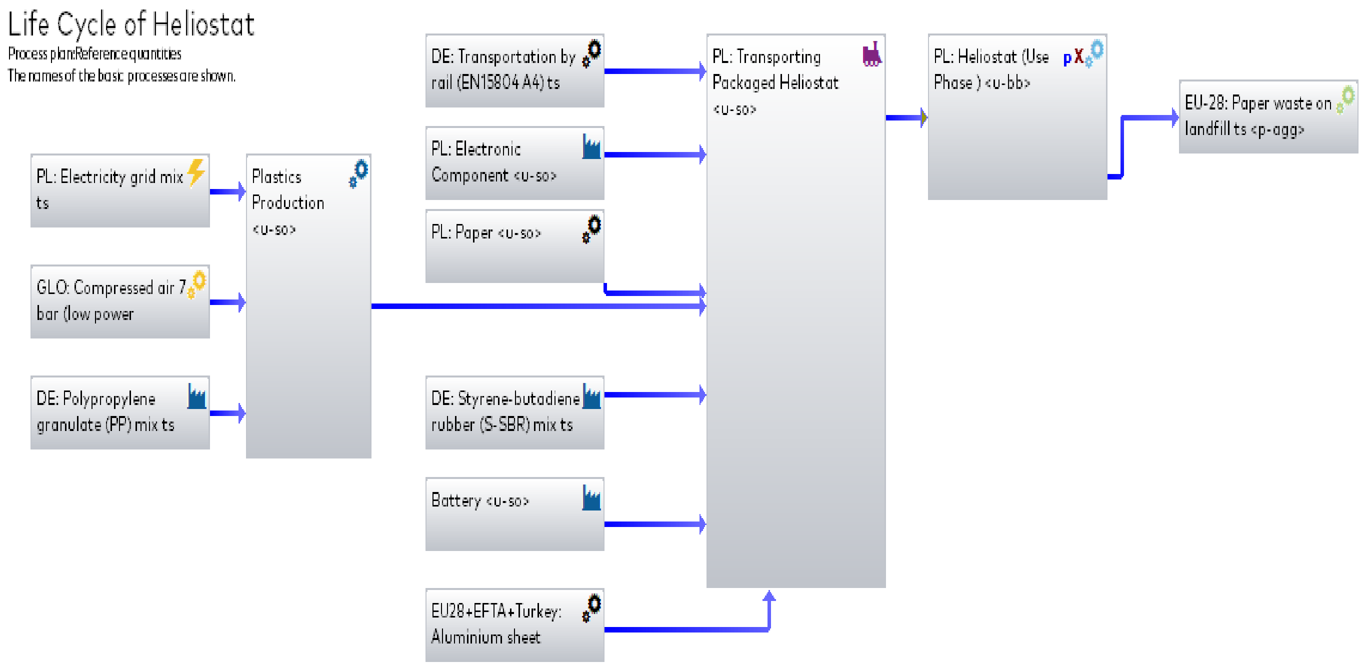
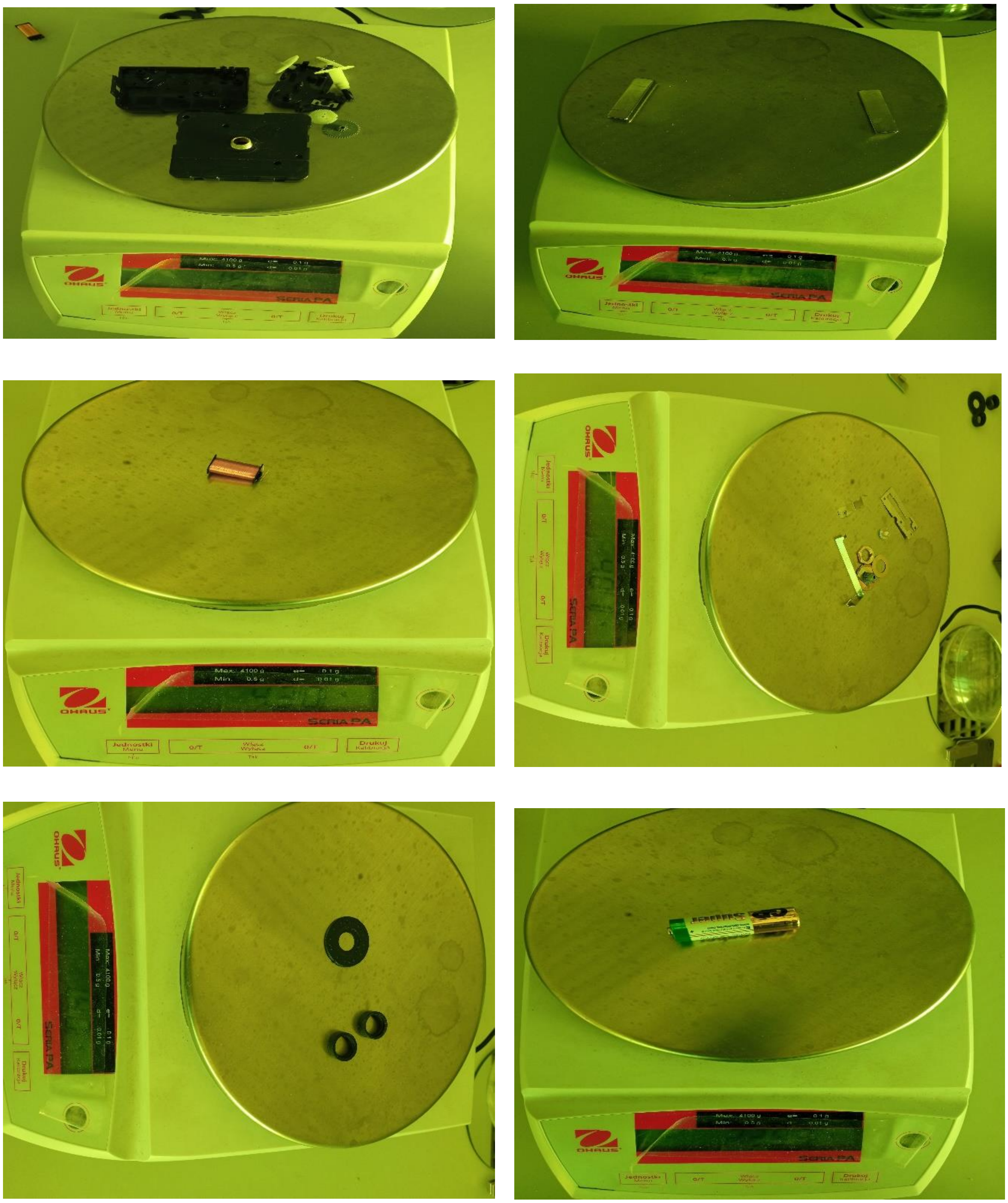
Appendix A : The Model



Source: Own

Appendix B: Pictures of Heliostat measurement. Source: Own



Source: Own

Appendix C: Table showing Part Measurement

Parts	Mass
Transparent Cover	75.43
Mirror	35.37
Metal Plates	68.7
Screws and bolts	3.3
Rubber parts	1.4
Other parts(unspecified)	13.97
Paper(Envelope)	25.3
Magnet	21.4
Electronic parts	0.78
Metallic parts	4.02
Copper	4.32
Plastics Parts	18.55
Battery	22.99
Total	295.53

Source: Own