OULUN YLIOPISTO

TEKNILLINEN TIEDEKUNTA

LIFE CYCLE ASSESSMENT OF SPECIFIC LIGHTING CONTROL COMPONENTS

Lotta Marjamäki

YMPÄRISTÖTEKNIIKKA
Diplomityö
Syyskuu 2022

ABSTRACT

Life Cycle Assessment of Specific Lighting Control Components

Lotta Marjamäki

University of Oulu, Degree Programme of Environmental Engineering

Master's thesis 2022, 91 pp. + 3 Appendixes

Supervisor(s) at the university: Mika Huuhtanen, Virpi Väisänen

The goal of this thesis was to gain insights into the environmental impacts of specific lighting control products and provide recommendations to improve their environmental performance by reflecting on Design for Sustainability guidelines. The environmental impacts were quantified using Life Cycle Assessment methodology. Key results were the carbon footprints and the distribution of the environmental burden across different lifecycle modules. The results are typical for lighting control components, and they were sufficient for pinpointing areas for improvement.

Most of the environmental burdens originate from the manufacturing and use stage but since energy saving products can be considered to compensate their own use, the manufacturing has the most significant burden. The electronic components contribute most to the environmental burden of the manufacturing, and their impacts are the most challenging to tackle. Although the environmental impacts of electronic devices are dependent on their hardware profiles, the results can be generalized to represent typical lighting control components.

Keywords: Life Cycle Assessment, lighting technology, carbon footprint

TIIVISTELMÄ

Elinkaariarviointi tietyille valaistuksen ohjauskomponenteille

Lotta Marjamäki

Oulun yliopisto, Ympäristötekniikan tutkinto-ohjelma

Diplomityö 2022, 91 s. + 3 liitettä

Työn ohjaaja(t) yliopistolla: Mika Huuhtanen, Virpi Väisänen

Tämän työn tarkoitus oli laskea ja ymmärtää valaistuksen ohjauskomponenttien ympäristövaikutuksia sekä antaa suosituksia ympäristövaikutusten vähentämiseksi Design for Sustainability -ohjeisiin perustuen. Ympäristövaikutukset laskettiin käyttäen elinkaariarviointia (LCA). Avaintuloksia olivat ohjauskomponenttien hiilijalanjäljet ja ymmärrys siitä, missä suurin osa hiilijalanjäljestä syntyy. Tulokset olivat elektroniikkalaitteille tyypillisiä, ja niitä voitiin hyödyntää kehityskohteiden kartoittamisessa.

Suurin osa ympäristövaikutuksista syntyi ohjauskomponenttien valmistuksessa ja käytössä, mutta ohjauskomponenttien energiansäästöominaisuuden takia käyttövaiheen vaikutukset voidaan katsoa kompensoiduiksi verrattaessa perinteiseen valaisimeen. Elektroniikan komponentit ovat kaikista merkittävin ympäristön kuormittaja, mutta myös kaikista haastavin osa-alue ympäristövaikutusten vähentämiselle. Vaikka elektroniikkatuotteiden ympäristövaikutukset ovat riippuvaisia tuotteessa käytetyistä komponenteista, voidaan osa tuloksista yleistää tyypillisiksi valaistuksenohjauskomponenteille.

Asiasanat: Elinkaariarviointi, valaisinsysteemikomponentti, hiilijalanjälki

PREFACE

This thesis was conducted for Helvar Ltd., and the main purpose of this work was to provide insight into the environmental impacts of lighting control components and find areas of improvement. The work was conducted between 10.1.2022–19.7.2022.

I would like to thank my university supervisors Mika Huuhtanen and Virpi Väisänen for providing feedback and tips during the writing process, and Henri Juslén for supervision at Helvar. During my time as a thesis worker I have been supported by the kind people at Helvar who have provided me help in many steps on the way, and I especially wanto to thank Mikael Marttila, Sari Äikäs and Simon Jasper. While conducting the assessment, I had the possibility to follow LCA Consulting's work on the another business vertical and I would like to thank Emma Salminen for great discussions, answers, and providing me with the energy consumption calculation table that IBU didn't.

I am very grateful for the love and support of my family during this time. I would like to thank my dearest friend Riina for her continuous encouragement, and my friends Simon, Samuel, Jennifer, Sofie, Viktor, and Pepe for the good times during this summer.

And for Mattias, I am grateful for all the love.

Tampere, 8.9.2022

Lotta Marjamäki
Lotta Marjamäki

TABLE OF CONTENTS

ABBREVIATIONS

AD	Abiotic depletion
BOM	Bill of materials
CFP	Carbon footprint
CTUe	Comparative toxic unit for ecotoxicity
CTUh	Comparative toxic unit for human health
DE	Germany
Depriv.	Deprivation
DIN	Deutsche Institut für Normung
EC	Electronic component
EOL	End-of-Life
EoW	End-of-Waste
EP	Eutrophication potential
EPD	Environmental Product Declaration
FCP	Product specific illuminance factor
FD	Correction factor
FI	Finland
fU	Functional unit
GHG	Greenhouse gases
GWP	Global warming potential
IBU	Institut Bauen und Umwelt e.V.
IC	Integrated circuit
ILCD	International Life Cycle Data system
IoT	Internet of Things
IPCC	International Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MY	Malaysia
PA	Active power

PCB	Printed circuit board
PCR	Product category rules
PIR	Passive infra-red
PMMA	Polymethyl methacrylate
Pp	Passive power
Pt	Production per unit of time
PWB	Printed wiring board
PSS	Product-service system
RSL	Reference service life
tD	Product lifetime in hours
VOC	Volatile organic compound
WEEE	Waste electric and electrical equipment

1 INTRODUCTION

Artificial lighting is a crucial part of daily lives, and it ensures the continuation of many activities after sunset. Artificial lighting is a design element used both outdoors and indoors, in homes and commercial buildings, and it has a profound effect to the human health and productivity. Light synchronizes the biological clock, affects hormonal rhythms, and has a direct effect on brain functions. The influence of artificial lighting on well-being depends on many factors, such as the lighting source’s brightness, illuminance, colour spectrum, and light distribution. When artificial lighting is adjusted for human health, the circadian rhythm becomes synchronised, concentration and performance are improved, and a sense of comfort is created. (Králiková et al. 2021) In addition to adjusting lighting to increase well-being, it can also be adjusted to optimize energy consumption. According to the Lighting Industry Association (2018), the energy savings achieved with lighting controls can be up to 60%, with significant economic and environmental benefits.

Devices that are used to adjust lighting are called lighting control components. They measure and interpret the environment to adjust lighting according to the environment, for example illuminance or occupancy. The lighting control systems consist of number of different control components, such as sensors, switches, and routers, in addition to luminaires. (The Lighting Industry Association 2018). In this study, life cycle assessment (LCA) methodology is employed to define the environmental impacts of the lighting control components in relation to the benefits they provide. LCA provides insight into where the environmental impacts originate from, and what should be considered in product design and development. This information is not only valuable to lighting control manufacturers but to customers as well, as there are increasing pressure and need for companies to improve the sustainability of their products as part of the global transition into sustainable and low carbon industry.

2 LIGHTING CONTROL COMPONENTS

Lighting controls are used to turn artificial light on or off, and to adjust the lighting output according to the needs of the users or the space. Lighting controls are typically associated with some sort of an electronic or automatic solution. Electronic and automatic solutions are very common in non-residential buildings, such as office buildings, shopping centres, or schools, and they have many functions beyond merely turning light on or off: they are used to alter the intensity from dim to bright, set scenes statically or dynamically, and change hue and intensity of coloured light sources. Lighting controls can consist of stand-alone movement sensors and time delay switches, or they can be fully networked lighting management systems in built environments as illustrated in Figure 1, where the lighting control system consists of sensors, a control panel (CP), a router, and cloud-based services. Cloud is used for the software, which can be used to program the lighting network, monitor control points, and record and display data. (Sinopoli 2010; The Lighting Industry Association 2018, p. 58; Dilouie, 2017) Lighting can consume significant shares of energy: up to one third of commercial buildings electricity use in United States, 20-40% of electricity in large office buildings in China, and 20% of electricity consumption in schools and 30% of hospitals in Finland (Xu et al. 2017; Motiva 2022). Use of lighting control systems in commercial buildings can drastically reduce energy consumption. The reductions can even be 60% depending on floor plans, extent of glazing and lighting layout. (The Lighting Industry Association 2018, p. 58)

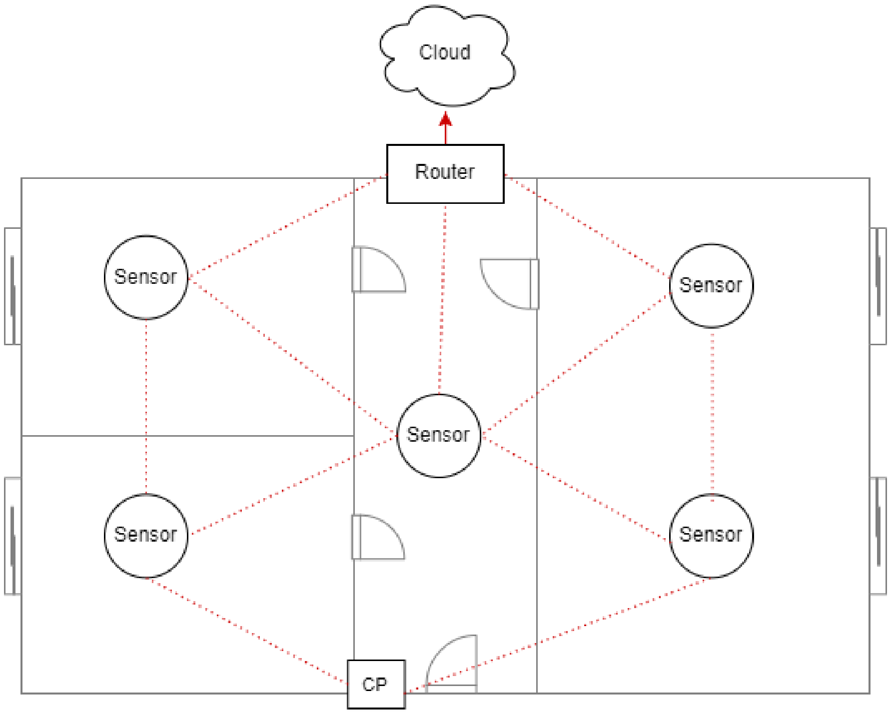


Figure 1. Lighting control components of a lighting system that is composed of sensors, a control panel (CP) and a router. The system is networked, meaning that the controls are wireless. The sensors detect light from windows and occupancy of the rooms, and the control system adjusts luminaires (not pictured) accordingly.

The most successful energy reduction control regime is so-called "request ON/OFF, auto OFF". This means that the lighting is switched ON/OFF by staff and turned off automatically by the lighting system. Automatic lighting control systems can also be enhanced with variable light level control. (The Lighting Industry Association 2018, p. 11-15) Control regimes can utilize (The Lighting Industry Association 2018, p. 11-15):

- Time control
- Occupancy control
- Daylight linked control
- Maintained illuminance
- Corridor hold (relating the status of one group of lights to another)
- Load shedding
- Links to other building systems.

A lighting control module is a unit that switches and/or dims the lighting. It can exist in a range of formats and be a single or multi-channel device. They can be plug-ins, hard wired, compact or luminaire mounted, Deutsche Institut für Normung (DIN) rail mounted, a lighting control panel, or a dimmer rack. (The Lighting Industry Association 2018, p. 44)

Sensors are used to detect and sense changes in the built environment, such as occupancy or daylight. They can function as a sensor connected to a lighting control system, or they can be stand-alone devices with integrated load controllers. Methods for occupancy detection are, for example, Passive Infra-Red (PIR), ultrasonic, microwave, camera and thermal detection. PIR sensors are the most popular. They use lens to sense the body heat in detection zones. PIR sensors can be adjusted and tailored to detect different types of movements. (The Lighting Industry Association 2018, p. 39)

Photocell sensors are used to detect illumination, and they are divided into four different types: photometers, external photocells, internal photocells and light sensors, and cameras. Photometers are the most accurate photocells, and they are used to measure the intensity of light, so that the output is a value instead of a decision. The sensing element of a photocell is typically a light dependent resistor or photodiode. (The Lighting Industry Association 2018, p. 42)

Data networks can be used to increase the number of functions and features of the lighting control systems. Networks typically require additional equipment beyond lighting control modules and sensors. Network components used are load controllers, processors, interfaces, routers, repeaters, bridges, and gateways/application controllers. All networked lighting control systems rely on at least some form of software for set-up, configuration, commissioning, and day-to-day operation. (The Lighting Industry Association 2018, p. 46)

Lighting control components, like many electronics, are composed of a variety of materials but can roughly be divided into few main categories based on materials or component types: the printed circuit board (PCB) consisting of a printed wiring board (PWB) and electronic components (ECs), casing of some sort made out of plastic or metal material, cabels, and screens (Hlavatska et al. 2021).

The PCBs typically contain a significant number of valuable materials, as they consist of roughly 30% plastics, 30% ceramics and 40% metals (Sousa et al. (2022); Marques et al. 2013). For example, Holgersson et al. (2016) found in their study that an internet router's PCB was around 43% of the products weight, and it consisted of 22% of copper, and 1213 ppm silver, 199 ppm gold, and 20 ppm lead. Toxic metals As, Be, Cr and Pb, were also present. (Holgersson et al. 2017) The metals are mostly contained in the electronic components and are critical to their performance. Metals carry a quite heavy environmental burden, as the mining sector has been estimated to make up 3.5% share of the global energy consumption (engeco Pte Ltd 2021). According to Nuss and Eckelman (2014), majority of the environmental impacts of metals come from the purification and refining stages and calculated that the total primary energy use of the metals production and mining sector was 9.5% of the global energy consumption in 2008. In addition, to being energy intensive, metals production has many other environmental impacts, such as contamination of waters, air pollution and greenhouse gases, toxic substances, and biodiversity loss (Van der Voet et al. 2013).

3 SUSTAINABILITY ISSUES

3.1 Sustainability as a concept

Sustainability has been defined as “meeting the needs of the present without compromising the ability of future generations to meet their own needs” by United Nations in 1987, and it is often thought to comprise of environmental, social and economical sustainability (United Nations 2022). Thiele (2016) similarly defined sustainability as a practice, relationship or institution that supports the social, economic and environmental conditions needed for its viability, and emphasizes that the scope of sustainability is not limited to the immediate direct participants but to all stakeholders who are impacted, including all people, future generations and other species.

Although, according to Thiele (2016), sustainability encompasses human rights and economic issues, this study focuses on environmental sustainability. Although lighting control components generate significant energy savings (The Lighting Industry Association 2018), it is important to inspect their environmental sustainability on multiple levels, such as planetary, regional, and industry-wise. And not only are there limits to our planet and resources, but the consumers, customers and government policies are also requiring more information and action from companies. Production and consumption of good and services is unsustainable, according to the European Environment Agency (2013), and thus considering the environmental sustainability of products is arguably crucial for the future state of society, natural environment, and achievement of sustainability.

3.2 The planetary boundaries

There are multiple aspects of environmental sustainability that should be considered. Furthermore, one should have a comprehensive picture of the state of the environment and critical areas of improvement to guide prioritising and decision making. One set of metrics for environmental constraints are the planetary boundaries, which are defined by the Stockholm Resilience Centre (2022) to be a set of global thresholds or boundaries, inside which humanity can continue to live without significant environmental risks. The quantitative boundaries and the state of the planet have been fully calculated for seven categories, and partly for one as shown in Figure 2. The boundaries have been calculated to be at a “safe distance” from thresholds for processes with evident threshold behaviour, or from dangerous levels for processes without. When a threshold is exceeded, important subsystems can change with unfavourable or devastating consequences. It should be noted that the thresholds are connected to each other, and overstepping the boundary on one category can influence another one to be exceeded. (Rockström et al. 2009)

It is critical to note from Figure 2 that over half of the planetary boundaries have exceeded the threshold for safe operating space, in categories of biosphere integrity (extinction per million species-years (E/MSY) i.e. the rate entire species are lost, biodiversity intactness index (BII) i.e, change in ecological communities), climate change, novel entities (i.e., chemical pollution), biochemical flows of phosphorus (P) and nitrogen (N), and land-system change categories. The secretary general of United Nations António Guterres has referenced to the phenomena illustrated as planetary boundaries, calling climate change, nature loss, and pollution, calling the combination of them a triple planetary crisis and the most serious existential threat to the humanity and urging for rapid, extensive measures to prevent the triple crisis (Guterres 2021). The need for corrective measures brings into the light the importance for awareness of one’s own actions and their consequences: it is extremely challenging to adequately improve on something unless one thoroughly knows what and where to improve.

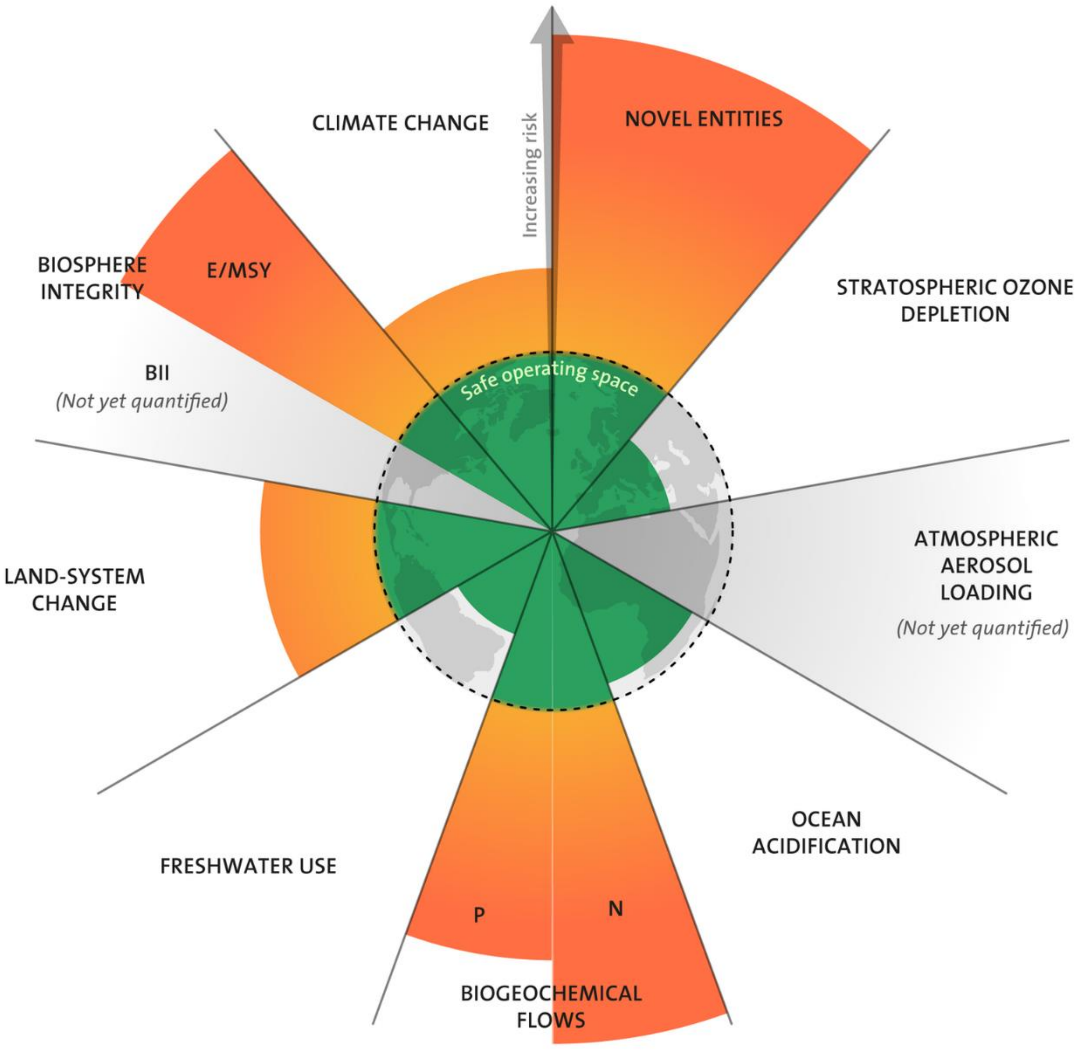


Figure 2. The current state of the environment and planetary boundaries. E/MSY means extinction per million species-years, and BII biodiversity intactness index. In biogeochemical flows boundary, P stands for phosphorus and N for nitrogen. (Azote for Stockholm Resilience Centre, based on analysis in Persson et al. 2022 and Steffen et al. 2015)

3.3 Sustainability within the industry

Sustainability issues have been widely discussed globally for the past years, and many industries have acknowledged them. Technology Industries of Finland (Teknologiateollisuus ry) has created both a climate road map and a circular economy road map for its members (Teknologiateollisuus ry 2020; 2021). In addition, Valaisinteollisuus (an association for lighting industry) has provided a roadmap for its members to reduce greenhouse gas emissions (AFRY Finland Oy 2022). In the climate road map by Technology Industries of Finland, the reduction of direct emissions was identified to be feasible by 38% by year 2035, and 80% by year 2050 in the model of accelerated technological development. The reductions were based on electrification of processes and machines, energy and material efficiency, circular economy, and use of digital solutions. (Teknologiateollisuus ry 2020) In the roadmap by Valaisinteollisuus (AFRY Finland Oy 2022), the lighting industry's carbon handprint during the use of lighting is identified to be five times bigger than the carbon footprint (CFP) of the production, but the map also considers actions needed to reduce the direct emissions. Carbon footprint refers to the sum of greenhouse gas (GHG) emissions in a product system expressed as carbon dioxide equivalents, while carbon handprint means the reduction of GHG emissions in a user's activities through a solution, compared to a baseline (Pajula et al. 2021). Means to decrease the emissions are similar to the ones in the climate road map by Technology Industries of Finland: alternative energy sources, electrification, increased energy efficiency, material and process changes, and optimization. Other ways to reduce emissions outside the scope of direct suppliers are recycling of raw materials and urban mining, utilization of waste, use of light-weight materials and structures, transportation means, longer product lifetimes and design for recycling. (AFRY Finland Oy 2022)

The circular economy roadmap by Technology Industries of Finland has identified key areas for multiple technology sectors. For electronics industry, circular materials and longer product lifetimes were selected as core business models. (Teknologiateollisuus 2021) Recycling is also an important part in the circular economy. The roadmap referred to a paper from Deloitte Sustainability (2016), that material recycling (mostly for metals and plastics) can reduce the greenhouse gas emissions (GHG) emissions of electric and electronic equipment by 45%.

Three recommendations are given in the Technology Industries of Finland roadmap for individual companies in three areas: material/product selection, value creation, and design (Teknologiateollisuus 2021):

1. Prefer reuse of components and parts or recycled materials.
2. Increase the value of products and create new value through services and new business models.

3. Design products according to circular economy principles, e.g., by making them easily reusable or recyclable.

3.4 Sustainability requirements from governments and customers

In addition to the planetary boundaries and the ambitions of the industries, customers and governments are also requiring companies to improve. The European Union has stepped up to combat climate change with e.g., The European Green Deal, sustainable finance taxonomy, and the Corporate Sustainability Reporting Directive proposal. The European Green Deal has a target of making Europe climate neutral by 2050, and it includes parts such as Circular Economy Action Plan, Biodiversity Strategy, and "renovation wave" for the building sector (European parliament 2021). Sustainable finance taxonomy defines the economic activities that can be considered sustainable. Presence and daylight controls for lighting systems are considered such, and they have been appointed circular economy transition criteria. (European Commission 2022a, 2022b) Corporate Sustainability Reporting Directive was adopted in April 2021, and it requires all large and all listed companies (excluding micro enterprises) on regulated markets to report how they operate and manage sustainability challenges. Sustainability standards to be used in reporting are to be adopted by October 2022. (European Commission 2022c) The first set of standards will be used for the year 2023, and a second set of updated and enhanced standards are meant to be used for year 2024 (European Financial Reporting Advisory Group 2021). The standards are to be applied for the first time in 2024, covering the financial year 2023 (European Commission 2020d).

Increased sustainability awareness among consumers and requirements from the European Union have increased the need and interest for sustainability data. Customers in the lighting industry that can be described as down-stream users, such as luminaire manufacturers, need the component sustainability data to improve their products and to communicate the total sustainability information (such as CFP) of their products. Sustainability is arguably becoming part of the selection criteria for components and products, and thus good environmental performance can be of competitive advantage. Indeed, Metz et al. (2016) found out that companies that have adopted sustainability mindset had more effective innovation and superior business results when compared to companies that had not. They argued that while sustainability-driven innovation is still an untapped business opportunity, competitive advantage will increasingly depend on sustainability as more companies are moving to that direction.

Customers may request and utilize Environmental Product Declarations (EPD) for decision making and to compare different products. EPDs consist of quantitative environmental information about the life cycle of a product. EPDs are typically meant for business-to-business communication. They involve standardised processes regarding LCA and reporting. (SFS-EN ISO 14025:2010)

3.5 Designing sustainable products, processes, and services

Design of environmentally sustainable products has been a topic for discussion for few decades now, and many principles and guidelines have been created as a result. According to Walker et al. in *The Handbook of Design for Sustainability* (2013), Design for Sustainability (DfS) is defined as a holistic perspective into all lifecycle stages of the product, service, or system to design sustainable outputs. It increases the environmental performance and social benefits of the products, service or system through improvement, redesign, new concepts, or system innovation. (Walker et al. 2013)

The DfS guidelines can be approached from various levels of design and innovation. They exist for incremental changes, such as focus on improvement of parts or redesign of product, and for completely new concepts and system innovations. (Walker et al. 2013) van Hemel (1998) clustered the Design for Environment guidelines and principles into strategies in *EcoDesign Empirically Explored* (1998), which are used to explore opportunities of DfS from the environmental point of view for incremental changes. The strategies are shown in Figure 3, and their content in Table 1. Strategies 1, 2, and 3 can be loosely grouped to consist of the manufacturing of the product. Strategies 4, 5, and 6 form the transportation and use of the product, and strategy 7 is for the End-of-Life (EOL) of the product.

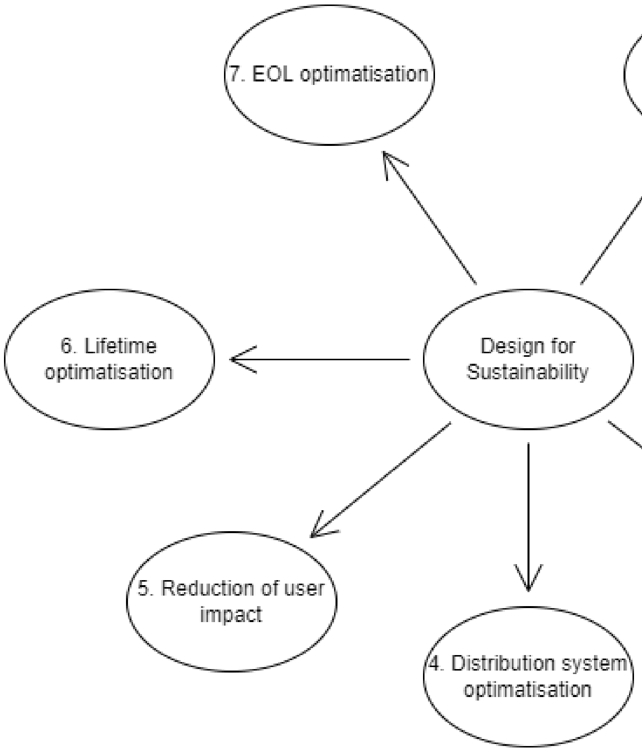


Figure 3. Design for Sustainability strategies to improve the environmental performance of a product (van Hemel 1998).

Table 1. The content of Design for Sustainability strategies summarized, based on numbering used in Figure 3. (van Hemel 1998).

Strategies	Material design	Process/product design
1,2,3	• Renewable, recyclable, recycled materials • From minimum to no additives	• Use renewable energy, increase energy efficiency in manufacturing • Minimize material consumption and waste in processes
4,5,6	• Minimize packaging material • Prefer reusable packaging	• Efficient logistics • Minimal energy & waste during lifetime • Extend the product lifetime • Enable maintenance and repair
7	• Easily recyclable materials • Safe, non-hazardous	• Design product to be easily disassembled, repurposed, refurbished, recycled etc.

Walker et al. (2013) have argued that system innovations contain most potential for sustainability. System innovations shift the attention to structural changes that can be made in production and consumption systems. One of the approaches is the product-service system (PSS) innovations, which are defined by Ceschin and Gaziulusoy (2020) as value propositions oriented to satisfy users through delivery of functions instead of products. The PSS can be product-oriented, use-oriented, or results-oriented. Vezzoli et al. (2014) defined the three PSS types:

- Product-oriented PSS, which adds value to the product lifecycle through services,
- Result-oriented PSS, which is focused on delivering “final results”, such as a customised services to provide an integrated solution,
- Use-oriented PSS to enable platforms for customers through services, i.e., access to products, tools, or opportunities for customers to meet a specific need for a specific timeframe.

In the result- and use-oriented PSS the customer does not own the product. PSS incentivises producers to reduce the number of resources consumed during use, re-use or re-manufacture components of disposed products, and to extend product lifecycle and material life. (Vezzoli et al. 2014) Economic, competitive, and socio-ethical benefits can also be associated with PSS. Perhaps the biggest benefit of the PSS is the possibility for material decoupling, although it should be noted that not all PSS have sustainability benefits, and harmful setbacks such as rebound effects can emerge as well. (Ceschin & Gaziulusoy 2020) Rebound effect means that a solution, such as increased efficiency of resource production, increases the overall consumption of it (Vezzoli et al. 2014).

4 LIFE CYCLE ASSESSMENT METHODOLOGY

4.1 Basic principles of Life Cycle Assessment

Life Cycle Assessment (LCA) is a method to calculate and analyse potential environmental impacts of products, processes, or services during their lifecycles. A life cycle consists of all processes and stages involved with a product, process, or service, including the raw material extraction, all processing and manufacture, transportation, use, and End-of-Life (EOL) treatment. (Klöpffer and Grahl 2014)

LCA consists of four stages, and it can provide valuable information about the environmental impacts. LCA can be used in product/process development, comparison of product/process with competitors, strategic planning, or decision-making. (Klöpffer and Grahl 2014) All the steps provided in chapters 4.3-4.6 must be present in any standard life cycle assessment, in the order presented.

4.2 LCA standardisation

The LCA method is standardised with ISO 14040:2006 and ISO 14044:2006 standards, which Klöpffer (2012) quoted in his critical review as “the leading and most important international standards for environmental assessment according to the life cycle or cradle-to-grave or holistic method”. ISO standards have been typically followed in LCA studies, such as ones by Tähkämö (2013) in LCA case studies of light sources, and by Pirson and Bol (2021) in LCAs of Internet of Things (IoT) edge devices. For the lighting control products to be assessed in this study, additional Institut Bauen und Umwelt e.V. (IBU) standards (IBU 2017; 2021), and EN 15804:2012 (2019) are applied in the LCA process as well. The following subchapters cover LCA using the mentioned standards and guidelines. An LCA study consists of four steps that are described in chapters 4.3, 4.4, 4.5, and 4.6.

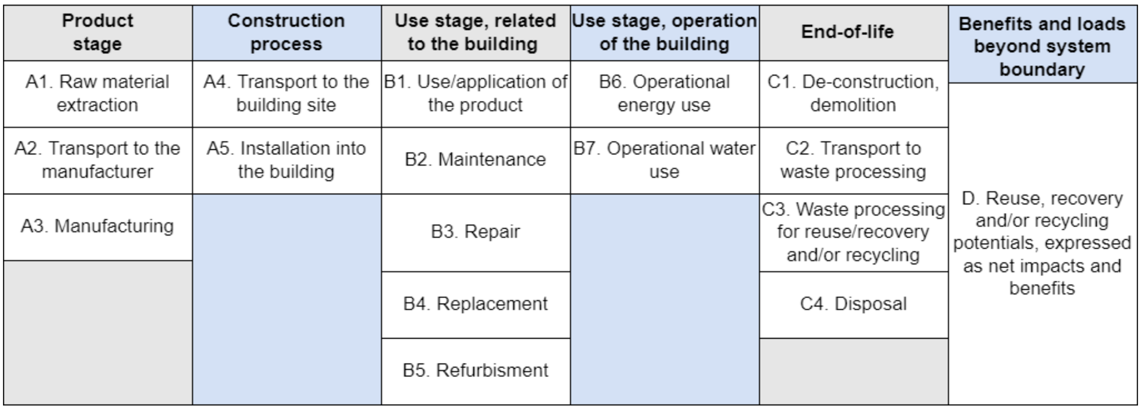
4.3 Step 1: Defining the goal and scope

The ISO 14040 requires the goal and scope of the LCA are to be determined first, although they might change due to the iterative nature of the LCA method. The goal and scope definition is an important step, as according to Jolliet et al. (2015, p. 23), the LCA results are strongly dependent of the choices made in this step, and the goal and scope definition acts as a plan for the consecutive steps. When the goal is defined, it should express the intended use, reasons for the LCA, intended audience and intent of public comparisons of the LCA (SFS-EN ISO 14040:2006 + A1:2020). For example, Choi et al. (2006) defined the goal in the LCA study of a personal computer and its recycling as to find the ideal or feasible rate of recycling for it, and they defined their intended audience as new product designers, developers, product recovery managers and environmental policy makers.

The scope should be defined to be sufficient with the goal in terms of extent, depth, and level of detail. It should consider the investigated product system, its boundaries, functions, functional unit, allocation methods, impact assessment methods and -types, used interpretation method, requirements on the information and its quality, assumptions, values and voluntary parts, limitations, critical assessment methods (if used), and the type of report to be done. (SFS-EN ISO 14044:2006 + A1:2018)

4.3.1 Product systems and system boundaries

A product system is best described as a process flow chart, where unit processes and their interrelations are presented. The product system includes all the functions of the system and is used as basis for the functional unit. All processes from the extraction of raw materials to the disposal of the product are to be considered. (Klöppfer et Grahl 2014 p. 28, 33) SFS-EN 15804 requires that all life cycle stages are divided into modules A1-A3, A4-A5, B1-B7, C1-C4 and module D. The modules and their intended contents are explained in Figure 4. Modules A1-A3 can be expressed as one aggregated module. Flows exiting the system at the End-of-Waste (EoW) boundary in modules A1-A3, i.e., flows from modules A1-A3 that cease to be waste, are treated as co-products. (SFS-EN ISO 15804:2012 + A2:2019 p. 15-17, 20)



Product stage	Construction process	Use stage, related to the building	Use stage, operation of the building	End-of-life	Benefits and loads beyond system boundary
A1. Raw material extraction	A4. Transport to the building site	B1. Use/application of the product	B6. Operational energy use	C1. De-construction, demolition	D. Reuse, recovery and/or recycling potentials, expressed as net impacts and benefits
A2. Transport to the manufacturer	A5. Installation into the building	B2. Maintenance	B7. Operational water use	C2. Transport to waste processing	
A3. Manufacturing		B3. Repair		C3. Waste processing for reuse/recovery and/or recycling	
		B4. Replacement		C4. Disposal	
		B5. Refurbisment			

Figure 4. Life cycle modules according to EN 15804 (SFS-EN ISO 15804:2012 + A2:2019).

The system boundaries define, which unit processes and inputs and outputs will be included in the assessment. When modelling the product system, it would be ideal that the inputs and outputs at the boundaries are basic streams and product streams. At first, based on existing information, unit processes to be included or excluded are recognised. After that the process is iterative to recognize feeds and products to be tracked to the environment. (SFS-EN ISO 14044:2006 + A1:2018) The IBU standard requires all inputs and outputs to be included, for which data is available or if data gaps can be filled by conservative assumptions with average or generic data (IBU 2021). EN 15804 gives two additional principles for setting the system boundaries. The first one is the modularity principle, which means that all environmental impacts and aspects must be declared in the life cycle stage they appear in. The second is the polluter pays principle, meaning that all processing of waste is assigned to the product system that generates it until the EoW stage is reached. (SFS-EN ISO 15804:2012 + A2:2019)

An input, an output, or a unit process can only be excluded if it doesn’t considerably influence the results, and if only insufficient input data or no data is available. All exclusion decisions must be recorded and justified in the process report. Exclusion criteria consists of mass, energy, and importance for the environment. (SFS-EN ISO 14044:2006 + A1:2018, SFS-EN ISO 15804:2012 + A2:2019) The cut-off criteria must be reported in the project report, and it must include description of the criteria, assumptions, and processes that are not considered (IBU 2021). All following three aspects are to be considered when making an exclusion, and the decision should not be based only on one criterion (e.g., mass). Typically, the cut-off criteria are (Klöppfer and Grahl 2014, p. 30):

- < 1% proportion of mass, energy or impact of the overall system is used as a cut-off criterion for exclusion.
- < 5% proportion of mass, energy, or impact per unit process.

The energy production, exhaust air purification, and waste treatment plants are withing the system boundary (Klöppfer and Grahl 2014, p. 33). When a perfect recognition of feeds and products have been conducted using collected, additional information, a sensitivity analysis should be conducted. (SFS-EN ISO 14044:2006 + A1:2018)

EN 15804 requires that waste treatment needs to be declared in modules C1-C5 until the EoW is reached, and that the recycling and recovery potentials are declared in module D. Requirements that apply for Waste from Electrical and Electronic Equipment (WEEE) are in Directive 2012/19/EU, and can be generalised as removal of plastics containing brominated flame retardants, removal of external electric cables, and removal of electrolyte capacitors containing substances of concern with height and diameter of over 25 mm or proportionately similar volume. (Directive 2012/19/EU) A specific EoW criteria only exists for few scrap metals, and is defined in Council Regulation (EU) No 333/2011, which is established under the Directive 2008/98/EC. The specific EoW criteria is for scrap iron, steel, and aluminium. For all of them, the EoW criteria relevant for assessed products can be summarized as (Council Regulation (EU) No 333/2011):

- The material has undergone all needed mechanical treatment needed for it to be used in production of material or articles,
- It is non-hazardous or has undergone necessary treatments required for WEEE,
- Foreign materials, such as non-metal materials, are not present in quantities larger than 2% for steel and iron and 5% for aluminium.

These criteria, although being designated only for three material types, can be extended to cover all metals used in products and to serve as a general guideline for determining the EoW status of other materials.

4.3.2 Functional unit

A functional unit (fU) is used to describe the quantified performance of a system to allow meaningful comparisons for systems or scenarios (Jolliet et al. 2015, p. 28). fU of a construction product should specify, according to the EN 15804 (SFS-EN ISO 15804:2012 + A2:2019):

- The application
- The reference quantity when integrated in the construction works
- The quantified:
    - key properties for the functional use,
    - or performance characteristics,
    - or minimum performance of the product, considering the functional equivalent of the building
- The minimum performance characteristics under defined conditions over the defined time of the functional unit
- The specified time-period under reference in-use conditions considering the reference service life.

An example of a functional unit can be taken from Kumar and Mani (2017): when they assessed the energy consumed by an occupancy sensor during its entire life cycle to analyse the effectiveness (payback time) of energy savings, the fU was defined as “production of one unit of occupancy sensor installed in an office building scenario”. It is recommended that the functional unit used for simple light sources such as lamps or luminaires is lumen-hours (Tähkämö 2013).

4.3.3 Data requirements and quality

Quality of the initial information should be sufficient for the LCA and the scope. Quality requirements include but are not limited to; time-related and geographical coverage, precision, and representativeness. Treatment of missing data should be documented, and treatment of missing data and data gaps should result in a “non-zero” value that is explained, a “zero” value that is explained, or a calculated value based on reported values from unit processes of similar technology. (SFS-EN ISO 14044:2006 + A1:2018) Stricter, more specific data quality requirements are expressed in the EN 15804 standard. Those include, but are not limited to (SFS-EN ISO 15804:2012 + A2:2019):

- Data must be as current as possible. Datasets used for calculations are valid for the current year and represent one reference year within 10 reference years for generic data, and for five reference years for producer specific data.
- Datasets are to be based on 1-year averaged data and shall be complete according to the system boundary, within the limits of the exclusion criteria for in/outputs.

However, Pirson and Bol (2021) pointed out that primary data is rarely available for ICT devices and electronic components in general, although the production is known to be very resource and energy intensive.

For systems to be compared, their equivalence is to be evaluated before the interpretation of results. Functional units and methodological comparisons shall be the same. (SFS-EN ISO 14044:2006 + A1:2018) In addition, the scope must define whether a critical review is necessary, how to conduct it, the type of critical review, and who would conduct it and with what level of expertise. The critical review ensures that the methods used to carry out the LCA are consistent with the ISO 14044 standard and scientifically and technically valid, that the data used is appropriate and reasonable to the goal, that the interpretation reflect the limitations and the goal, and that the study is transparent and consistent. It can be conducted by an internal expert unless the study is meant to be used in comparative assertations intended to be disclosed to the public. (SFS-EN ISO 14044:2006 + A1:2018)

4.4 Step 2: Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) step should follow the goal and scope. High quality data and information should be collected for and from every unit process in the product system. For data with significance for the results, a reference to the quality indicators, acquiring process and date should be made. Data and information can be collected from a variety of different sources, such as databases or studies, in addition to collecting in-situ data. (SFS-EN ISO 14044:2006 + A1:2018) For example, in the LCA of a smartphone made for Sony company, Ercan et al. (2016) utilized Bills of Materials (BOM), Sony company data, and direct supplier data for the manufacture of components, as well as GaBi and Ecoinvent LCA databases to form the inventory (Ercan et al. 2016).

4.4.1 The use of collected information

All calculations must be documented, and assumptions shall be explained and reported clearly. When defining the basic flows of the production, real product distribution should be used. The eligibility of the data should be checked during the collection process. Due to the iterative nature of the LCA, the system boundary may be changed because of a sensitivity analysis. (SFS-EN ISO 14044:2006 + A1:2018)

4.4.2 Allocation

Allocation means assigning environmental burdens during the life cycle for co-production, recycling, and disposal, i.e., the environmental load (inputs and outputs) should be fairly assigned for multiple products. (Klöppfer and Grahl 2014, p. 92) The EN 15804 requires that flows exiting the system at the EoW boundary of the product (A1-A3) stage are allocated as co-products. Allocation should be applied uniformly to similar inputs and outputs (SFS-EN ISO 14044:2006 + A1:2018). According to the ISO 14044 (SFS-EN ISO 14044:2006 + A1:2018), the allocation should proceed as follows:

- Allocation should be avoided by either dividing allocatable unit process into two or more subprocesses and collecting their input/output information, or by expanding the product system.
- If allocation cannot be avoided, the inputs and outputs of the system should be divided between its products and functions, in a way it reflects the physical relations between them. Allocation should be based on the way the system's quantitative changes (of products and operations) influence inputs and outputs.
- If allocation cannot be based on physical relations, the allocation should be based on other interrelations, e.g., economical value. (SFS-EN ISO 14044:2006 + A1:2018)

Allocation for reuse and recycling requires additional elaboration, and the system boundary should be carefully defined. The allocation can be closed-loop or open-loop. The open-loop allocation is applied if the material is recycled into other product systems and its inherent properties undergo a change. The basis for allocation should proceed with following as a basis for allocation, in the order: physical properties, economic value, number of subsequent uses of the recycled material. (SFS-EN ISO 14044:2006 + A1:2018)

4.5 Step 3: Life Cycle Impact Assessment

The third step of a LCA study is the Life Cycle Impact Assessment (LCIA), in which the general principle is to link inventory data to environmental changes or damages in environment using pathways (Jolliet et al. 2015 p. 106). The LCIA phase should be carefully planned to achieve the goal and scope of the study. Mandatory elements of the LCIA are selection of impact categories, category indicators and characterization models, assignment of LCI results to the selected impact categories (classification), and calculation of category indicator results (characterization). (SFS-EN ISO 14044:2006 + A1:2018)

4.5.1 Impact categories, indicators, and characterisation factors and models

The impact categories, impact category indicators and characterisation factors and models used in the LCA are to be defined in the scope. The methodology is based on the grouping of substances with similar environmental impacts. The groups are called impact categories, and at the intermediary level more specifically midpoint categories (e.g., photochemical ozone formation). Each midpoint category has a midpoint indicator (e.g., formation potential of tropospheric ozone). The contribution of an emission or a resource to a midpoint category is calculated with a characterisation factor. The midpoint category results can be assigned further to damage categories, such as human health or ecosystem quality, but the uncertainty of the results tends to increase that way. (Jolliet et al. 2015, p. 107)

ISO 14044 requires a LCA study to include the selection of the impact categories, category indicators and characterisation models in the LCIA stage, and the LCI results must be assigned to the selected impact categories and calculated. ISO 14044 recommends that the chosen impact categories, indicators, and characterisation models are internationally accepted, value choices and assumptions are minimized, double counting is avoided, characterisation models and their extent are scientifically and technically valid and identified, and that the indicators are environmentally relevant. Each indicator's ability to reflect the consequences of the LCI on the category endpoints should be clearly stated, as should the addition of environmental data/information to the characterisation model. (SFS-EN ISO 14044:2006 + A1:2018, p. 77, 81-82)

EN 15804 standard lists the core environmental impact indicators and characterisation models that are required in each module declared in the EPD. Characterisation factors to be applied are the ones from the European Commission Joint Research Centre (EC-JCR) that have been listed in an excel file called EN_15804. (SFS-EN ISO 15804:2012 + A2:2019) The core environmental impact categories, indicators, and characterisation models according to the EN 15804 are listed in Annex 1.

4.5.2 Optional elements

Normalization, grouping, weighting or data quality analysis can be used if they help to achieve the goal and scope of the LCA. Normalization is the calculation of the magnitude of the category indicator results relative to reference information (e.g., emissions per capita). Grouping means assigning impact categories into sets as predefined in the goal and scope definition. It can be done by sorting impact categories on nominal basis, or by ranking impact categories in a given hierarchy. Weighting is based on value-choices and thus is not scientifically based and uses numerical factors to convert indicator results. Additional data quality analysis can provide better understanding of the uncertainty, sensitivity and significance of the results, and help e.g., identify negligible LCI results. Additional analysis techniques are gravity analysis, uncertainty analysis, and sensitivity analysis. (SFS-EN ISO 14044:2006 + A1:2018 p.81-83) Jolliet et al. (2015, p. 160) emphasize that studying the uncertainty and sensitivity within used parameters is important to understanding the accuracy and validity of the results.

4.6 Step 4: Interpretation of the results

The interpretation process, according to ISO 14044, consists of identifying significant factors influencing the LCI and LCIA results, evaluating the completeness, sensitivity and consistency, and conclusions, limitations, and recommendations. Jolliet et al. (2015

p. 149) argue for a more specific purpose to the final step: to find life cycle stages where the environmental impacts can be reduced, and to identify priorities for taking action. The ISO 14044 requires interpretation of the LCI and LCIA results to be in line with goal and scope, and it should include evaluation and sensitivity analysis of significant inputs, outputs and methodologies used. The appropriateness of the definitions used for system function, fU, and system boundary, as well as the limitations identified in data quality assessments should be considered. Jolliet et al. (2015 p. 149) recommend that interpretation is conducted thoroughly on each LCA phase, and that all stages are discussed and analysed before moving forward. Contributions of each life cycle stage and each system components are recommended to be reviewed, compared, and analysed before moving on to the pollutants and extracted substances.

Voluntary assessments can be applied, and they include completeness checks, sensitivity checks and consistency checks. The completeness check ensures that all relevant information and data are available and complete for interpretation. If any relevant information is missing or incomplete, the necessity of it should be considered and either action taken (SFS-EN 14044:2006 p. 84-88):

- If it is necessary for determining significant issues, LCI and LCIA phases should be revisited, or the goal and scope should be readjusted.
- If unnecessary, reason must be recorded.

The purpose of a sensitivity check is to analyse the reliability of the final results and conclusions. The effects of uncertainties in data, allocation methods and calculation of category indicator results etc. are determined using sensitivity and uncertainty analysis results from LCI and LCIA phases. The predetermined issues in goal and scope, results from other phases, and expert judgements and precious experiences are to be considered as well. (SFS-EN 14044:2006 +A2018 p. 88)

Consistency check determines if the assumptions, methods, and data are in line with the goal and scope. Questions that should be addressed in consistency check are (SFS-EN ISO 15804:2012 + A2:2019 p. 89):

- Differences in data quality, in product system life cycle or between different product systems consistent with the goal/scope?
- Are regional/temporal differences constantly applied?
- Are allocation rules and system boundary constant to all product systems?
- Are elements of impact assessment consistently applied?

5 LIFE CYCLE ASSESSMENT OF LIGHTING CONTROL COMPONENTS

5.1 Assessed products and systems

In this study, the LCA was conducted for five lighting control component products of a certain company. Two sensors were assessed: an area sensor, and a self-learning sensor. Three other products studied are a control panel, a driver and a router. In addition, two lighting control systems with the sensors were studied. The products are introduced in Table 2.

Table 2. Product and system descriptions.

Product	Description	Weight (g)
Area sensor	PIR and light sensor used to save energy by occupancy and light levels. Can be mounted on the ceiling or other solid surface.	57
Self-learning sensor	Wireless, self-learning PIR and light sensor for controlling luminaires.	29
LED Driver	A device installed in the luminaire to regulate power to LED arrays.	227
Control panel	Touch panel user interface with advanced lighting control, offering dimming and colour control options. Available with plastic and glass panel fascia.	140/200 depending on fascia
Router	DALI-2 network controller that can be used to form large scalable system and be integrated with other building systems.	519
Lighting system with an area sensor	A system with four luminaires controlled by one area sensor.	--
Lighting system with a self-learning sensor	A luminaire controlled by one self-learning sensor.	--

5.2 Goal and Scope

The main goal of the study is to provide information to recognize and understand the environmental impacts, especially the carbon footprints, of the products to pinpoint areas for improvement. Lighting systems are studied to understand how the environmental burden of the products affects their environmental performance in different types of electricity grids.

Other uses for the LCA results obtained in this study are:

- to enable internal comparison of products
- to enable and support creation of Environmental Product Declarations (EPDs) if needed
- and to be more conscious about the environmental impacts to prepare for the future changes.

The assessment was intended to be primarily used in the company operations. Some information, such as carbon footprints, will be communicated to the key customers. Depth and accuracy should be the same as in other LCAs that were conducted for products of another business unit in the company. LCA was conducted separately for every product using ISO 14040, ISO 14044, EN 15804 and IBU Product Category Rules (PCR) standards. OpenLCA software version 1.10.3 was used with the ecoinvent v.3.8 database. The impact assessment method used was EN 15804 + A2 Method from OpenLCA.

The benefits generated from waste treatment were allocated separately to module D: Benefits beyond the system boundary. The study was conducted using data quality requirements of EN 15804 whenever possible, and the data quality assessments were done according to the EN 15804 standard Annex E. Critical review was not conducted as the study is not meant for public comparisons. The interpretation was conducted using structuring based on modules and processes. Sensitivity analysis was conducted for components that significantly contribute to the results.

5.3 Product system for sensors, router, and driver

The manufacturing process was similar for the sensors, router, and driver. The control panel had a slightly more complicated manufacturing process, which is explained separately in chapter 5.4. Their components, such as printed circuit boards (PCBs), plastic cases and capacitors, all came from various suppliers from Europe and Asia. Their production was modelled using generic data from ecoinvent 3.8. The components were assembled in Malaysia, or in a factory of the company in Karkkila (Finland). Components were automatically mounted on the PCB using either through-hole or surface mounting and glue. Some components were mounted by hand. After mounting the products underwent soldering. If the product contained processors, they were programmed at this point. The assembled PCBs were cut into appropriate sizes and shapes, and assembled with insulators, covers and cases into the final product. A mounted but not yet cut PCBs are shown in Figure 5. The product was then packed with the instructions and ancillary parts (e.g., screws), and then distributed forward. Storage was not considered in the study. The product system for all products except the control panel sensor are shown in the process flowsheet in Figure 6 where the most significant inputs and outputs are shown.

Figure 5. 12 pieces of uncut, mounted PCBs for the self-learning sensor. One PCB unit (38 mm x 18 mm) is marked in red (Photo: Lotta Marjamäki).

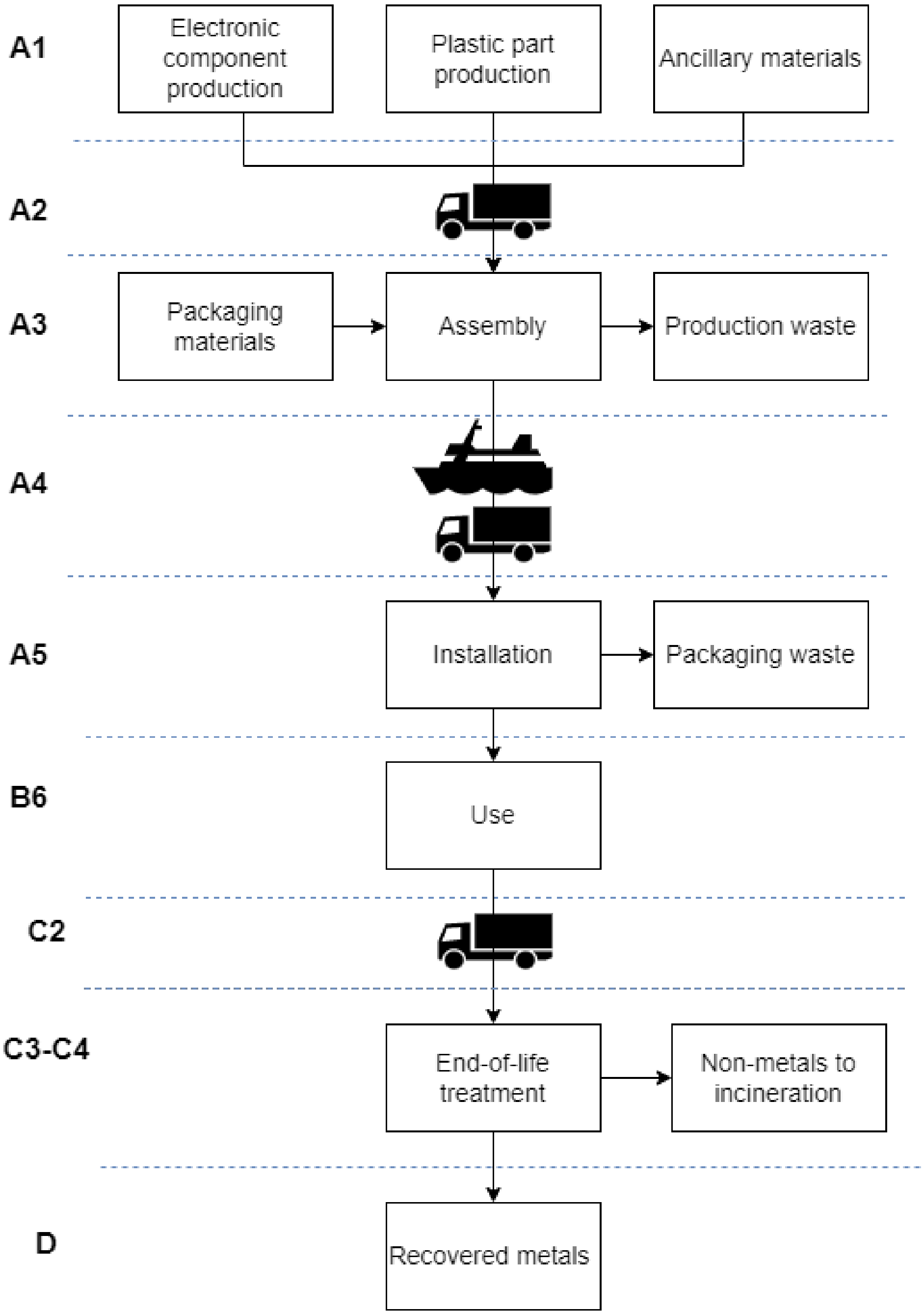


Figure 6. The product systems for the area sensor, router, LED driver and self-learning sensor as a flowsheet with the most significant material inputs and outputs. Blue line indicates module boundaries.

Production data for electronic and plastic components, packaging materials and ancillary materials were derived from ecoinvent 3.8 database. The products were transported from the factory by lorry and container ship transport. Transportation data was specific data derived from both internal and external sources. Construction stage and use stage data was based on assumptions, expert knowledge, and technical knowledge of the products and processes. The assumed use was 15 years for all products other than the self-learning sensor, for which the use time is 5 years due to the calculation rules required for EPDs in IBU 2017. Only module B6 was claimed for the use stage, as electricity is the only consumed resource during the products' use. Germany was chosen to represent a typical use location for the products. The EOL and recycling potential data was derived from both literature, company data, and ecoinvent 3.8 database. The use of generic data limits the study, especially in the Product and EOL stages where the use of generic data was highest. There was a high amount of variation between electronic components that the generic data in ecoinvent 3.8. didn't account for, which increased the inaccuracy of the study.

Based on studies by Zhou and Qiu (Sousa et al. (2022)), and He et al. (Marques et al. 2013), it was assumed in the EOL stage that plastic components that were known to contain flame retardants were incinerated. The electronic components (ECs) and their material fractions were divided into two rough categories: metal and non-metal fraction. The non-metal fraction is typically 30% ceramics and 30% plastics. The non-metal fraction was modelled to be incinerated and disposed, while the metallic fraction was modelled to be recycled. The product system boundary was drawn to consider only the lifecycle of the lighting control component, and not the lighting system it was part of.

5.4 Product system of control panel

The production process of the control panel differs somewhat from the other products, although the PCB mounting process is similar. The touch panel, which can be either glass or plastic, is cut and printed using the silk screening method in England. Both plastic and glass versions were modelled separately. The system boundary and unit processes are demonstrated in Figure 7. For clarity, prefix "CP" was added in front of the module coding to signify control panel. The PCB is assembled in Malaysia and shipped to England for final assembly of the panel fascia, from where they are distributed to Germany, which represented a typical Central European market for the products.

In the installation stage, packaging materials and an installation leaflet were modelled to go into the waste treatment, and the panel was assumed to be attached using the ancillary materials provided. Any use of hand tools was excluded from the assessment. Impacts of the packaging waste treatment were allocated in their own module, numbered as CP-A4-A5. The packaging waste from installation was assumed to be separately collected accordingly and completely recycled.

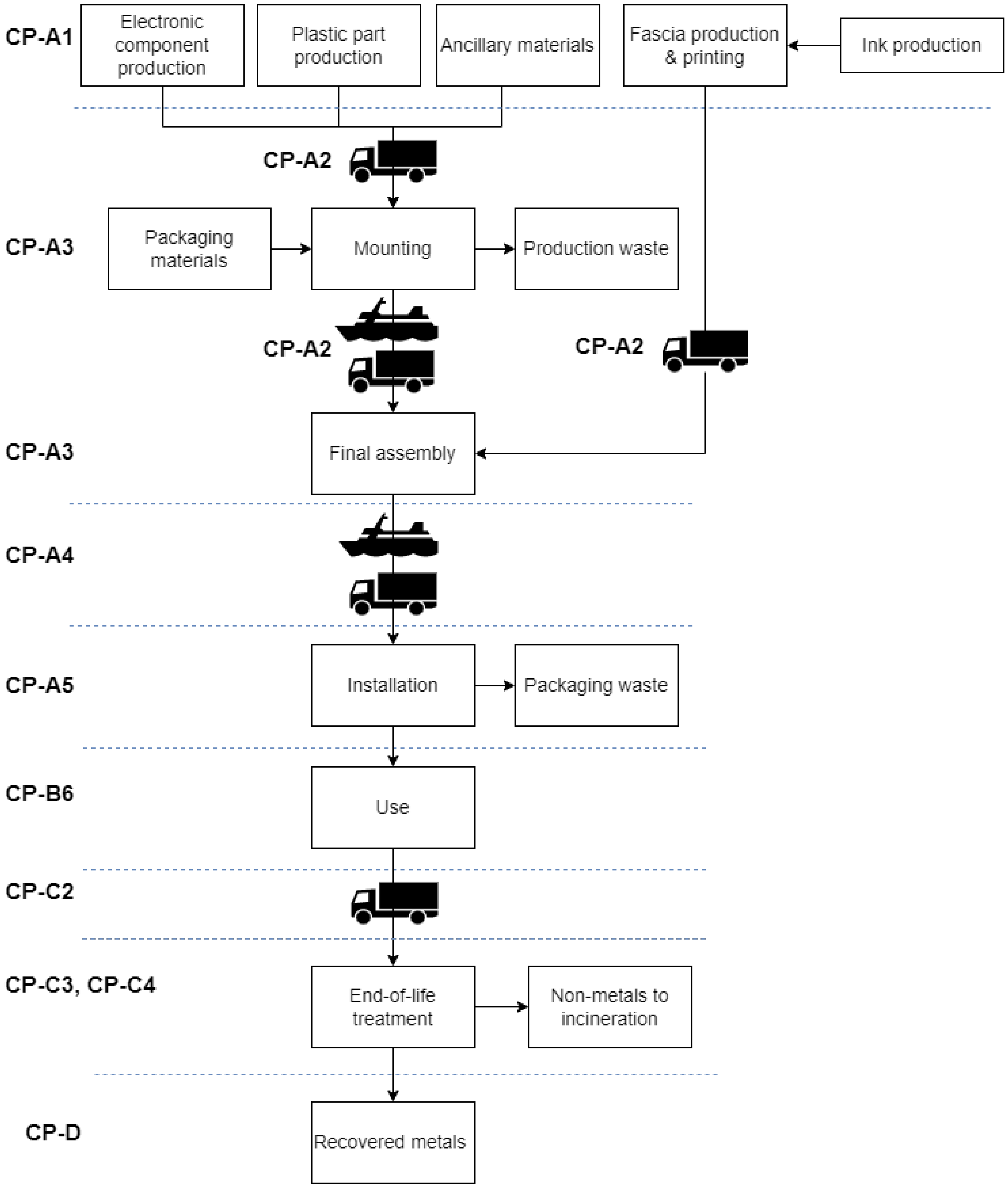


Figure 7. The product system for the control panel.

The lifetime of the control panel was estimated to be 15 years in Germany. As it is a touch panel, it might be subject to different levels of cleaning, but that was cut off from the product system. Cleaning is not directly connected to the properties or the function of the product, but to the needs of the end of user, and sufficient estimates of the number of resources needed for cleaning are hard to make. However, assuming that the cleaning of the panel is e.g., a quick wipe with a damp cloth, the cleaning materials, energy and environmental impacts of cleaning were considered to adhere to the cut-off criteria and the unit process can be excluded.

Deconstruction, i.e. removal of the control panel, was considered to produce two flows: product waste and ancillary waste. Ancillary waste refers to the screws. At the EOL stage of the control panel, it was assumed that the appliance is correctly send to the waste treatment. The waste is transported to a treatment facility, where it is shredded and sorted into metal and non-metal fractions. The metal fraction is further sorted for recycling, using magnetic separation and eddy-current separation (Chagnes et al. 2016). The non-metal fraction, which consists mostly of plastic and glass, is sorted into plastics for recycling, plastics for incineration and non-plastic fraction (Maisel et al. 2020). The plastic fascia, which is made out of polymethyl methacrylate (PMMA), is assumed to go into incineration as only 10% PMMA produced is currently being recycled, and most of the recycled material is post-industrial scrap (MMAtwo 2019). The plastic frame and glass were assumed to be incinerated.

5.5 Lighting system description

To inspect the positive impacts of the sensor products in their use stage, a lighting system model was created. Four scenarios are investigated: a lighting control system with a self-learning sensor in a 50 W luminaire, a conventional lighting system with a 50 W luminaire, a lighting control system with an area sensor and four 20 W luminaires, and a conventional lighting system of four 20 W luminaires. The lighting systems with sensors were compared to conventional systems, i.e., systems without sensors, to see how much the use of sensors decreased environmental impacts of lighting. The lighting control systems are shortly described in Table 3.

Table 3. Lighting control system descriptions.

Assessment of the lighting system with a self-learning sensor	Assessment of the lighting system with an area sensor
• One 50W luminaire • One sensor is mounted on the luminaire. • Sensor, driver, and luminaire lifecycles are considered.	• Four 20 W luminaires • One area sensor controls four luminaires. • Sensor, driver, and luminaire lifecycles are considered.

The luminaires used in the comparisons were modelled based on assumptions and data in AFRY Finland Oy's (2022) carbon footprint calculator for luminaire manufacturers. The calculator was made for luminaire manufacturers to calculate their cradle-to-gate carbon footprints. Each luminaire consists of steel frame, led arrays and a driver. The driver was modelled using the LED driver that was assessed as part of this study and deemed representative for this case. Since a driver is the component that conveys the electricity in the luminare, the electricity consumption of the luminaire can be calculated as the energy consumption of the driver. The active energy consumption was estimated by industry experts to be 4000 hours per year, and the passive consumption 4760 hours per year. The total lifetime of the lighting systems was assumed to be 15 years. In the scenarios investigated in this study, the passive energy consumption was calculated based on the worst-case scenario of 0.5 W, which makes 2.35 kWh per year. Newer products typically have lower passive consumption. Luminous efficacy of 18 lm/W was used, based on AFRY Finland Oy (2022).

The self-learning sensor is installed in the luminaire, and it is powered by the driver. The self-learning sensor was modelled to control only one luminaire, and the production, use, and waste treatment of the components are included in the product system. The product system for both the self-learning sensor and area sensor are shown in Figure 8. The blue line indicates the system boundary for the conventional lighting system (i.e., without the control components), and the red line indicates the system boundary for the lighting system with control components (a sensor and a driver). An average luminaire was assumed to consume 50 Wh, based on industry experts' knowledge. Company estimate was that luminaire electricity consumption was reduced by 50% when the sensors were used.

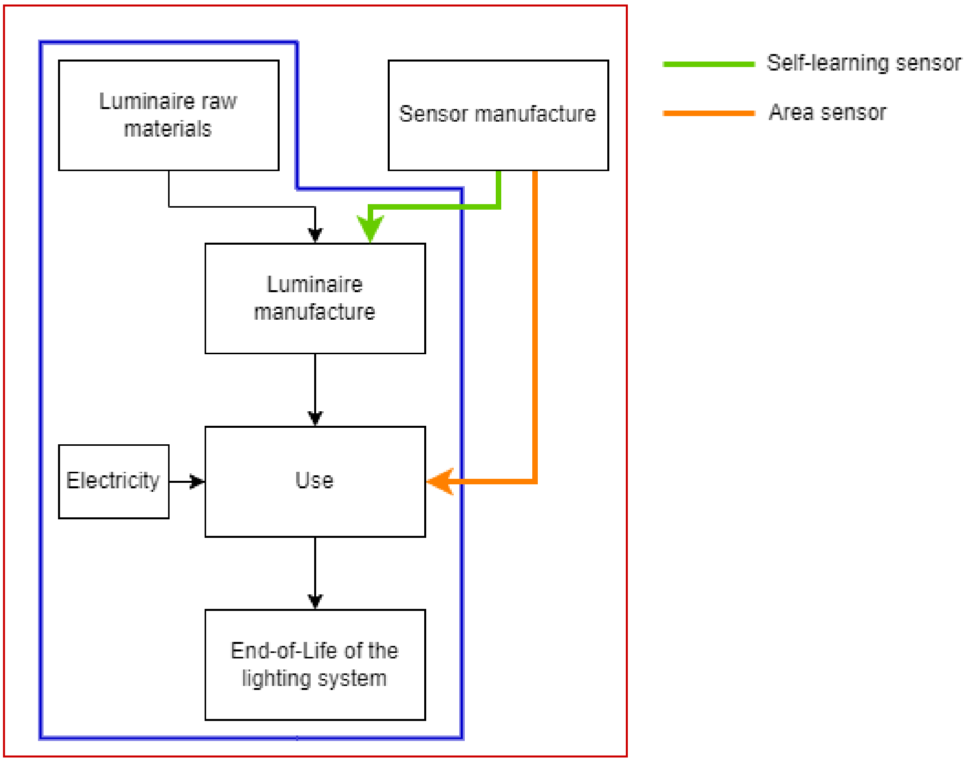


Figure 8. Product systems flowchart for the investigated lighting systems. The blue line indicates the system boundary for the conventional lighting systems, and the red one for the lighting system with the sensors included. Green arrow shows the flow for the self-learning sensor and orange arrow for the area sensor.

The area sensor can be installed on the roof or on the wall, for example. It was assumed to control four luminaires. Each luminaire was estimated to consume 20 W of energy when used. It was assumed that the sensor can reduce the luminaire electricity consumption by 30%.

Comparisons between the conventional and controlled lighting systems were made to see whether the environmental impacts of the lighting system decreased proportionally with the reduced energy consumption, or if the lifecycle of the sensor and its environmental impacts reduce the benefits it brings. It is important to note that the energy savings are based on industry expert's knowledge, and the actual energy saving potential of a lighting system depends mostly on the use scenario.

5.6 Functional units

The functional units used in the study are shown in Table 4.

Table 4. Functional units of the products and lighting scenarios in this study.

Product	Functional unit
Area sensor	Manufacturing, installation, 15 years of use, and EOL of one unit of product
Self-learning sensor	Manufacturing, installation, 5 years of use, and EOL of one unit of product
Control panel	Manufacturing, installation, 15 years of use, and EOL of one unit of product
Router	Manufacturing, installation, 15 years of use, and EOL of one unit of product
Lighting system with an area sensor	Lighting of a space with lighting system using an area sensor for 15 years
Lighting system with a self-learning sensor	Lighting of a space with lighting system using a self-learning sensor for 5 years
Conventional lighting with one 50 W luminaire	Lighting of a space with lighting system using one luminaire for 15 years
Conventional lighting with four 20 W luminaires	Lighting of a space with lighting system using four luminaires for 15 years

5.7 Life Cycle Inventory

5.7.1 Product manufacture

The production of the ECs in the products, which are printed wiring boards, capacitors, integrated circuit components, transformers, resistors, LEDs, transistors, and diodes, was based on the datasets from ecoinvent 3.8. The ecoinvent datasets are mainly based on manufacturer datasheets of components, environmental reports of component manufacturers, and literature data. The manufacturers from whom the data is acquired from are mostly from Europe and United States that are representative for global production. The number of components was determined from bills of materials provided by the company. Since most of the components in the bills of the materials didn’t have weights assigned to them, the weights were collected either from the component manufacturers’ product datasheets or material declarations, or from component distributors. It was clear that in many of these weights there were uncertainties, especially if the weight was acquired from a distributor. The datasets and amounts of components for each product are shown in Annex 2. For the router, three electronic components out of 288 components were left out due to data being unavailable for them.

A significant uncertainty was included in the modelling of the sensors, which both contained a PIR sensing component. No weight was available for the exact component, but a corresponding component weight was acquired. The sensing component comprised of an integrated circuit (IC), a metal package, and a lens. The lens was assumed to be neglectable in this study. The weight of the corresponding component was 1.01 g, and most of it is known to come from its metal packaging. The weight of the doped silicon is known to be 5 mg. The issue in the modelling was that the *integrated circuit, logic type* dataset in ecoinvent 3.8 was not thought to be as representative for this component as for other ICs based on the descriptions and sources of the dataset. Not enough sufficient information was available, however, to enable more precise modelling of the component, so the total mass of the component was allocated to the IC dataset.

The assembly was modelled to happen at the factory in Malaysia for the area sensor, control panel, and router, and in Finland for the self-learning sensor and the driver. Assembly was modelled by using surface- and through-hole mounting data sets. Electricity usage in mounting was adjusted for the country. For production in Finland, the emission factor for electricity consumed was provided by the electricity provider. Production of plastic parts was modelled using material production and injection moulding datasets. For parts with polycarbonate/acrylonitrile butadiene styrene blend their component ratio was estimated to be 50:50. The processing of production waste was based on the product weights and given estimate of the waste generated in production. The waste generated in the assembly process was expected to consist only of ECs and to be disposed. Its amount was estimated by the company to be 0.01% of the total mass of production.

5.7.2 Transportation

Transportation scenarios for the router and the area sensor were as in Table 5. The transportation route differed for the control panel, which was transported from Malaysia to England for final assembly of the fascia, after which it was sent to the customer in Germany. The control panel transportations are shown in Table 6. The self-learning sensor is manufactured in Finland, so the transportations are as in Table 6.

Table 5. Transportation data for the router and the area sensor.

Point of departure	Point of arrival	Distance (km)	Type(s) of dataset	Source
Component suppliers	Factory, Malaysia (MY)	1000	Lorry, 16-32 t, EURO 5	Estimation
Factory, MY	Harbour, MY	33	Lorry, 16-32 t, EURO 5	Google Maps
Harbour, MY	Harbour, Finland (FI)	17113	Container ship	Searates.com
Harbour, FI	Company, FI	72	Lorry, 16-32 t, EURO 5	Google Maps
Company, FI	Customer, Germany (DE)	On land: 480 On water: 2100	Lorry, 16-32t, EURO5 Container ship	Searates.com
Customer	Waste Treatment	250	Lorry, 16-32t, EURO 5	EeBGuide Project 2012

Table 6. Transportation data for the control panel.

Point of departure	Point of arrival	Distance (km)	Type(s) of dataset	Source
Component suppliers	Factory, Malaysia MY	1000	Lorry, 16-32 t, EURO 5	Estimation
Plastic part supplier, UK	Factory, MY	On land: 56 On water: 15105	Lorry, 16-32 t, EURO5 container ship	Searates.com
Fascia suppliers, UK	Factory, United Kingdom (UK)	471 glass /405 plastic	Lorry, 16-32 t, EURO 5	Google Maps
Factory, MY	Harbour, MY	33	Lorry, 16-32 t, EURO 5	Google Maps
Harbour, MY	Harbour, UK	15075	Container ship	Searates.com
Harbour, UK	Company, UK	494	Lorry, 16-32 t, EURO 5	Tracking details from transportation companies
Company, UK	Customer, DE	On land: 43 On water: 908	Lorry, 16-32 t, EURO5 container ship	Searates.com
Customer	Waste Treatment	250	Lorry, 16-32t, EURO 5	EebGuide project 2012

Table 7. Transportation data for the self-learning sensor.

Point of departure	Point of arrival	Distance (km)	Type(s) of dataset	Source
EC producers, Asia	Company factory, Finland (FI)	On land: 197 On water: 19575 km	Lorry, 16-30t, EURO 5	Estimated from BOMs, 60% coming from Asia. Source: Searates.com
EC producers, Europe	Company factory, (FI)	On land: 200 On water: 7802	Lorry, 16-30t, EURO 5	Estimated from BOMs, 40% of components coming from Europe. Source: Searates.com
Company factory, FI	Customer, Germany (DE)	On land: 480 On water: 2100	Lorry, 16-32t, EURO5 Container ship	Searates.com
Customer	Waste management	250	Lorry, 16-32t, EURO 5	EebGuide project 2012

5.7.3 Screen printing of the control panel fascia

There was no data set available in the databases for the screen printing of glass or plastic fascia for the control panel, so it was modelled based on energy consumption derived from machinery datasheets, and ink consumption that was very roughly estimated. No emissions or waste were modelled, due to the lack of sufficient information. The screen printing, cutting, and curing of the fascia was modelled based on following information sources and aggregated into one process:

- Electricity consumption of the machinery used from respective datasheets available online (Sakurai 2022; Natgraph 2022),
- Curing time of ink from respective ink supplier data sheet and website (Apollo Colours Limited 2022),
- Environmental footprint of ink from “Eco Footprint of a generic reference – version 2020” by European Printing Association (2020),
- Information from “Environmental impact of printing inks” by European Printing Association (2013),
- Correspondence with the respective supplier.

The information available from the supplier was very limited, which is why several assumptions had to be made, and thus the unit process is not only limited but has high inaccuracy. Estimating the curing time of the ink was difficult as the datasheet for the ink and the datasheets for the machinery were conflicting. Thus, worst case scenario, i.e., the longest curing time for ink to be touch dry, was selected. This was not, however, expected to greatly affect the results, as according to EUPIA (2020), printing typically accounts for less than 5% of the total environmental footprint of a plastic substrate, and can be assumed to be even less for the whole electronic product. Data for the adhesive that was used to attach the fascia was modelled according to its datasheet information. Information of screen printing is summarised in Table 8.

Table 8. LCA data of the screen printing of the fascia.

Input flow	Dataset	Amount	Source
Float glass	Flat glass, uncoated	89.9 g	Company data
Ink	Modelled using the environmental footprint for average printing ink	34.9 g	European Printing Association (2020)
Adhesive	Methyl methacrylate	1.1 g	Product datasheet from 3M™ (2017)
Energy	Electricity, medium voltage	52 Wh	Ink and machinery datasheets

5.7.4 Installation stage

Any use of hand tools or materials used in installation was estimated to be neglectable, so only waste treatment of the product packaging waste was included in the model. It was assumed that a part of the packaging waste goes to incineration and a part of it goes to recycling. The portion of waste going to recycling was assumed to be 60% based on Eurostat packaging waste data from 2019 (Eurostat 2022). Polluter pays -principle is enforced in the European Union and following it no benefits beyond the EoW status were allocated to the product system. The EUR-pallet, which is used for the driver, was assumed to be reused and was not accounted for.

5.7.5 Use stage

The use phase (module B6) consists only of the operative energy consumption during 15 years of use, which was estimated to be 46.26 kWh for the control panel, 28.91 kWh for the area sensor, and 4602.05 kWh for the router based on the product datasheets. As all products are typically used e.g., in offices, the energy was modelled as low voltage electricity consumption from the German grid.

The energy consumptions of the driver and the self-learning sensor were calculated using the formula 1 in IBU's *PCR B: Requirements on the EPD for Luminaires, lamps and components for luminaires* (2017):

Energy consumption [kWh] = $(Pa \times FCP \times FD \times tD + 2 \times Pp \times tD) \times 1/1.000$, (1)

Where Pa is the active power, Pp is the passive power, FCP is the product-specific illuminance factor, FD is a correction factor from IBU's PCR, and tD is the product lifetime in hours specified by the manufacturer. The formula was used to enable use in EPDs if necessary.

The active power of the self-learning sensor is 0 W, and the estimated lifetime is 43800 hours, which is five years. Based on formula 1, the energy consumption was:

Energy consumption = $(0 + 2 \times 0.06 \times 43{,}800) \times \frac{1}{1.000} = 5.26\ kWh$

The product lifetime of the LED driver is 100 000 hours. Active power is 52.5 W on assumed current and voltage, and passive power using worst-case scenario is 0.5 W. The total consumption of energy is then

$$(52.5 \times 1 \times 0.8 \times 100{,}000 + 2 \times 0.5 \times 100{,}000) \times \frac{1}{1.000} = 4300\ kWh$$

5.7.6 End-of-life stage

It was assumed that there are no material or energy flows in deconstruction module C1. EOL module C3 for the product was done using two EOL datasets from ecoinvent 3.8: *treatment of scrap printed wiring boards*, and *treatment of waste electric and electronic equipment*. Scrap printed wiring boards consist of the PWB and the ECs for products. The PWB treatment dataset consists of weighting, shredding, and sampling of the printed circuit board. It was used on all products, even if the PCB size wouldn't require it according to the WEEE Directive (2012/19/EU). The dataset *Treatment of waste electric and electronic equipment* was modelled to have two shredders, and two magnetic and two eddy current separators for metals. The material streams from shredders were separated flows of metals, plastics, and ceramics/glass. Plastics and ceramics, when separated, were modelled as disposed of in module C4 with *market for waste plastic, mixture* and *market for waste glass* datasets that represent disposal. *Market for waste glass* was used to represent both glass and other ceramic materials found in the products. The known metal fractions from C3 were allocated to module D. It was assumed that the metal recyclate is directly used in metal production in global markets. The number of metals recovered and allocated to module D were estimated from the company data for average component material composition. Metals in quantities lower than 2%, such as tin or nickel, were not allocated. The allocated metals are shown in Table 9. The module D was calculated separately.

Table 9. Metal compositions of the PCB for Module D.

Product	Metals (percentage of PCB weight)
Control panel	10% copper, 7% aluminium
Area sensor	30% copper, 2% aluminium
Router	13% copper, 7% aluminium, 8% nickel
Self-learning sensor	46% copper, 5% tin
LED Driver	6% copper, 8% aluminium

5.7.7 Lighting system study

For the lighting system study, the annual electricity consumption of the luminaire(s) was calculated and multiplied for 15 years. Total electricity consumption and reductions that can be achieved with control products are shown in Table 10. The use of luminaires was estimated to be 4000 active hours per year, and 4760 passive hours. The active consumption of the luminaires was 20 W with area sensor and 50 W with self-learning sensor. The passive power consumption was 0.5 W. A comparison for different electricity grids were made to see how the electricity sources affect the environmental benefits of sensor. The comparison was made by using the German and Icelandic electricity grids. The ecoinvent 3.8 dataset used for the German electricity grid was *market for electricity, low voltage, DE*. The dataset was based on 2018 data from International Energy Agency. According to International Energy Agency (2022a), the electricity generation by source in the German grid in 2018 was 37.17% coal, 17.10% wind, 12.98% natural gas, 11.82% nuclear energy, and 20.93% other sources, such as solar, geothermal and oil. For the comparison, *market for electricity, low voltage, IS* was used to see how sensors perform in almost fossil-free grid. Iceland's grid was composed of geothermal energy (69.66%), hydro energy (30.31%), wind (0.02%) and oil (0.01%) in 2018. (International Energy Agency 2022a, 2022b).

Table 10. Electricity consumptions and savings for the lighting system over 15 years of use.

Lighting systems	Electricity consumption without the sensor	Electricity saving	Electricity consumption with the sensor
Area sensor in the lighting system	4942.8 kWh	-30%	3488.9 kWh
Self-learning sensor in the lighting system	3035.7 kWh	-50%	1517.9 kWh

The luminaire life cycle inventory was partly based on AFRY Finland Oy ’s roadmap (AFRY Finland Oy 2022), where information and material balances for a reference luminaire were given. The LED component weights were taken from the publication by Tähkämö (2013). In the EOL stage of the luminaire it was assumed that the metal case of the luminaire is recycled, and the rest is disposed of. The used data is shown in Annex 2 Table A2.7. Although installing the sensor was in the product system, it was estimated to consume such a small amount of energy and material that it wasn’t considered.

6 LIFE CYCLE IMPACT ASSESSMENT AND INTERPRETATION OF RESULTS

6.1 Results

The most relevant impact assessment results of the study are shown for each product and scenario in chapters 6.1.1–6.1.6. Complete results for all SFS-EN 15804 impact categories are in Appendix 3. Climate change, toxicity, and resource use for metals and minerals were identified as most relevant impacts and studied more in depth for the products. The lighting system comparison results were visualized for all impact categories. Calculations were performed using OpenLCA software and EN 15804 + A2 method, which is based on impact assessment methods in Appendix 1.

6.1.1 Area sensor

The complete results for the area sensor are shown in Appendix 3 in Table A3.1. They are shown with and without module D, which contains the allocated benefits (reduction of impacts in another product system) from the use of recovered metals. The total Climate Change category result for GHG emissions is 18.7 kg CO_2 eq. in total (from module A1 to D) and 2.5 kg CO_2 eq. for modules A1 to A3, i.e., cradle-to-gate. The biggest part of the carbon footprint comes from the use stage (module B6). The distribution of GHG emissions across all the modules is shown in Figure 9.

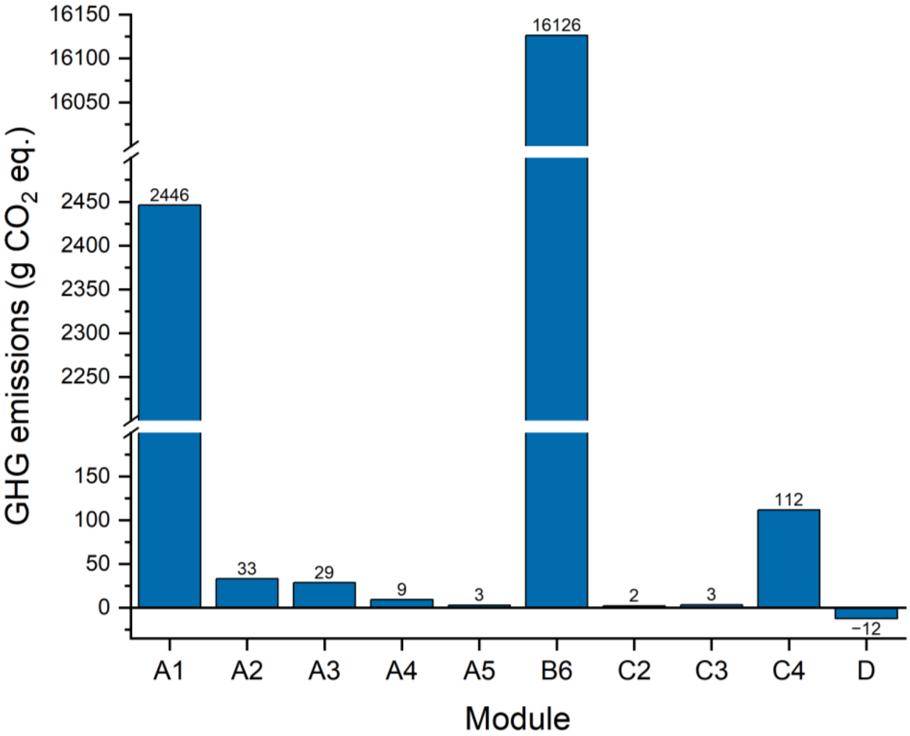


Figure 9. Distribution of the carbon footprint as grams of CO_2 eq. across all life cycle modules for the area sensor. Module A1 is the manufacturing of the components, A2 the transportation of the components to the manufacturer, A3 the assembly and production of packaging materials, A4 distribution to the customer, A5 is the waste-treatment of the packaging waste, B6 is the operational energy use, C2 the transportation to the waste treatment, C3 the waste processing, C4 disposal and D the allocated avoided impact of recycled metals.

After component production module A1 and operational energy use module B6, the disposal module C4 has the highest GHG emissions, although it is’s still significantly smaller in comparison. To better understand the emissions generated by the manufacturing of the product (cradle-to-gate), the most contributing materials and processes were analysed from modules A1-A3, and the results are shown in Figure 10.

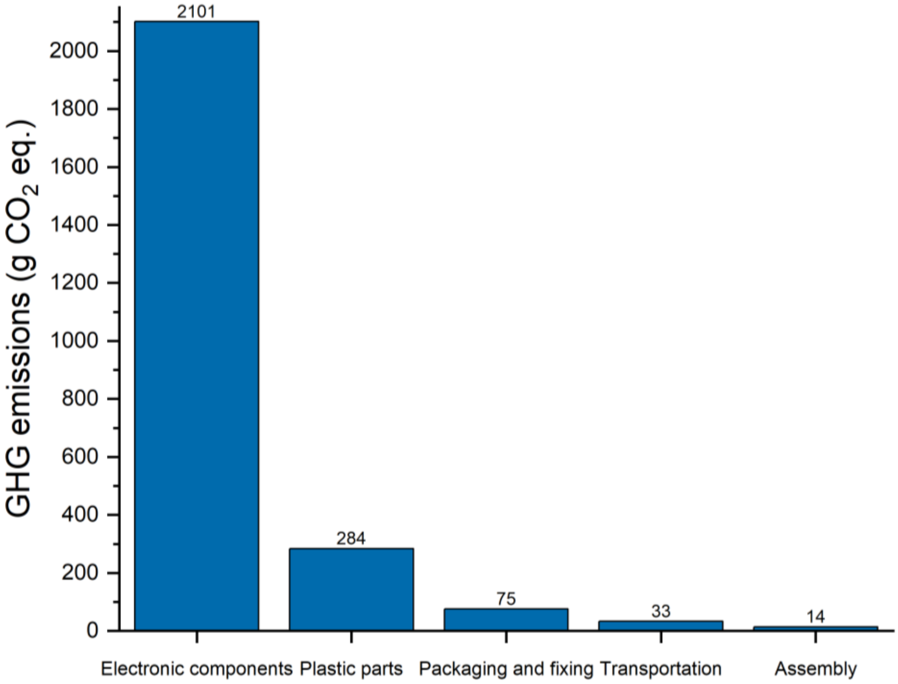


Figure 10. GHG emissions for components production, transportation, packaging materials and assembly in modules A1-A3 for the area sensor.

Most of GHG emissions in the manufacturing of the product originates from the production of ECs as shown in Figure 10. The biggest contributor of all electronic components was the PIR sensing component due to its heavy weight. There is a possibility for inaccuracy in this case however, as the complete weight of the PIR component available may not have been represented in the dataset well. Expert knowledge and similar components were used to estimate the weight for the dataset.

The impact category result from Annex 3 for total *human toxicity, cancer* is $6.942 \cdot 10^{-9}$ CTUh and *human toxicity, non-cancer* $2.772 \cdot 10^{-7}$ CTUh. The *ecotoxicity, freshwater* is 362.781 CTUe. The unit CTUh stands for Comparative Toxic Unit for Human, and the CTUe for Comparative Toxic Unit for Ecotoxicity. Figure 11 shows that the EOL stage (C1-C4) has virtually no toxicity impacts, while manufacturing (A1-A3) and use stage (A4-B6) do. All use stage toxicity impacts originate from the electricity use. Module D is not included in Figure 11.

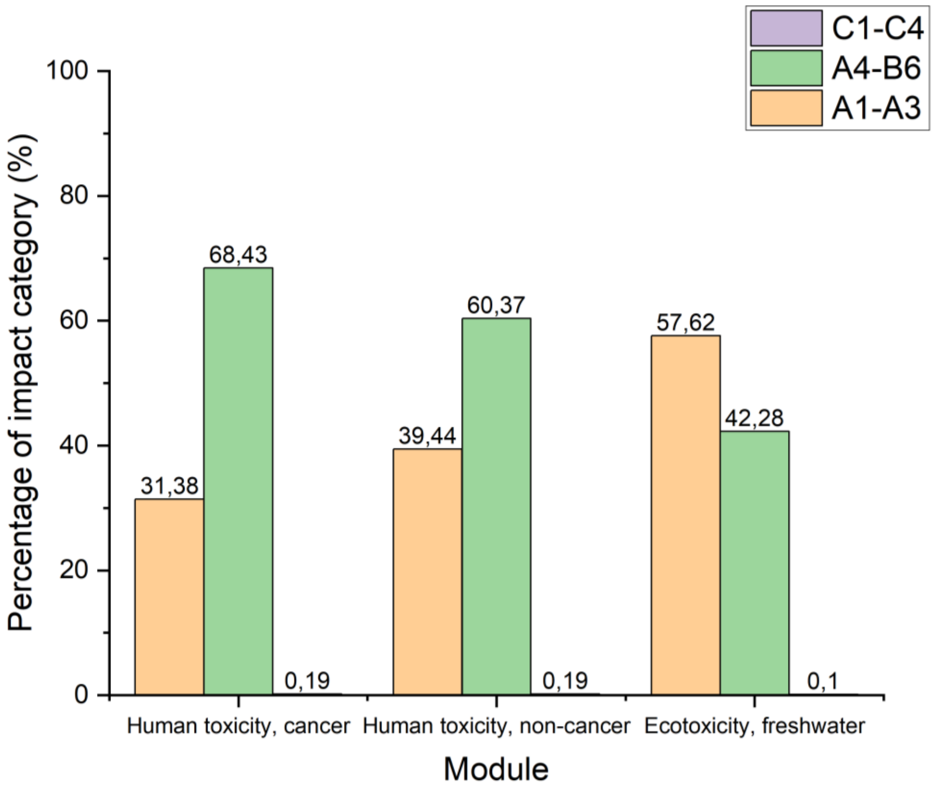


Figure 11. The distribution of human toxicity and ecotoxicity impacts across three main sets of lifecycle stages of the area sensor. Set A1-A3 comprises of manufacturing of the product and its components, A4-B6 of transportation to customer, packaging waste treatment and use, and C1-C4 of the waste treatment of the product.

The *resource use, minerals and metals* impact category indicates depletion of mineral and metal resources. The total resource use, minerals and metals result for the area sensor is 0.99 g Antimony equivalents (g Sb eq.), which comes from the product stage (86.7%) and use stage (13.3%). Module D has a very small impact result compared to the total resource use, only 27.4 mg Sb eq.

6.1.2 Router

The complete impact category results for the router are shown in Annex 3 in Table A3.2. They are shown with and without module D. The distribution of GHG emissions across the modules are shown in Figure 12. The total Climate Change impact category result is 2600.6 kg CO_2 eq., and 30.7 kg CO_2 eq. for modules A1-A3.

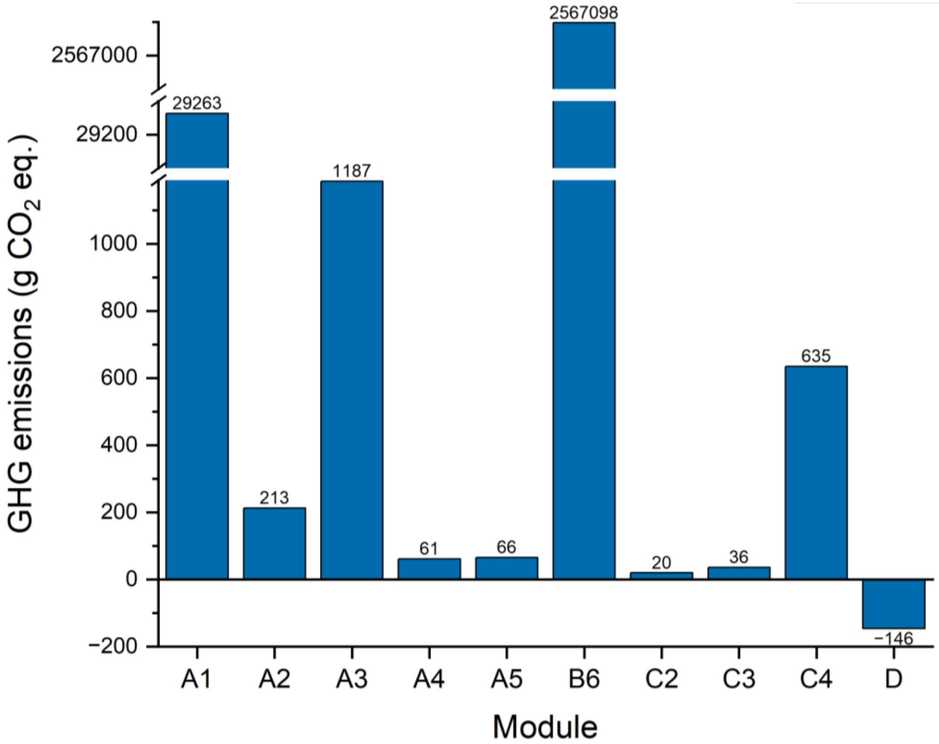


Figure 12. Distribution of the carbon footprint as grams of CO_2 eq. across all life cycle modules for the router. Module A1 is the manufacturing of the components, A2 the transportation of the components to the manufacturer, A3 the assembly and production of packaging materials, A4 distribution to the customer, A5 is the waste-treatment of the packaging waste, B6 is the operational energy use, C2 the transportation to the waste treatment, C3 the waste processing, C4 disposal and D the allocated avoided impact of recycled metals.

The distribution of the GHG emissions among the top five most contributing elements in modules A1-A3 are shown in Figure 13. Comparing the results of Figure 12 and Figure 13, it is clear that the electronic components are the biggest contributor to the product carbon footprint when the electricity consumption from use stage was not considered. The router has a significantly high carbon footprint, which is reasonable as it contains the highest number of electronic components by mass and consumes high amounts of energy.

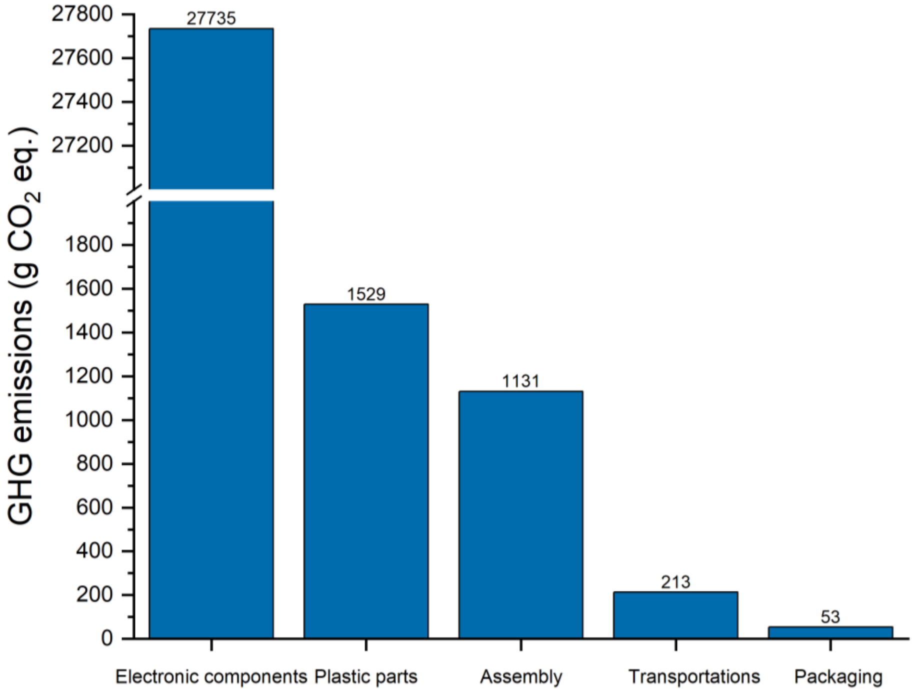


Figure 13. GHG emissions for components production, assembly, transportation, and packaging in modules A1-A3 for the router.

The toxicity impacts of the router are shown in Figure 14. The total results are $7.98 \cdot 10^{-7}$ CTUh for *human toxicity, cancer,* $2{,}83 \cdot 10^{-5}$ CTUh for *human toxicity, non-cancer* and 27799.9 CTUe for *ecotoxicity, freshwater.* The toxicity effects are very low for the EOL stages.

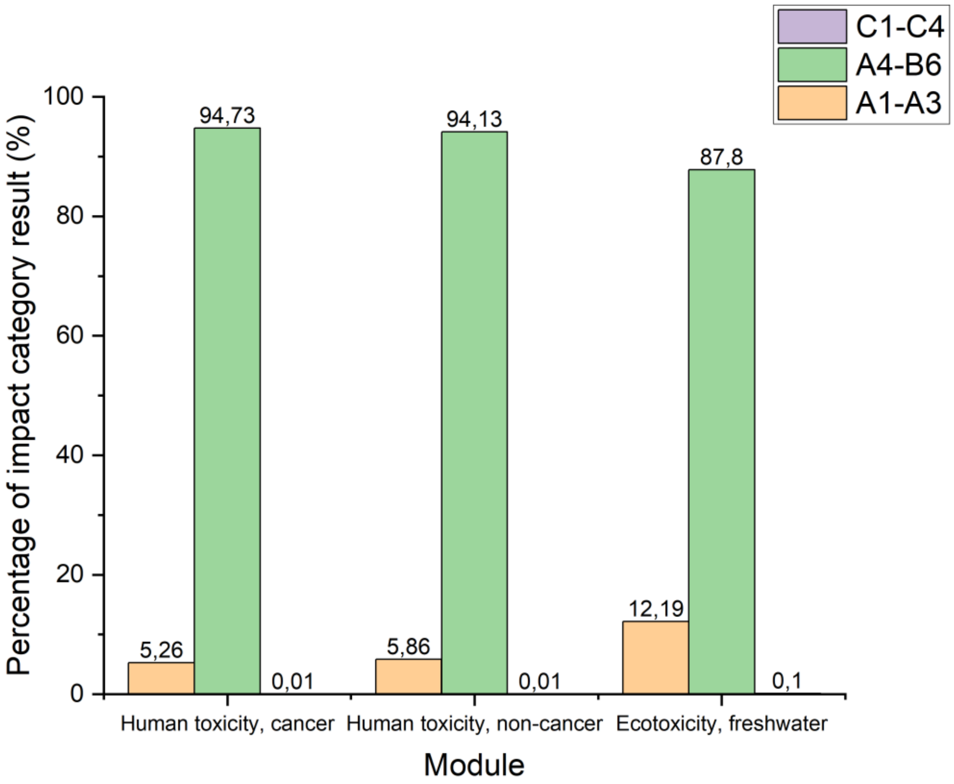


Figure 14. The human toxicity and exotoxicity impacts of the router over its lifecycle. The lifecycle is divided into three sets, of which first comprises of modules A1 to A3, second from modules A4 to B6, and last from modules C1 to C4.

The total impact category result for *resource use, minerals and metals* is 33.04 g Sb eq. for the router. All resource use comes from the A1-A3 modules (36.68%) and the use module (63.32%). The D module has a positive impact of 19 mg of Sb eq.

6.1.3 Self-learning sensor

Complete EN 15804 + A2 impact category results for the self-learning sensor are shown in Annex 3, in Table A3.5. The distribution of the carbon footprint over the modules is shown in Figure 15. The total carbon footprint of the product is 5.7 kg CO_2 eq. and cradle-to-gate result 2.7 kg CO_2 eq.

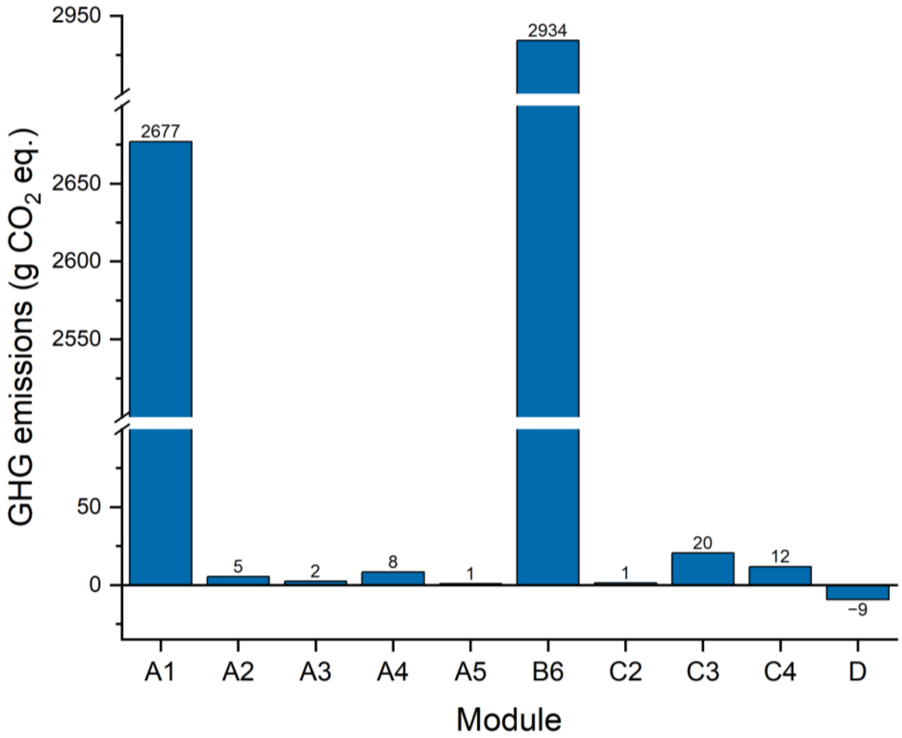


Figure 15. Distribution of the carbon footprint as grams of CO_2 eq. across all life cycle modules for the self-learning sensor. Module A1 is the manufacturing of the components, A2 the transportation of the components to the manufacturer, A3 the assembly and production of packaging materials, A4 distribution to the customer, A5 is the waste-treatment of the packaging waste, B6 is the operational energy use, C2 the transportation to the waste treatment, C3 the waste processing, C4 disposal and D the allocated avoided impact of recycled metals.

The modules A1 and B6 have the biggest contribution to the lifecycle footprints, but since the energy consumption is very low, the difference between module A1 and B6 is significantly smaller than for the other products in this study. It should be noted that the self-learning sensor also contains a PIR sensing component. Another difference when compared to the other results is that the impacts of disposal are not significantly higher compared to the other categories, and can be for the most part compensated by the amount of metals recovered, since a significant amount of metals could be identified from the sensor PCB. The waste processing category C3 is very high due to the dataset that was used for the waste treatment of the cable. The dataset included both the processing and disposal of the cable, which means that only disposal of the plastic parts and PCB were modelled in module C4.

Since the sensor was manufactured in Finland in the company’s own factory, a more specific energy consumption could be estimated for it. The emission factor of the purchased energy was also available. The energy production for mounting was attributed to the assembly process in Figure 16, which shows the contribution of different processes for the A1-A3 carbon footprint.

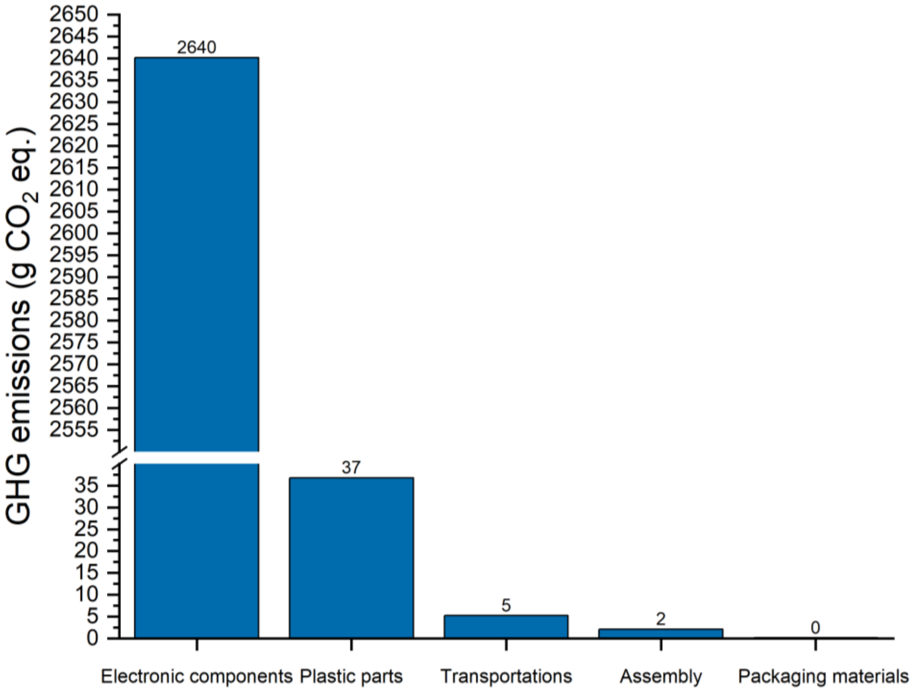


Figure 16. GHG emissions for components production, transportation, assembly, and packaging materials in modules A1-A3 for the self-learning sensor.

Due to the very low energy consumption of the sensors, most of the toxicity impacts come from the product stage (A1-A3). The distribution of toxicity impacts is shown in Figure 17. The total *human toxicity, cancer* results is $4.30 \cdot 10^{-9}$ CTUh, *human toxicity, non-cancer* $2.37 \cdot 10^{-7}$ CTUh and *ecotoxicity, freshwater* 318.94 CTUe.

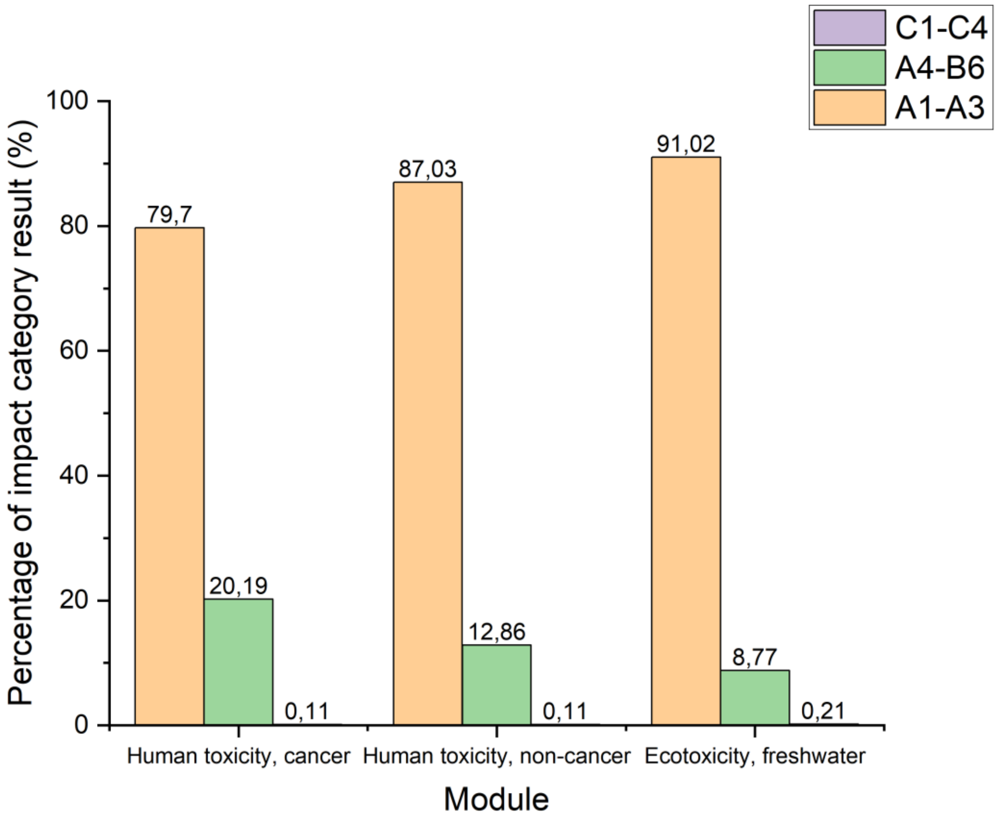


Figure 17. Toxicity distribution for the self-learning sensor.

*Resource use, minerals and metal*s impact category result for the self-learning sensor is 1.2 g Sb eq., of which 97.95% comes from the manufacturing and 2.05% from the use. Compared to the area sensor, the result is higher. The module D impact result is 19 mg Sb eq.

6.1.4 LED Driver

The results for the LED driver are shown in Annex 3 Table A3.6. Distribution of climate change results are shown in Figure 18, where the use stage (B6) has the biggest contribution. This is to be expected, as the driver is typically the only energy consuming component in a luminaire and thus has a high energy consumption. The total climate change category result is 2696.4 kg CO_2 eq., and 4.8 kg CO_2 eq. for cradle-to-gate.

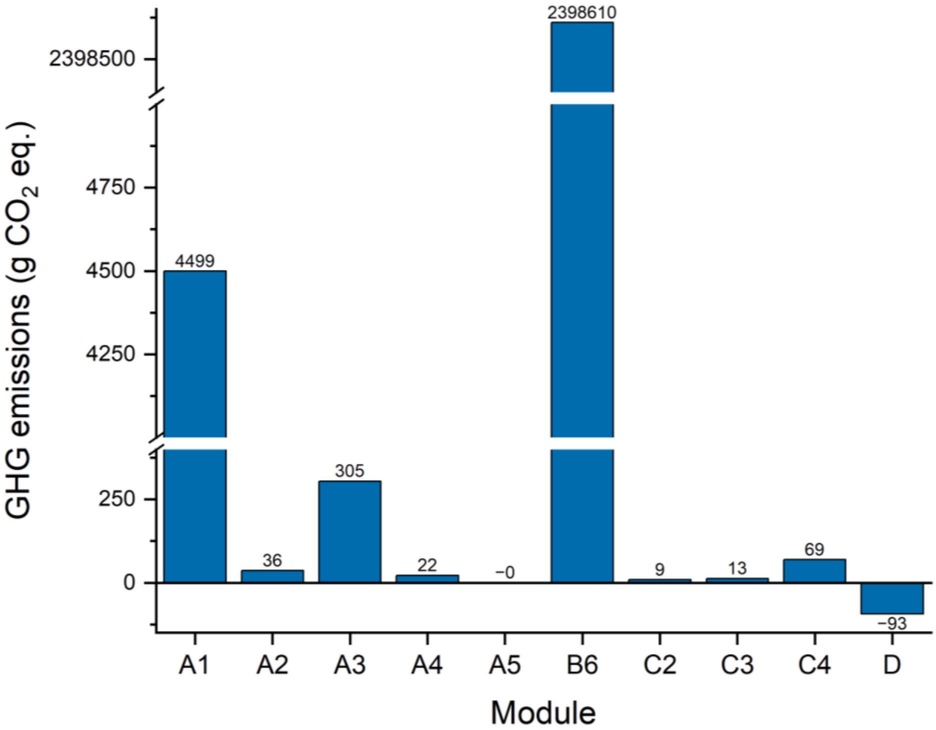


Figure 18. Distribution of GHG emissions over the modules of LED driver. Module A1 is the manufacturing of the components, A2 the transportation of the components to the manufacturer, A3 the assembly and production of packaging materials, A4 distribution to the customer, A5 is the waste-treatment of the packaging waste, B6 is the operational energy use, C2 the transportation to the waste treatment, C3 the waste processing, C4 disposal and D the allocated avoided impact of recycled metals.

The contribution over the most considrable elements in A1-A3 modules are shown in Figure 19. The contribution of packaging material is left out, as it had a very small impact that could not be visualized properly.

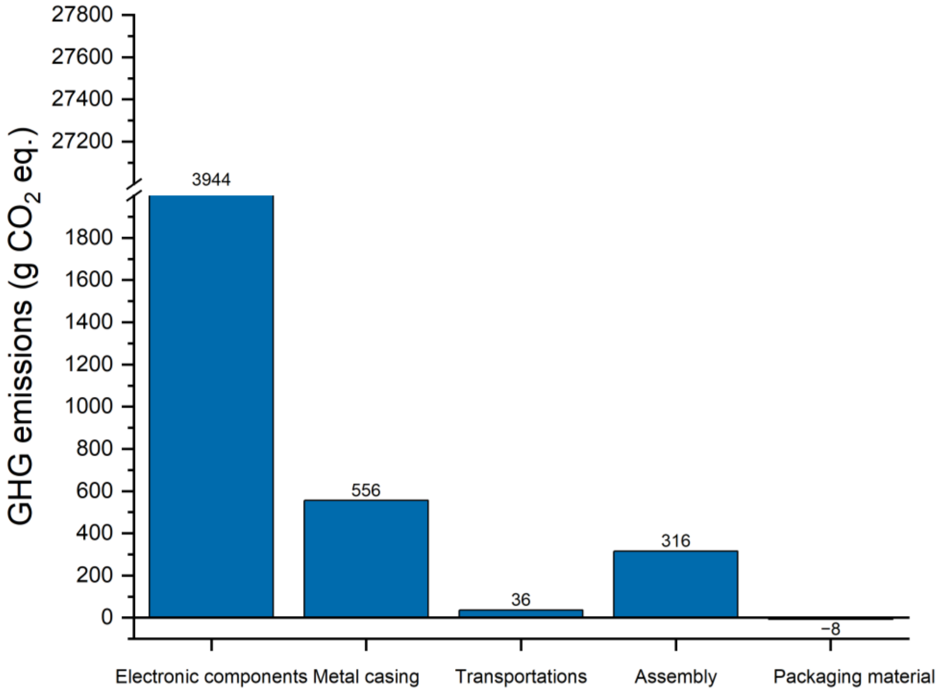


Figure 19. Distribution of GHG emissions for component production, transportation, assembly and packaging materials in A1-A3 modules for the LED driver.

The distribution of toxicity impacts is shown in Figure 20. When the total lifecycle and 15 years of use are assumed, practically all toxicity impacts originate from the use stage, i.e., the electricity use. The result for *human toxicity, cancer* are $7.19 \cdot 10^{-7}$ CTUh, and $2.53 \cdot 10^{-5}$ CTUh for *human toxicity, non-cancer*. The *ecotoxicity, freshwater* result is 23241 CTUe.

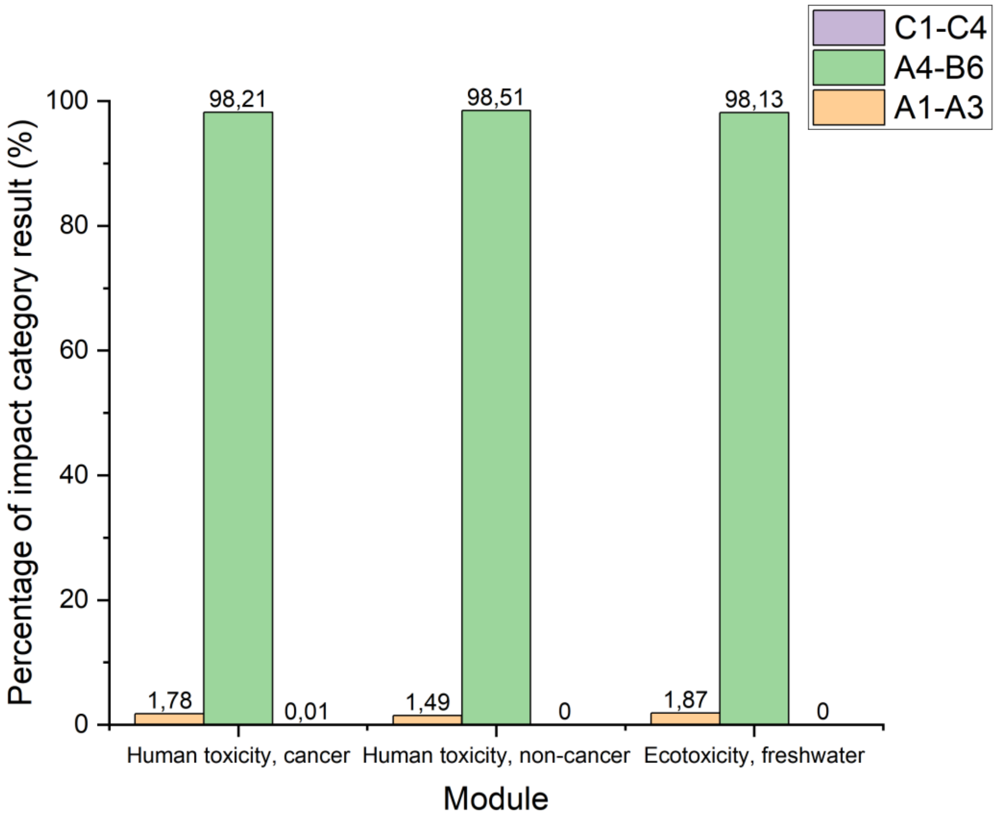


Figure 20. Distribution of toxicity impacts of the LED driver.

The *resource use, minerals and metals* impact category result for the LED driver is 20.8 g Sb eq., of which 5.49% came from the manufacturing and 94.51% from the electricity use. The result was roughly two thirds of the result gained for the router. The module D impact is 35.4 mg Sb eq.

6.1.5 Control panel

The complete LCIA results of the control panel are shown in Tables A3.3 and A3.4. in Annex 3. The distribution of the GHG emissions was inspected and visualised for both glass fascia and plastic fascia versions in Figure 21. For better reability of the results, the y-axis was cut from two points. The highest results are in A1 and B6 modules, both of which are significantly higher than for any other module.

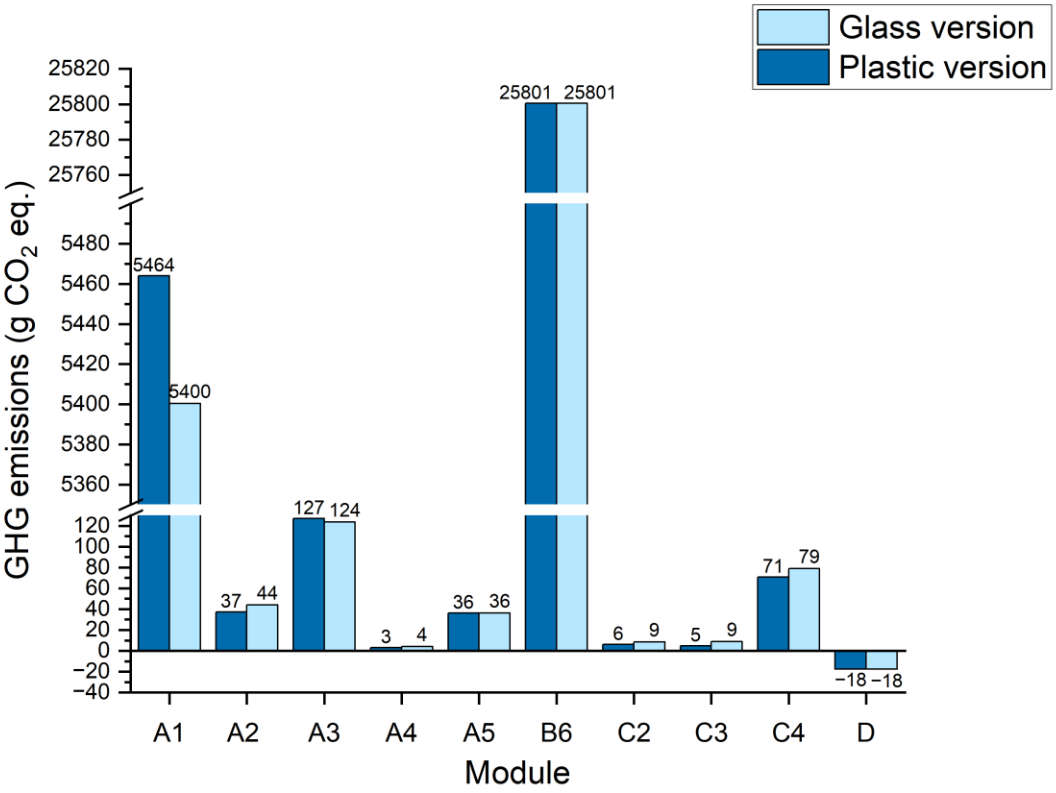


Figure 21. Distribution of the carbon footprint as grams of CO_2 eq. across all life cycle modules for the control panel. Module A1 is the manufacturing of the components, A2 the transportation of the components to the manufacturer, A3 the assembly and production of packaging materials, A4 distribution to the customer, A5 is the waste-treatment of the packaging waste, B6 is the operational energy use, C2 the transportation to the waste treatment, C3 the waste processing, C4 disposal and D the allocated avoided impact of recycled metals.

The difference between the glass and plastic versions is most considerable in A1 module, where the plastic fascia has a higher impact in the Climate Change impact category than its glass counterpart. This can also be confirmed from Figure 22. Manufacturing of PMMA has a considerably higher burden than manufacturing of glass, but since the glass fascia is heavier it has higher transportation burdens. Since neither the glass nor plastic fascia was assumed to be recycled, there is no difference in module D.

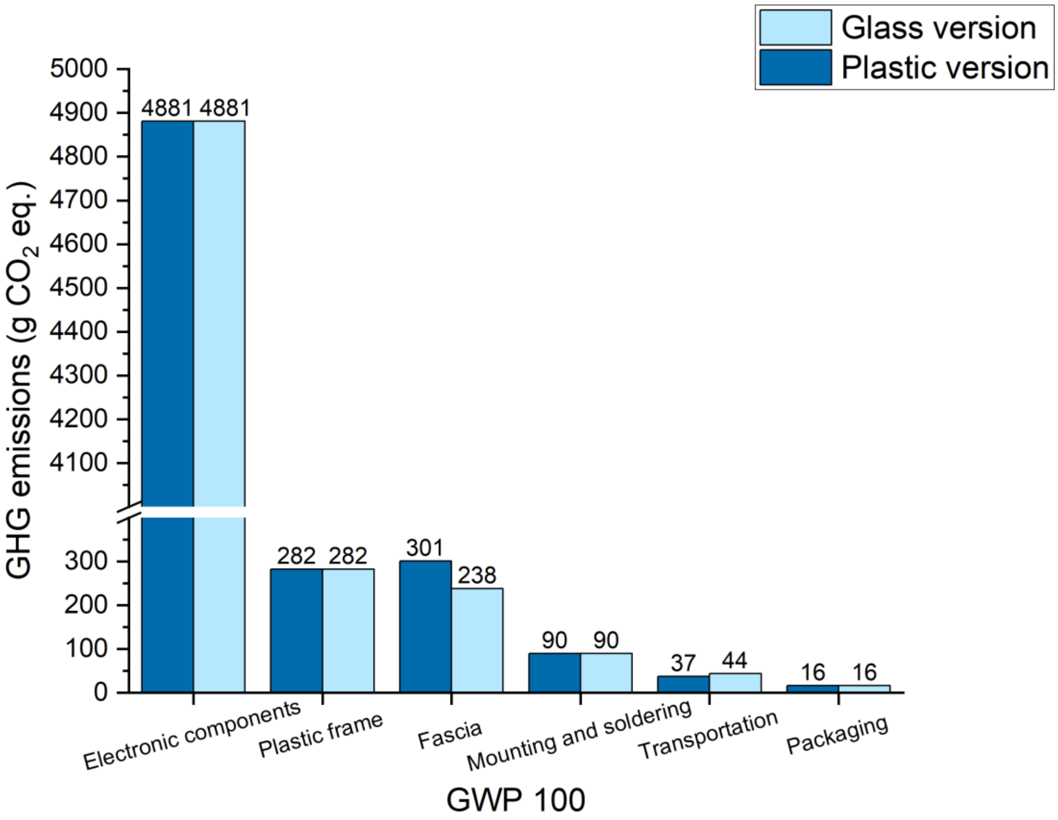


Figure 22. Distribution of components production, assembly, transportation and packaging carbon footprint over CP A1-A3 modules for the control panel.

The human toxicity impacts of the control panel are divided rather fairly between the manufacturing and use stage, EOL having little to no toxicity impacts. The total *human toxicity, cancer* impact for plastic version is $1.26 \cdot 10^{-8}$ CTUh and *human toxicity, non-cancer* is $4.68 \cdot 10^{-7}$ CTUh. The ecotoxicity impact share of the manufacturing stage (CP A1-A3) is considerably high compared to the other stages, the total *ecotoxicity, freshwater* result being 577.82 CTUe. The toxicity of different lifecycle stages for the plastic version is shown in Figure 23. For the glass version, the results are $1.27 \cdot 10^{-8}$ CTUh for *human toxicity, cancer,* $4.69 \cdot 10^{-7}$ CTUh for *human toxicity, non-cancer*, and 57.31 CTUe for *ecotoxicity, freshwater.* The distribution of toxicity impacts for the glass version are shown in Figure 24.

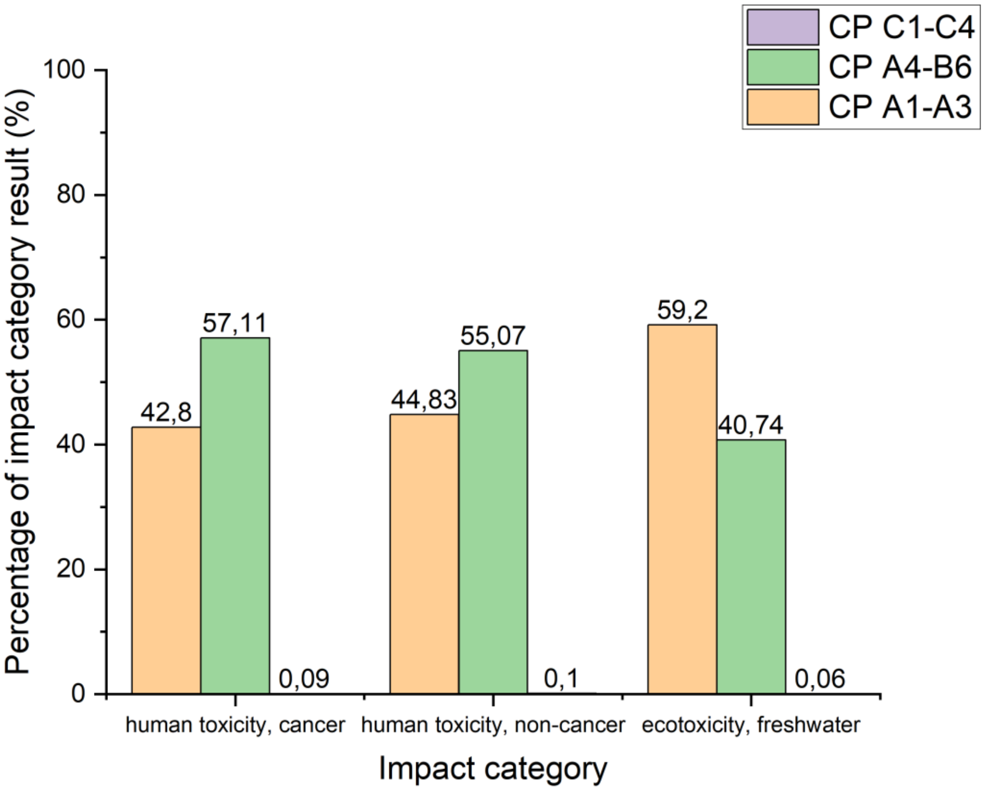


Figure 23. Toxicity impacts of the plastic fascia version of the control panel, as percentages of modules per impact category.

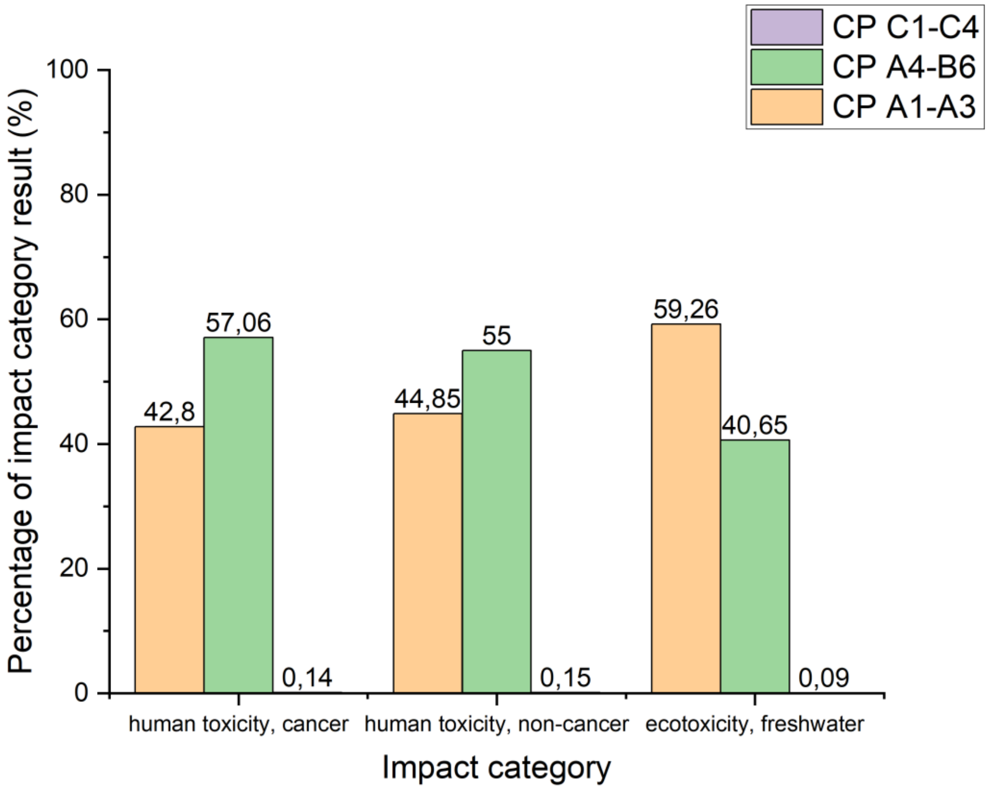


Figure 24. Toxicity impacts of glass fascia version of the control panel, shown as percentage of impact category by module.

For both versions of the control panel, 85% of the *resource use, minerals and metals* category impact come mostly from the A1-A3 modules and 15% from the energy consumption in B6 module. In total, the resource use result is 1.4 g Sb eq., slightly more than the result for the sensors. D module impact reduction potential is 36 mg Sb eq.

6.1.6 Lighting control systems

The impact results of the lighting systems with and without sensors are presented in Annex 3 in Table A3.7 and A3.8 for the lighting system with the area sensor and Tables A3.9 and A3.10**.** The comparisons of conventional lighting and sensor-aided lighting is shown in Figure 25, Figure 26, Figure 27, and Figure 28.

Figure 25, showing the comparison for the area sensor in the German grid and conventional lighting system without the area sensor in the German grid, indicates that the area sensor has no significant burden in the lighting system, and that the environmental burdens of the lighting system are reduced mostly in relation to the energy consumption of the lighting system. Figure 26, which shows the comparison of the area sensor to a conventional lighting system without the sensor in the Icelandic grid, shows that the composition of the grid has an effect on the environmental benefits. The environmental impacts are not reduced as much as in the German grid, and in some impact categories the difference between conventional lighting system and a lighting system with the area sensor is only 10–15%.

It is shown in Figure 27 that as the lighting system’s environmental impacts decrease mostly in proportion to the energy savings achieved with the self-learning sensor in the German grid. The same observation can be made from Figure 28 as was made from Figure 26: the environmental impacts do not decrease uniformly in relation to the energy saving in the Icelandic grid and decrease significantly less in certain categories.

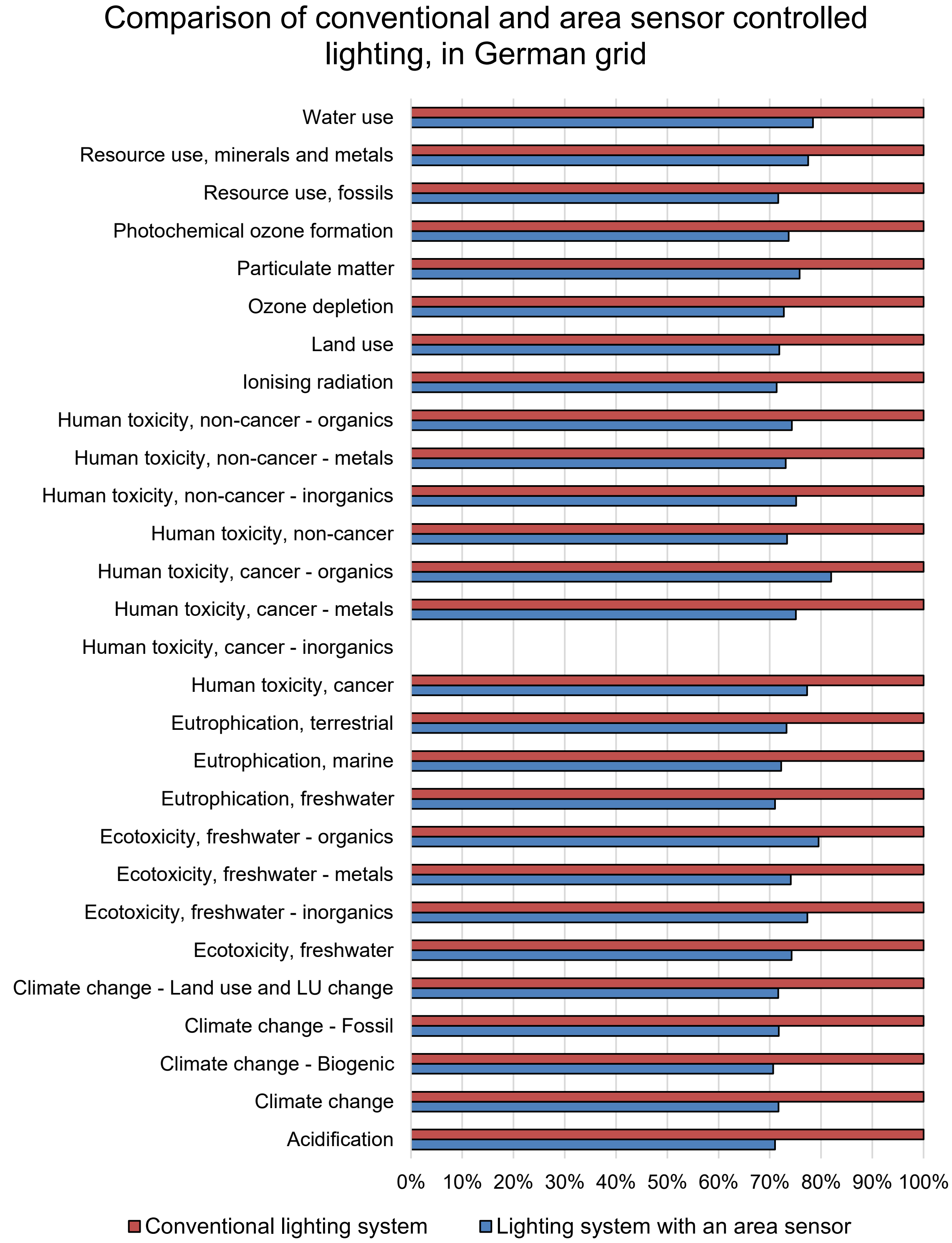


Figure 25. Comparison of the environmental impacts of the conventional lighting system and the lighting system with the area sensor, for 15 years of use in the German grid. The environmental impacts shown are relative to each other, highest results in the impact category being set 100%.

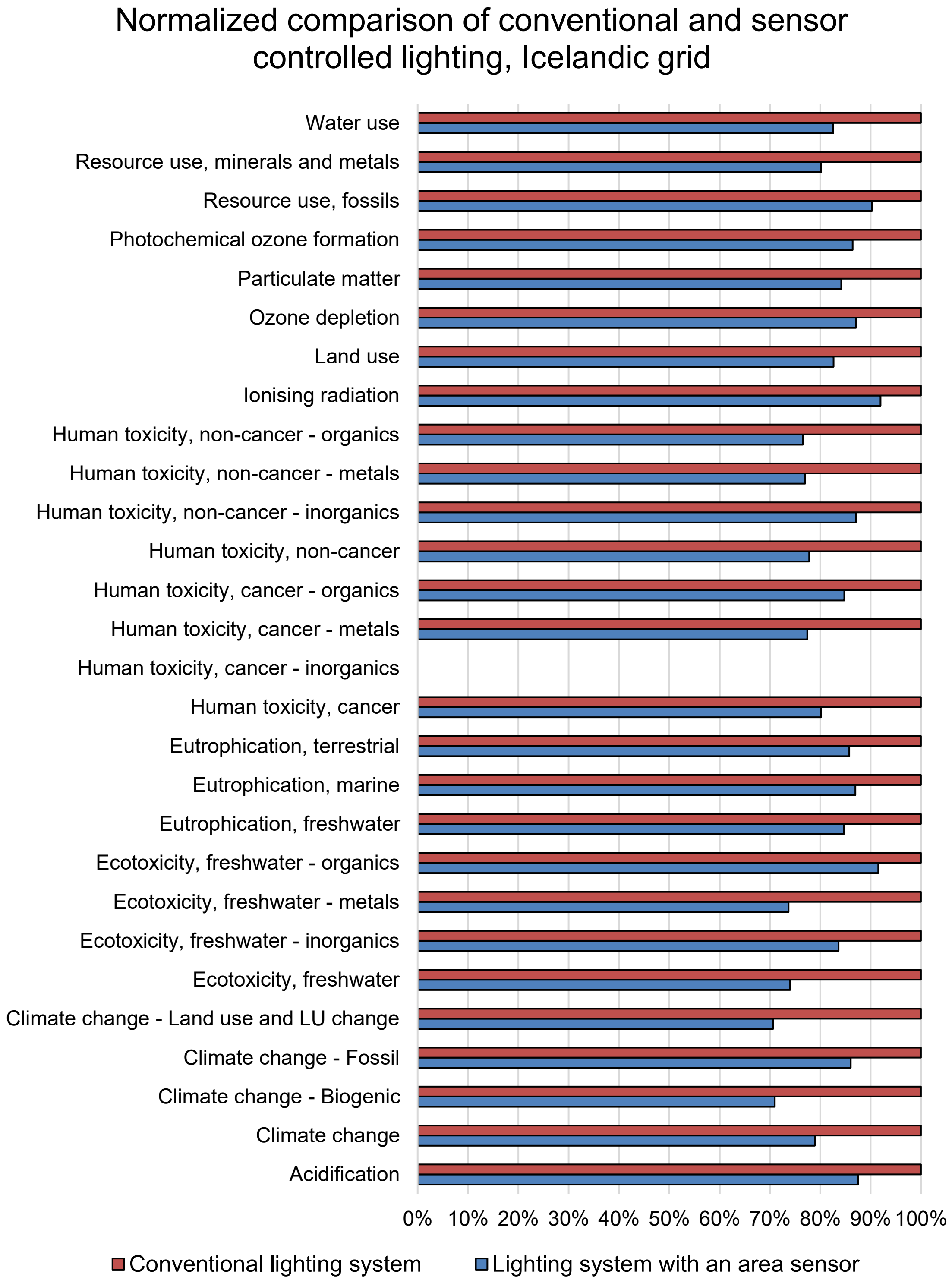


Figure 26. Comparison of the environmental impacts of the conventional lighting system and the lighting system with the area sensor, for 15 years of use in the German grid. The environmental impacts shown are relative to each other, highest results in the impact category being set 100%.

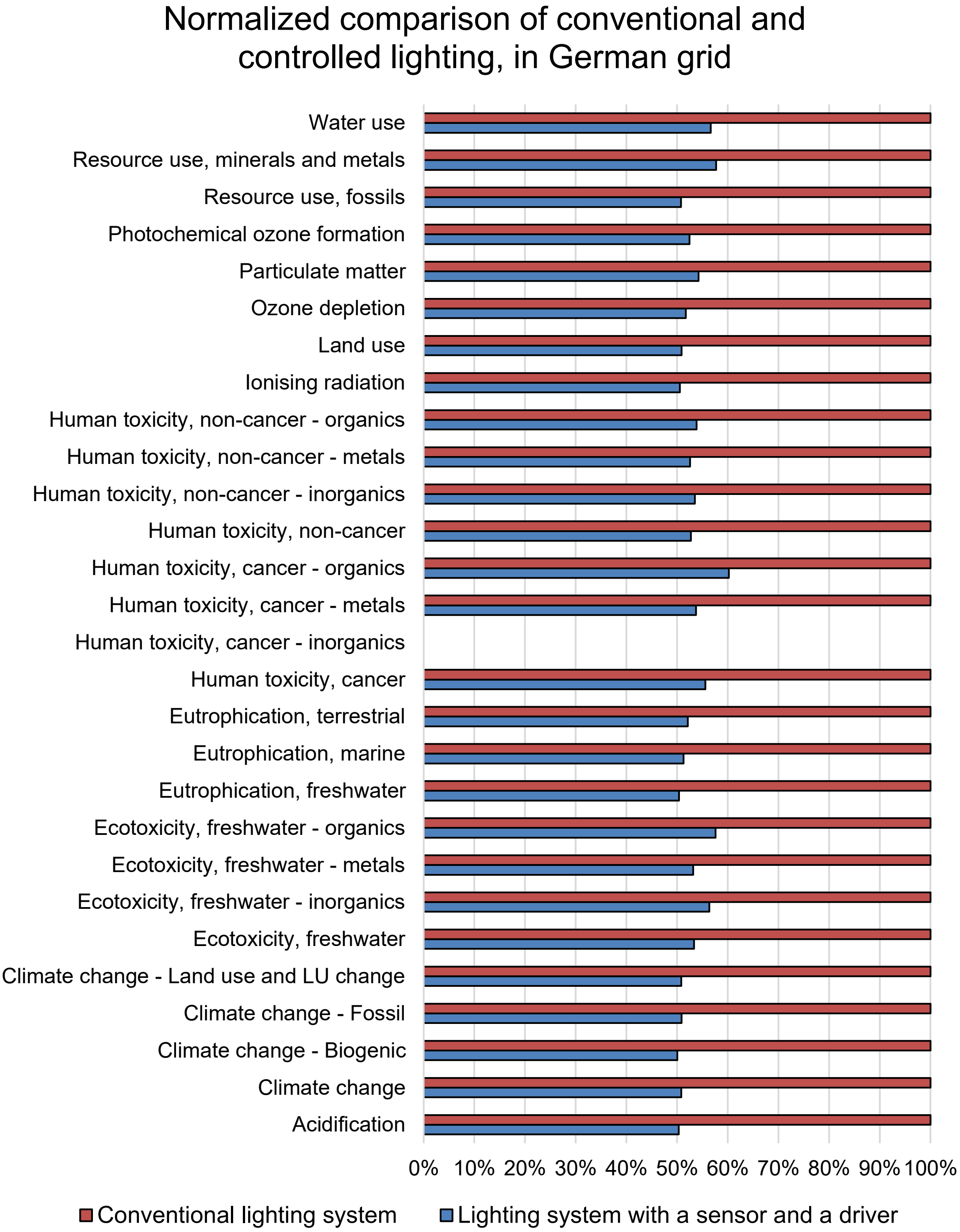


Figure 27. Comparison of the environmental impacts of the conventional lighting system and the lighting system with the self-learning sensor, for 15 years of use in the German grid. The environmental impacts shown are relative to each other, highest results in the impact category being set 100%.

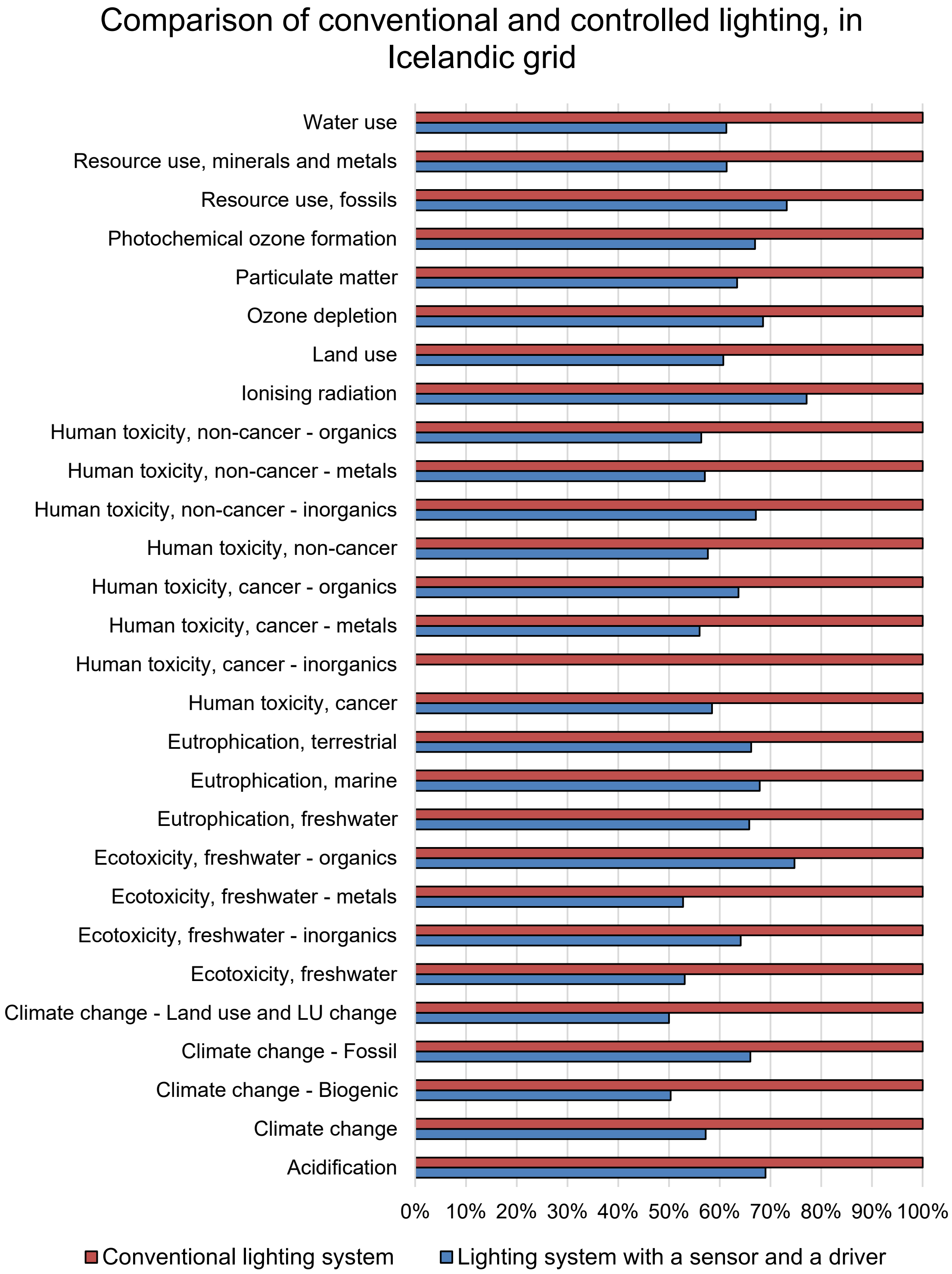


Figure 28. Comparison of the environmental impacts of the conventional lighting system and the lighting system with the self-learning sensor, for 15 years of use in the German grid. The environmental impacts shown are relative to each other, highest results in the impact category being set 100%.

6.2 Consistency and quality

The study is consistent with the goal and scope, as it provides information about the environmental impacts and helps to understand where improvements need to be made. It has increased the consciousness of the environmental impacts and the study can be utilized in EPD creation. Valuable information about the environmental performance in lighting systems was obtained as well. The results provide insight into the environmental impacts of the products and can be used to pinpoint improvement points. The study was conducted according to ISO 14040, ISO 14044, ISO-EN 15804, and IBU PRC standards. The data quality of processes stayed mostly consistent for all products. Generic data was from Ecoinvent 3.8, and it should be noted that this data was collected mostly in mid-2000's and it is possibly not very accurate for the electronic components of today. There can be significant variations between electronic components that cannot be accounted for with datasets available in ecoinvent, that are based on average data and assumptions of typical components. This may reduce the accuracy of the results.

There are two products with exceptions in data consistency and quality: the control panel and the self-learning sensor. For the control panel, the screen-printing process had a significantly lower data quality than other processes, as it was strongly based on assumptions and available literature data. The self-learning sensor had more accurate manufacturing data than the rest of the products, as the factory was company's own, and data of the total electricity consumption and composition was available. For other products, only the electricity consumption of the mounting dataset was considered since no factory data was available. All benefits after the EoW were allocated to a separate module, and only the distinguishable metal fractions were considered recovered. Regional data was used for whenever possible, most importantly for market datasets, electricity consumption and waste processing. Otherwise, global or Rest of World (average global production) geographies were used. A data quality assessment compiled according to EN 15804 is shown in Table 11.

Table 11. Data quality analysis according to the requirements and categorisation from Annex E of EN 15804.

Description of datasets	**Geographical representativeness**	**Technical representativeness**	**Time representativeness**
Electronic components	Fair	Good	Poor
Plastic components	Good	Very good	Very poor
Packaging materials	Good	Good	Very poor
Mounting process	Fair	Good	Very poor
Transportation	Fair	Fair	Fair
Energy consumption	Very good	Very good	Good
Waste treatment	Poor	Good	Good
Disposal	Very good	Fair	Good

Comparisons with other studies were also made to evaluate the reliability of results. Pirson and Bol (2021) have calculated cradle-to-gate footprints for different types of IoT devices and reported the carbon footprint to be around 1.4 kg CO_2 eq. (0.6 to 3.2 kg CO_2 eq.) for an occupancy sensor. Another reported finding was that IC components and the PCB are most significant contributors, especially for heavier hardware profiles. (Pirson and Bol 2021) The same conclusion was drawn for this assessment as well. The area and self-learning sensors' carbon footprints for cradle-to-gate, 2.5 and 2.7 kg CO_2 eq., fall into the same range as the Pirson and Bol (2021) results.

The PIR sensing component was a significant contributor in the carbon footprints of the sensors due to its high weight. Most of the IC component weights were available from the manufacturers or distributors, but the PIR component weight had to be estimated using expert knowledge and other corresponding components. The weight of the IC component is 1.01 grams, but the metal can around it has most of the weight. The composition of the PIR component differs from the *integrated circuit, logic type* dataset's composition, and assigning the total weight of the PIR component to the dataset could have resulted in overestimating the amount of the silicon die, which is a significant contributor in the dataset. However, due to unavailability of sufficient information, more accurate modelling was not possible. To determine whether uncertainties in the IC component weights are significant for the sensor carbon footprint results, sensitivity analysis was conducted for the IC components of the area sensor. The sensitivity analysis is shown in

Table 12 and Table 13. Carbon footprint is shortened as CFP. Other sensitivity analyses were not deemed necessary.

Table 12. Sensitivity analysis of the IC components in the area sensor.

Electronic components	**IC, logic type**	**Other components**	**Total PCB**
Base case, g	1.0712	12.175	13.246
Altered assumption, g	1.339	12.175	13.514
Altered assumption, g	0.803	12.175	12.978
Deviation, g	0.268	0	0.268
Deviation, %	±25	0	±2
Sensitivity, %	25	0	2

Table 13. Sensitivity analysis of the IC components in the area sensor, calculated using IPCC 2013 Global Warming Potential over 100 years method.

Electronic components	**IC, logic type**	**Other components**	**Total PCB**
Base case, CFP [kg CO_2 eq.]	1.699	0.411	2.11
CFP [kg CO_2 eq.], with 25% increase in IC, logic type mass	2.110	0.411	2.521
CFP [kg CO_2 eq.], with 25% decrease in IC, logic type mass	1.288	0.411	1.699
Deviation, %	±25	0	±19
Sensitivity, %	±25	0	±19

Although the change in the total mass of the electronic components is not significant, the change in the PCB carbon footprint is. The sensitivity in the cradle-to-gate footprint is significant and should be considered. The inaccuracy is not significant for the total carbon footprint of the lifecycle. This is because the use stage has such an overwhelming impact. The uncertainty of the IC components in cradle-to-gate footprint can be deemed significant. It should be noted that the actual carbon footprint of the area and self-learning sensors was likely somewhat smaller than the calculated result, cradle-to-gate footprint being closer to the result gained by Pirson and Bol (2021).

7 DISCUSSION

7.1 Achieving low-carbon products

Considering the planetary boundaries, the safe operating space has been exceeded for the climate change, and reduction of greenhouse gas emissions is crucial for minimizing its risks. Design for Sustainability strategies can be utilized to achieve needed reductions and to explore new opportunities in design and business model. The LCA done in this study gave valuable insight into the environmental impacts of the lighting control products and helped to pinpoint the most relevant areas to focus on. The results very clearly demonstrate that most of the carbon footprints come from the modules A1 and B6. The burden of the use stage comes solely from the electricity consumption during the product's lifetime and is heavily dependent on the electricity market. The assumed lifespan of the products was also considerably high. Although the use stage has a significant burden, these products function as electricity saving devices in lighting systems and ultimately save considerably more energy than they consume. In this sense, it is reasonable to focus on module A1 when reducing environmental impacts.

7.1.1 Materials and manufacturing

The Design for Sustainability guidelines for materials encourage the use of renewable, recyclable, recycled and low-impact materials, and that should prove to be an effective strategy for reducing the carbon footprint. Recycled materials have a lot of potential for reducing the footprint, as they enter the product system without the "burden of production" from the earlier lifecycle per the polluter pays -principle, meaning that only burdens after the EoW status are associated with it. These guidelines can arguably be applied on plastic parts or packaging materials, where the decision over the material can be made by the manufacturer.

A challenge appears with the electronic components used in the products, which contribute most to the carbon footprint when the use stage is excluded. The product manufacturer has a limited number of options for choosing between electronic components, and sufficient sustainability data is often not available to enable comparison. As component-by-component evaluation is not yet possible, it's recommended that the component suppliers would be evaluated by overall sustainability, including environmental, social and economic aspects and overall governance, and those committed to sustainability would be preferred. Arguably, the best way for the product manufacturer to lower the carbon footprint of the electronic components is to optimize the hardware to produce maximal value from the least number of resources. This means, for example, minimizing the number of electronic components used and replacing hardware with software.

Product-service system innovations could contain a lot of potential for reducing carbon footprint as they tend to prolong the product lifetime and incentivise reuse and remanufacture, as established by Vezzoli et al. (2014). It is highly recommended that all three types of PSS innovations are explored by the manufacturer. PSS innovations are also closely linked to the circular economy business models, which are mentioned in the roadmaps made by Teknologiateollisuus (2020; 2021).

For the manufacturer's own production operations, mainly the mounting and assembly of the products, electricity consumption and material efficiency are the key. Since electricity is the biggest contributor for the carbon footprint of the mounting process, it is recommended that the purchased electricity is composed of renewable and clean energy sources. To improve material efficiency, all waste from production should be minimized.

7.1.2 Use and End-of-Life

At the use stage, the lighting components function as electricity saving devices and compensate for their own carbon footprint. When energy consumption can be regarded as compensated, relevant issues are the product lifetime and how the value of the product can be retained. Reusability and repairability of the products and reuse of the components have positive benefits that could reduce product footprints. Circular economy thinking and DfS principles combined could enable more efficient use and thus maximize the value derived with the same carbon footprint.

EOL stage has a significant impact, especially for the disposal in C4 module. Most of the product mass was assigned to disposal, and a rather small part could be identified and assigned to be recycled. While the EOL stage is modelled after generic data and is based on assumptions, it is important to realise that decisions made in the design of the product have a major impact to the end of life. To enable efficient recovery of materials (and thus reduce need for disposal), design should consider how the product can be easily and safely disassembled and materials separated. From the DfS point of view, the PCB should be easily removable from the plastic parts. The plastic parts should be recyclable, and adhesives should be eliminated from the products. To enable better EOL for the products, circular economy design principles can be utilised as well.

7.2 Other sustainability issues of the products

Similar observations can be made for environmental impacts as were made for the GHG emissions. Most environmental burdens originate from the manufacturing of components and use. Arguably, toxicity and resource use should be considered as impacts that should be swiftly mitigated. Chemical pollution, which causes the toxicity impacts, has already exceeded the planetary boundary for safe operating space and should be viewed as a serious threat to the human health and the state of natural environment. The state of resources on the other hand is important for the industry, as electronics are highly dependent on many types of metals and materials, many classified as critical raw materials. Material efficiency and recovery is crucial to avoid material shortages. Focusing on resource efficiency and strategies to keep the critical materials circulating is also important for sustainability, as they are needed for the technology that enables e.g., fossil-free energy. And whilst planetary boundaries and ensuring availability of resources themselves make a strong argument why products need to become more sustainable, a more specific reasoning can also be argued through the functioning of the products. As energy saving devices, lighting control components can significantly reduce all environmental impacts of lighting in current electricity grids, almost in relation to the energy savings. However, as was seen in the comparisons of the lighting control systems in this study, the environmental benefits of lighting control components are significantly reduced in an electricity grid with fossil-free composition. Although the environmental impacts of the sensors are somewhat overestimated, it can be argued that the environmental performance of the components are more pronounced in fossil-free lighting systems and should be considered. Maintaining the environmental benefits during and after the global energy transition at the same level is only possible if the environmental impacts of lighting control components are decreased.

Arguably, the best way to minimize the environmental impacts is to minimize and avoid activities can cause them. In this case, it would mean manufacturing long-lasting products that can be reused, repurposed, refurbished or recycled efficiently at their EOL. Low-impact, clean and save materials are utilized, and the use of the products is efficiently optimized through PSS innovations and circular economy principles. For example, delivery of lighting control services instead of lighting control products could be a viable way to avoid environmental impacts, as long-lasting products could be provided as a service multiple times in multiple locations, instead of manufacturing a new product for each location and generating unnecessary waste. This way, intensive manufacturing processes and environmental impacts can be avoided while the same amount of value can be provided to customers, and recycling at the EOL stage is guaranteed.

Product-wise, this means that the manufacturer should address the material content of the components and the environmental management of supplier companies in addition to their own. Although regulations exist that limit the hazardous chemical content in the products, the production processes can also involve use and release of harmful chemicals. A recommendation would be that suppliers with certified environmental management systems and transparent environmental policies are preferred. When enough data is available to assess the sustainability of the components, it is recommended to switch to a component-based decision making.

When the EOL stage is achieved, the materials and value should be recovered to the highest degree. In addition to the recyclability, materials such as plastics should contain minimum amounts of additives to enable high-degree recycling. Circular economy principles offer multiple good strategies and guidelines to be used, and those are highly recommended. Since the products contain critical materials, such as cobalt or silicon, material recovery should be of high priority.

8 CONCLUSIONS

In this study, the carbon footprints of the lighting control products were successfully calculated, alongside the other environmental impacts. The operational carbon footprint can be regarded as compensated due to the energy savings that can be achieved with the products, and thus the product manufacturing and especially the electronic components should be the focus in decreasing the carbon footprint. Other environmental impacts are distributed similarly to the carbon footprint, and similar conclusion can be made. The environmental impacts are significant when inspected in lighting systems that operated in a renewable energy grid, and the comparisons made between lighting systems with and without sensors showed that the environmental benefits decreased. This should further incentivise lighting control manufacturers to consider the products' environmental performance.

Design for Sustainability strategies were identified as useful for decreasing the environmental impacts. Lower environmental footprints can be achieved by tackling the environmental impacts of manufacturing through more environmentally conscious material and component selection, minimalization and replacement of hardware with software, and use of renewable energy. Since electronic components are the biggest contributor, the main challenge the product manufacturer has to face is the supplier and component selection. Sustainability data can be scarcely available on component basis, and the product manufacturer has little to no control over the material content of the components. It is recommended that at least the material suppliers are evaluated and those with better environmental performance are preferred. If available, component-based evaluations should be conducted. This could also incentivise some EC manufacturers to consider their environmental issues. For other components such as the plastic parts or packaging materials, use of recycled, recyclable, and renewable materials are encouraged.

While focusing on electronic components and materials used in products can be effective, product-service system innovations were recognized as having even higher potential for sustainability. The high potential is based on the idea of providing the same or more functions to the same number of customers with less resources needed, which can mean adding services to the purchase of the products or even considering lighting as a service instead of a product. This potential can be achieved, for example, through circular economy-based principles and business models. Although switching to a new business model or creating circular economy products is not a simple task, it can be argued that due to the scarcity of future raw materials and the urgent need to lower the industry’s carbon footprint the transition to product-service systems is inevitable. Thus, companies could gain competitive advantage from adopting circular economy and sustainability principles early on.

BIBLIOGRAPHY

3M. (2017). 3M™ Adhesive Transfer Tape 468MP. A product datasheet. Acquired from manufacturer.

AFRY Finland Oy. (2022). Valaisinteollisuuden vähähiilisyystiekartta. Loppuraportti 23.2.2022.

Apollo Colours Limited. (2022). Information. A product datasheet. Acquired from manufacturer.

Canal Marques, A., Cabrera, J. & de Fraga Malfatti, C. (2013). Printed circuit boards: A review on the perspective of sustainability. Journal of environmental management, 131, 298-306. https://doi.org/10.1016/j.jenvman.2013.10.003

Chagnes, A., Cote, G., Ekberg, C., Nilsson, M. & Retegan, T. (2016). WEEE Recycling: Research, Development, and Policies. ISBN 978-012803364-7. Available: https://research.chalmers.se/publication/249861

Ceschin F., Gaziulusoy I. (2020). Design for Sustainability. A Multi-level Framework from Product to Socio-technical Systems. Routledge. Available: www.taylorfrancis.com ISBN: 978-1-138-31516-7 (hbk).

Choi, B., Shin, H., Lee, S. & Hur, T. (2006). Life Cycle Assessment of a Personal Computer and its Effective Recycling Rate (7 pp). The international journal of life cycle assessment, 11(2), 122-128. https://doi.org/10.1065/lca2004.12.196

Choudhury, A. K. (2014). Principles of Colour and Appearance Measurement. Woodhead Publishing. pp. 1-52. Available: https://www.sciencedirect.com/science/article/pii/B9780857092298500012

Council Regulation (EU) No 333/2011 of 31 March 2011 establishing criteria determining when certain types of scrap metal cease to be waste under Directive 2008/98/EC of the European Parliament and of the Council. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705 [Accessed 8.8.2022]

Deloitte Sustainability. (2016). Circular economy potential for climate change mitigation. pp. 42. Available: https://www2.deloitte.com/content/dam/Deloitte/fi/Documents/risk/Deloitte%20-%20Circular%20economy%20and%20Global%20Warming.pdf [Accessed 20.7.2022]

Dilouie, C. (2017). Introduction to Lighting Control. Lighting Controls Association, a Council of the National Electrical Manufacturers Association. Available: https://lightingcontrolsassociation.org/2017/07/21/introduction-to-lighting-controls/ [accessed 30.8.2022]

Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02008L0098-20180705 [Accessed 8.9.2022]

Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE). Available: http://data.europa.eu/eli/dir/2012/19/2018-07-04 [Accessed 8.9.2022]

EeBGuide Project. (2012). C-05 Transport of wastes to landfill, incineration and recycling facilities - screening and simplified LCA. Available: https://www.eebguide.eu/eebblog/?p=1636 [accessed 28.3.2022]

Engeco Pte Ltd. (2021). Mining Energy Consumption 2021. Commissioned by Weir. Available: https://info.global.weir/Enduron_HPGR [Accessed 7.9.2022]

Ercan M., Malmodin, J., Bergmark, P., Kimfalk, E., & Nilsson, E. (2016). Life cycle assessment of a smartphone. In Proceedings of ICT for Sustainability 2016 (pp. 124–133). Atlantis Press.

European Commission 2022a. EU taxonomy for sustainable activities. Available: https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en [accessed 26.1.2022]

European Commission 2022b. EU Taxonomy Compass. Available: https://ec.europa.eu/sustainable-finance-taxonomy/tool/index_en.htm [accessed 26.1.2022]

European Commission 2022c. Corporate Sustainability Reporting. Available: https://ec.europa.eu/info/business-economy-euro/company-reporting-and-auditing/company-reporting/corporate-sustainability-reporting_en [accessed 26.1.2022]

European Commission 2020d. Questions and Answers: Corporate Sustainability Reporting Directive proposal. Available: https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_1806 [accessed 20.6.2022]

European Environment Agency (2013). Environmental Pressures from European consumption and production. ISBN978-92-9213-351-1. Available: https://www.eea.europa.eu/publications/environmental-pressures-from-european-consumption [Accessed 9.9.2022]

European Financial Reporting Advisory Group. 2021. Proposals for a relevant and dynamic EU sustainability reporting standard-setting. Available: https://ec.europa.eu/info/sites/default/files/business_economy_euro/banking_and_finance/documents/210308-report-efrag-sustainability-reporting-standard-setting_en.pdf [accessed 23.6.2022]

European Parliament 2021. Legislative Train Schedule. A European Green Deal. Available: https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-european-green-deal [accessed 26.1.2022]

European Printing Association 2013. Environmental impact of printing inks. Available: https://www.eupia.org/key-topics/sustainability [accessed 14.3.2022]

European Printing Association. 2020. Eco Footprint of a generic reference. Available: https://www.eupia.org/key-topics/sustainability [accessed 14.3.2022]

Eurostat. 2022. Packaging waste statistics. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Packaging_waste_statistics&oldid=559603#Recycling_and_recovery_targets_and_rates [accessed 13.7.2022]

Finnish Standards Association SFS 20.9.2010. SFS-EN ISO 14025:2010. Environmental labels and declarations. Type III environmental declarations. Principles and procedures.

Finnish Standards Association SFS 16.10.2020. SFS-EN ISO 14040:2006 + A1:2020. Environmental management. Life cycle assessment. Principles and framework (ISO 14040:2006). 3rd edition.

Finnish Standards Association SFS 16.2.2018. SFS-EN ISO 14044:2006 +A1:2018. Environmental management. Life cycle assessment. Requirements and guidelines.

Finnish Standards Association SFS 8.11.2019. SFS-EN 15804:2012 +A2:2019. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products. 3rd edition.

Guterres A. (2021). Opening remarks at press encounter on the Appointment of the Secretary-General of the United Nations to a Second Term of Office. United Nations. Available: https://www.un.org/sg/en/content/sg/speeches/2021-06-18/press-remarks-appointment-of-secretary-general-of-un-second-term-of-office [accessed 30.8.2022]

Hlavatska L., Ischenko V., Pohrebennyk V., Salamon I. (2021) Material Flow Analysis of Waste Electrical and Electronic Equipment in Ukraine. Journal of Ecological Engineering 2021, 22 (9), 198-207. Doi: https://doi.org/10.12911/22998993/141571

Holgersson S., Steenari B., Björkman M., Cullbrand K. (2017) Analysis of the metal content of small-size Waste Electric and Electronic Equipment (WEEE) printed circuit boards - part 1: Internet routers, mobile phones and smartphones. Resources, Conservation and Recycling 133 (2018). pp. 300-308.

Institut Bauen und Umwelt e.V. (2021) Part A: Calculation Rules for the Life Cycle Assessment and Requirements on the Project Report. Version 2.1. Available: www.ibu-epd.com [Accessed 19.1.2022]

Institut Bauen und Umwelt e.V. (2017) Part B: Requirements on the EDP for Luminaires, lamps and components for luminaires. Available: www.ibu-epd.com [Accessed 24.3.2022]

International Energy Agency 2022a. Germany. Data browser. Available: https://www.iea.org/countries/germany [accessed 18.5.2022]

International Energy Agency 2022b. Iceland. Data browser. Available: https://www.eia.org/countries/iceland [accessed 18.5.2022]

Jolliet, O., Saade-Sbeih, M., Shaked, S., Jolliet, A. & Crettaz, P. (2016). Environmental life cycle assessment. CRC Press. pp. 332.

Klöpffer, W. (2012). The critical review of life cycle assessment studies according to ISO 14040 and 14044. The international journal of life cycle assessment, 17(9), 1087. https://doi.org/10.1007/s11367-012-0426-

Klöpffer, W. & Grahl, B. (2014). Life Cycle Assessment (LCA) - A Guide to Best Practice. Weinheim: Wiley-VCH Verlag GmbH & Co. pp. 396.

Králiková R, Lumnitzer E, Džuňová L, Yehorova A. Analysis of the Impact of Working Environment Factors on Employee's Health and Wellbeing; Workplace Lighting Design Evaluation and Improvement. Sustainability. 2021; 13(16):8816. https://doi.org/10.3390/su13168816

Kumar, T. & Mani, M. (2017). Life Cycle Assessment (LCA) to Assess Energy Neutrality in Occupancy Sensors. Doi: https://doi.org/10.1007/978^{-9}81^{-10}-3521-0_9

Maisel, F., Chancerel, P., Dimitrova, G., Emmerich, J., Nissen, N. F. & Schneider-Ramelow, M. (2020). Preparing WEEE plastics for recycling – How optimal particle sizes in pre-processing can improve the separation efficiency of high quality plastics. Resources, conservation and recycling, 154, 104619. Doi: https://doi.org/10.1016/j.resconrec.2019.104619

Metz, P., Burek, S., Hultgren, T. R., Kogan, S. & Schwartz, L. (2016). The Path to Sustainability-Driven Innovation: Environmental sustainability can be the foundation for increasing competitive advantage and the basis for effective innovation. Research technology management, 59(3), 50-61. Doi: https://doi.org/10.1080/08956308.2016.1161409

MMAtwo. (2019). Today’s challenge. Web page, available: https://www.mmatwo.eu/mmatwo-in-a-nutshell/todays-challenge/ [accessed 4.3.2022]

Motiva. 2022. Valaistus. Available: https://www.motiva.fi/julkinen_sektori/kiinteiston_energiankaytto/valaistus [accessed 8.9.2022]

Natgraph Limited. (2022). Air Force UV Combination Dryers. Available: http://hmantel.ch/pdf/5_Nat_AirforceUVCombinationDryers.pdf [accessed 9.8.2022]

Nuss P., Eckelman M. (2014). Life Cycle Assessment of Metals: A Scientific Synthesis. PLoS ONE 9(7): e101298. Doi: https://doi.org/10.1371/journal.pone.0101298

Pajula T., Vatanen S., Behm K., Grönman K., Lakanen L., Kasurinen H., Soukka R. (2021) Carbon handprint guide. V. 2.0. Applicable for environmental handprint. VTT Technical Research Centre of Finland Ltd.

Pirson T., Bol D. (2021). Assessing the embodied carbon footprint of IoT edge devices with a bottom-up lifecycle approach. Journal of Cleaner Production 322 (1), 128966. Doi: http://dx.doi.org/10.1016/j.jclepro.2021.128966

Regulation No 333/2011 of 31 March 2011 establishing criteria determining when certain types of scrap metal cease to be waste under Directive 2008/98/EC of the European Parliament and of the Council. Available: http://data.europa.eu/eli/reg/2011/333/oj [Accessed 14.9.2022]

Rockström, J., Steffen, W., Noone, K., Persson Å., Chapin III F., Lambin E., Lenton T., Scheffer M., Folke C., Schellnhuber H., Nykvist B., de Wit C., Hughes T., van der Leeuw S., Rodhe H., Sörlin S., Snyder P., Costanza R., Svedin U., Falkenmark M., Karlberg L. . Corell R., Fabry V., Hansen J., Walker B., Liverman D., Richardson K., Crutzen P., Foley J. (2009). A safe operating space for humanity. Nature 461, 472–475. Doi: https://doi.org/10.1038/461472a

Sakurai 2022. Maestro MF-80VII. Available: https://www.sakurai-gs.co.jp/en/products/screen/mf80v2.html [accessed 9.8.2022]

Sinopoli, J. (2010). Smart building systems for architects, owners, and builders. Elsevier/Butterworth-Heinemann. pp. 231. ISBN 978-1-85617-653-8

Skowranek, R. & Bielefeld, B. (2017). Basics Lighting Design. pp. 80. Birkhouser. ISBN 9783035609301.

Sousa P., Martelo L., Marques A., Bastos M., Soares H. (2022). A closed and zero-waste loop strategy to recycle the main raw materials (gold, copper and fiber glass layers) constitutive of waste printed circuit boards. Chemical Engineering Journal, 434, 134604. https://doi-org.pc124152.oulu.fi:9443/10.1016/j.cej.2022.134604

Stockholm Resilience Centre. (2022). Planetary boundaries. Stockholm University. Available: https://www.stockholmresilience.org/research/planetary-boundaries.html [accessed 13.5.2022]

The Lighting Industry Association (The LIA). (2018). Lighting Control Guide. Available: https://cdn.ymaws.com/www.thelia.org.uk/resource/resmgr/technical/guides/lia_lighting_control_guide_-.pdf [Accessed 12.2.2022]

Thiele L. (2016) Sustainability. John Wiley & Sons. Pp. 256. ISBN 1509511105, 9781509511105.

Teknologiateollisuus ry. (2020). Teknologiateollisuuden vähähiilitiekartta 2035. Available:https://teknologiateollisuus.fi/sites/default/files/inline-files/Teknologiateollisuuden-va%CC%88ha%CC%88hiilitiekartta-tiivistelm%C3%A4_2020-06-08_FINAL_0.pdf [Accessed 14.9.2022]

Teknologiateollisuus ry. (2021) Teknologiateollisuuden kiertotalousohjelma 2035. Available: https://teknologiateollisuus.fi/sites/default/files/inline-files/Teknologiateollisuuden%20kiertotalousohjelma%202035.pdf [Accessed 14.9.2022]

Tähkämö, L. (2013). Life cycle assessment of light sources - Case studies and review of the analyses. [Doctoral dissertation, Aalto University]. Aalto University publication series DOCTORAL DISSERTATIONS 111/2013. pp. 95. http://urn.fi/URN:ISBN:978-952-60-5250-2

United Nations. (2022). Sustainability. Available: https://www.un.org/en/academic-impact/sustainability [accessed 30.8.2022]

Van der Voet E, Salminen R, Eckelman M, Mudd G, Norgate T, et al. (2013). Environmental Risks and Challenges of Anthropogenic Metals Flows and Cycles. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. United Nations Environment Programme (UNEP). Available: https://www.resourcepanel.org/reports/environmental-risks-and-challenges-anthropogenic-metals-flows-and-cycles [Accessed 9.9.2022]

Van Hemel, C. G. (1998). EcoDesign Empirically Explored: Design for Environment in Dutch Small and Medium Sized Enterprises. Delft University of Technology. Delf, the Netherlands. pp. 271. Available: https://repository.tudelft.nl/islandora/object/uuid%3A75508637-dede-40f1-b232-85e12fcc4440

Vezzolini C., Kohtala C., Srinivasan A., with Diehl J. C., Fusakul S. M., Xin L., Sateesh D. (2014). Product-Service System Design for Sustainability. Greenleaf Publishing Limited. United Kingdom. pp. 502. Available: https://www.researchgate.net/publication/260831608_Product-Service_System_Design_for_Sustainability

Villanueva Krzyzaniak A, Eder P. (2014) End-of-waste criteria for waste plastic for conversion. Technical proposals. EUR 26843. Luxembourg (Luxembourg): Publications Office of the European Union; 2014. JRC91637. pp. 251. doi: http://dx.doi.org/10.2791/13033

Walker, S., Giard, J. & Walker, H. L. (2013). The handbook of design for sustainability. Bloomsbury Education. Available in EBSCOhost Ebook Academic Collection. 528 p

Xu, L., Pan, Y., Yao, Y., Cai, D., Huang, Z. & Linder, N. (2017). Lighting energy efficiency in offices under different control strategies. Energy and buildings, 138, 127-139. https://doi.org/10.1016/j.enbuild.2016.12.006

Appendix 1. Impact categories, indicators, and characterisation models

Table A1. Impact categories, indicators, and characterisation models according to EN 15804 (Modified from SFS-EN ISO 15804:2012 + A2:2019 Table C1).

Impact category	Characterisation model	Indicator
Climate change - total	Baseline model of 100 years of the IPCC. based on IPCC 2013	Global Warming Potential (GWP) total
Climate change - fossil	Baseline model of 100 years of the IPCC, based on IPCC 2013	GWP fossil fuels
Climate change - biogenic	Baseline model of 100 years of the IPCC. based on IPCC 2013	GWP biogenic
Climate change - land use and land use change	Baseline model of 100 years of the IPCC, based on IPCC 2013	GWP land use and land use change
Ozone Depletion	Steady-state ODPs, WMO 2014	Depletion potential of the stratospheric ozone layer
Acidification	Accumulated Exceedance, Seppälä et al. 2006, Posch et al., 2008	Acidification potential, Accumulated Exceedance
Eutrophication aquatic freshwater	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe	Eutrophication potentialfraction of nutrients reaching freshwater end compartment
Eutrophication aquatic marine	EUTREND model, Struijs et al., 2009b, as implemented in ReCiPe	EP, fraction of nutrients reaching marine end compartment
Eutrophication terrestrial	Accumulated Exceedance, Seppälä et al. 2006, Posch et al.	EP, accumulated exceedance
Photochemical ozone formation	LOTOS-EUROS ,Van Zelm et al., 2008, as applied in ReCiPe	Formation potential of tropospheric ozone
Depletion of abiotic resources - minerals and metals	CML 2002, Guinée et al., 2002, and van Oers et al. 2002.	Abiotic depletion (AD) potential for non-fossil resources
Depletion of abiotic resources - fossil fuels	CML 2002, Guinée et al., 2002, and van Oers et al. 2002.	AD for fossil resources potential
Water use	Available WAter REmaining (AWARE) Boulay et al., 2016	Water (user) deprivation (depriv.) potential, deprivation-weighted water consumption

Appendix 2. Datasets used for the products

Table A2.1. Area sensor, datasets and amounts used.

Flow	**Amount**	**Unit**
capacitor, electrolyte type, > 2cm height	0.44	g
capacitor, for surface-mounting	$5.34\cdot10^{-2}$	g
diode, auxiliaries and energy use	0.152	g
electric connector, wire clamp	3.6	g
integrated circuit, logic type	1.064	g
integrated circuit, memory type	$4.80\cdot10^{-2}$	g
light emitting diode	0.15	g
printed wiring board, for surface mounting, Pb free surface	145	mm^2
resistor, surface-mounted	$1.40\cdot10^{-2}$	g
transformer, low voltage use	$6.40\cdot10^{-2}$	g
transistor, surface-mounted	$2.40\cdot10^{-2}$	g
connector (modelled separately from materials)	0.94	g
brass	0.51	g
Metal working, average for copper product manufacture	0.51	g
Injection moulding	0.43	g
Nylon 6-6	0.31	g
Polyethylene terephalate, granulate, amorphous	0.12	g
Plastic parts		
Acrylonitrile-butadiene-styrene copolymer production	15.20	g
Polycarbonate	18.97	g
Injection moulding	34.38	g
Packaging		
Corrugated board box	26.0	g
Packaging film, low density polyethylene	1.0	g
Paper, woodfree, uncoated	9.37	g
Ancillary materials		
Nylon 6-6	0.7	g
Steel, chromium steel 18/8	7.34	g
Metal working, average for steel product manufacturing	7.34	g
Injection moulding	0.7	g

Table A2.2. Router, datasets and amounts used.

Flow	**Amount**	**Unit**
capacitor, electrolyte type, < 2cm height	8.3	g
capacitor, for surface-mounting	40.20	g
diode, auxiliaries and energy use	1.86	g
electric component, passive, unspecified	10.0	g
integrated circuit, logic type	6.28	g
integrated circuit, memory type	0.62	g
Liquid crystal display, unmounted	11.0	g
printed wiring board, for surface mounting, Pb free surface	2574	mm^2
resistor, surface-mounted	2.25	g
transformer, low voltage use	10.9	g
transistor, surface-mounted	2.95	g
Silicon, electronic grade	2.61	g
Injection moulding	2.61	g
Electronic connector, peripheral interconnect bus	2.72	g
Electronic connector, wire clamp	4.4	g
Connectors, modelled separately from materials	57.64	g
Plastic parts		
Nylon 6	3.00	g
Nylon 6-6	3.00	g
Polycarbonate	155.20	g
Injection moulding	161.20	g
Packaging		
Corrugated board box	88.0	g
Paper, woodfree, uncoated	9.98	g

Table A2.3. Control panel, EC datasets and amounts used.

Flow	**Amount**	**Unit**
connector production (modelled from materials)	0.59	g
capacitor, electrolyte type, > 2cm height	3.0	g
capacitor, for surface-mounting	1.84	g
diode, auxilliaries and energy use	0.24	g
integrated circuit, logic type	1.03	g
integrated circuit, memory type	0.39	g
light emitting diode	2.44	g
printed wiring board, for surface mounting, Pb free surface	10893	mm^2
resistor, surface-mounted	$4.8 \cdot 10^{-2}$	g
transformer, low voltage use	0.14	g
transistor, surface-mounted	$1.4 \cdot 10^{-2}$	g
Plastic parts		
Acrylonitrile-butadiene-styrene copolymer	13.89	g
Polycarbonate	14.33	g
Polystyrene, high impact	9.91	g
Injection moulding	38.13	g
Fascia, plastic		
Polymethyl methacrylate, beads	17.58	g
Injection moudling	17.58	g
Ink, modelled from EUPIA	34.9	g
Methyl methacrylate	1.11	g
Fascia, glass	34.9	g
Flat glass	89.94	g
Ink, modelled from EUPIA	34.9	g
Methyl methacrylate	1.11	g
Packaging		
Corrugated board box	38.0	g
Packaging film, low density polyethylene	1.0	g
Paper, woodfree, uncoated	9.98	g
Ancillary/Fixing		
Nylon 6-6	0.51	g
Injection moulding	0.51	g
Steel, chromium steel 18/8	1.98	g
Metal working, average for steel product manufacture	1.98	g

Table A2.4. Self-learning sensor, EC datasets and amounts used

Flow	**Amount**	**Unit**
cable, unspecified	21.85	g
capacitor, for surface-mounting	$3.15\cdot10^{-2}$	g
integrated circuit, logic type	1.24	g
integrated circuit, memory type	0.43	g
light emitting diode	$1.38\cdot10^{-3}$	g
printed wiring board, for surface mounting, Pb free surface	456	mm^2
resistor, surface-mounted	$1.53\cdot10^{-3}$	g
transformer, low voltage use	0.018	g
transistor, surface-mounted	$7.10\cdot10^{-4}$	g
Connectors, modelled separately from materials	0.29	g
Plastic parts		
Polycarbonate	3.87	g
Injection moulding	3.87	g
Packaging		
Corrugated board box	1.6	g
Packaging film, low density polyethylene	$2.4\cdot10^{-6}$	g
Paper, woodfree, uncoated	1	g

Table A2.5. Components of the driver

Dataset	**Amount**	
capacitor, electrolyte type, < 2cm height	6.4	g
capacitor, film type, for through-hole mounting	12.6	g
capacitor, for surface-mounting	1.2	g
diode, auxilliaries and energy use	0.92	g
integrated circuit, logic type	0.35	g
integrated circuit, memory type	0.19	g
printed wiring board, for surface mounting, Pb free surface	7168	mm^2
resistor, surface-mounted	1.36	g
silicon, electronics grade	4.4	g
transformer, low voltage use	67.7	g
transistor, surface-mounted	1.3	g
Connector		
nylon 6-6	2.91	g
injection moulding	2.91	g
copper, cathode	1.07	g
metal working, average for copper product manufacturing	1.07	g
Casing		
deep drawing, steel, 650 kN press, automode	183	g
sheet rolling, steel	183	g
steel, unalloyed	183	g
zinc coat, pieces	0.02247	pieces
Flow	**Amount**	
corrugated board box	0.5	g
EUR-flat pallet	0.00033	Item
packaging film, low density polyethylene	0.21	g

Table A2.6. Transportation of the LED driver.

Transportation to the factory	**km**	**Other**
Lorry, 16-32 t, EURO5	197	60% of ECs
Lorry, 16-32 t, EURO5	200	40% of ECs
Container ship	19576	60% of ECs
Container ship	7802	40% of ECs
Transportation to the luminaire manufacturer (customer)		
Lorry, 16-32 t, EURO5	480	km
Container ship	2100	km
Transportation to waste treatment		
Lorry, 16-32 t, EURO5	250	km

Table A2.7. Datasets for the luminaire (AFRY Finland Oy 2022, Tähkämö 2013)

Metal parts	Amount	Unit
Steel, unalloyed	197	g
Sheet rolling, steel	3300	g
Aluminium, cast alloy	23.0	g
Metal working, average for aluminium product manufacturing	23.0	g
Plastic parts		
Acrylonitrile-butadiene-styrene copolymer	100.6	g
Polymethyl methacrylate, beads	201.2	g
Silicon, electronics grade	4.4	g
Polycarbonate	100.6	g
Injection moudling	493.1	g
Electronics		
LED Driver	1	Piece
Light emitting diode	28.0	g
Transportation to the end-user		
Lorry, 16-32 t, EURO5	419	kg·km
Transportation to the waste treatment		
Lorry, 16-23 t, EURO5	925	Kg·km
Waste treatment		
Iron scrap, sorted, pressed	3.3	kg
Waste electric and electronic equipment	3.7	Kg
Waste plastic, mixture	0.4	Kg

Appendix 3. Impact results

Table A3.1. Impact assessment results for the area sensor, with and without module D.

Name of the impact category	*Impact result, without D*	*Impact results, with D extracted*	*Unit*
Acidification	0.80	0.79	mol H+ eq.
Climate change	18.76	18.67	kg CO_2 eq.
• *Climate change - Biogenic*	1.24	1.24	kg CO_2 eq
• *Climate change - Fossil*	17.50	17.40	kg CO_2 eq.
• *Climate change - Land use and LU change*	0.02	0.02	kg CO_2 eq.
Ecotoxicity, freshwater	365.15	302.79	CTUe
• *Ecotoxicity, freshwater - inorganics*	38.49	34.81	CTUe
• *Ecotoxicity, freshwater - metals*	327.54	268.85	CTUe
• *Ecotoxicity, freshwater - organics*	1.07	1.05	CTUe
Eutrophication, freshwater	0.03	0.02	kg P eq.
Eutrophication, marine	0.01	0.01	kg N eq.
Eutrophication, terrestrial	0.01	0.01	mol N eq.
Human toxicity, cancer	$7.82\cdot10^{-9}$	$6.41\cdot10^{-9}$	CTUh
• *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
• *Human toxicity, cancer - metals*	$6.15\cdot10^{-9}$	$4.76\cdot10^{-9}$	CTUh
• *Human toxicity, cancer - organics*	$1.68\cdot10^{-9}$	$1.65\cdot10^{-9}$	CTUh
Human toxicity, non-cancer	$2.79\cdot10^{-7}$	$1.74\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$2.40\cdot10^{-8}$	$2.35\cdot10^{-8}$	CTUh
• *Human toxicity, non-cancer - metals*	$2.49\cdot10^{-7}$	$1.50\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - organics*	$6.79\cdot10^{-9}$	$1.77\cdot10^{-9}$	CTUh
Ionising radiation	3.03	3.02	kBq U-235 eq.
Land use	51.24	51.84	Production per unit of time (Pt)
Ozone depletion	$6.20\cdot10^{-7}$	$6.15\cdot10^{-7}$	kg CFC11 eq.
Particulate matter	$2.86\cdot10^{-7}$	$2.69\cdot10^{-7}$	disease inc.
Photochemical ozone formation	0.03	0.03	kg NMVOC eq.
Resource use, fossils	237.41	236.28	MJ
Resource use, minerals and metals	$9.90\cdot10^{-4}$	$8.00\cdot10^{-4}$	kg Sb eq.
Water use	1.87	1.75	m^3 deprivation

Table A3.2. Impact results for router with and without module D.

Category name	*Impact result without D*	*Impact result with D*	*Unit*
Acidification	121.09	121.08	mol H+ eq.
Climate change	2598.58	2598.43	kg CO_2eq
• *Climate change - Biogenic*	199.83	199.83	kg CO_2eq.
• *Climate change - Fossil*	2395.46	2395.31	kg CO_2eq.
• *Climate change - Land use and LU change*	3.29	3.29	kg CO_2eq.
Ecotoxicity, freshwater	2.78E+04	2.77E+04	CTUe
• *Ecotoxicity, freshwater - inorganics*	1.53E+03	1.53E+03	CTUe
• *Ecotoxicity, freshwater - metals*	2.62E+04	2.62E+04	CTUe
• *Ecotoxicity, freshwater - organics*	95.18	95.15	CTUe
Eutrophication, freshwater	3.58	3.58	kg P eq
Eutrophication, marine	1.81	1.81	kg N eq..
Eutrophication, terrestrial	10.87	10.87	mol N eq.
Human toxicity, cancer	$7.98\cdot10^{-7}$	$7.96\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
• *Human toxicity, cancer - metals*	$5.98\cdot10^{-7}$	$5.96\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - organics*	$2.00\cdot10^{-7}$	$2.00\cdot10^{-7}$	CTUh
Human toxicity, non-cancer	$2.83\cdot10^{-5}$	$2.8\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$3.07\cdot10^{-6}$	$3.07\cdot10^{-6}$	CTUh
• *Human toxicity, non-cancer - metals*	$2.46\cdot10^{-5}$	$2.45\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - organics*	$8.23\cdot10^{-7}$	$8.18\cdot10^{-7}$	CTUh
Ionising radiation	441.31	441.29	kBq U-235 eq.
Land use	6614.73	6614.73	Pt
Ozone depletion	$6.70\cdot10^{-5}$	$6.70\cdot10^{-5}$	kg CFC11 eq.
Particulate matter	$2.62\cdot10^{-5}$	$2.62\cdot10^{-5}$	disease inc.
Photochemical ozone formation	3.38	3.38	kg NMVOC eq.
Resource use, fossils	$3.30\cdot10^{4}$	$3.30\cdot10^{4}$	MJ
Resource use, minerals and metals	0.03	0.03	kg Sb eq.
Water use	175.53	175.39	m3 depriv.

Table A3.3. Impact category results for Control panel, without module D.

Impact category	*Impact result, plastic fascia*	*Impact result, glass fascia*	*Unit*
Acidification	1.31	1.31	mol H+ eq.
Climate change	31.55	31.51	kg CO_2 eq.
• *Climate change - Biogenic*	2.03	2.04	kg CO_2 eq.
• *Climate change - Fossil*	29.47	29.43	kg CO_2 eq.
• *Climate change - Land use and LU change*	0.04	0.04	kg CO_2 eq.
Ecotoxicity, freshwater	602.26	603.76	CTUe
• *Ecotoxicity, freshwater - inorganics*	53.76	54.32	CTUe
• *Ecotoxicity, freshwater - metals*	549.63	550.57	CTUe
• *Ecotoxicity, freshwater - organics*	1.86	1.86	CTUe
Eutrophication, freshwater	0.04	0.04	kg P eq.
Eutrophication, marine	0.02	0.02	kg N eq.
Eutrophication, terrestrial	0.17	0.18	mol N eq.
Human toxicity, cancer	$1.33\cdot10^{-8}$	$1.33\cdot10^{-8}$	CTUh
• *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
• *Human toxicity, cancer - metals*	$9.65\cdot10^{-9}$	$9.65\cdot10^{-9}$	CTUh
• *Human toxicity, cancer - organics*	$3.66\cdot10^{-9}$	$3.67\cdot10^{-9}$	CTUh
Human toxicity, non-cancer	$4.86\cdot10^{-7}$	$4.87\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$4.43\cdot10^{-8}$	$4.43\cdot10^{-8}$	CTUh
• *Human toxicity, non-cancer - metals*	$4.31\cdot10^{-7}$	$4.32\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - organics*	$1.33\cdot10^{-8}$	$1.32\cdot10^{-8}$	CTUh
Ionising radiation	5.05	5.05	kBq U-235 eq.
Land use	83.84	84.21	Pt
Ozone depletion	$1.11\cdot10^{-6}$	$1.12\cdot10^{-6}$	kg CFC11 eq.
Particulate matter	$5.17\cdot10^{-7}$	$5.20\cdot10^{-7}$	disease inc.
Photochemical ozone formation	0.05	0.05	kg NMVOC eq.
Resource use, fossils	399.23	398.03	MJ
Resource use, minerals and metals	0.00	0.00	kg Sb eq.
Water use	3.55	3.56	m3 depriv.

Table A3.4. Impact results for Control panel with module D extracted.

Impact category	***Impact result, plastic fascia***	***Impact results, glass fascia***	***Unit***
Acidification	1.31	1.31	mol H+ eq.
Climate change	31.53	31.49	kg CO_2 eq.
• *Climate change - Biogenic*	2.03	2.04	kg CO_2 eq.
• *Climate change - Fossil*	29.45	29.41	kg CO_2 eq.
• *Climate change - Land use and LU change*	0.04	0.04	kg CO_2 eq.
Ecotoxicity, freshwater	590.49	591.99	CTUe
• *Ecotoxicity, freshwater - inorganics*	53.06	53.63	CTUe
• *Ecotoxicity, freshwater - metals*	538.55	539.49	CTUe
• *Ecotoxicity, freshwater - organics*	1.85	1.86	CTUe
Eutrophication, freshwater	0.04	0.04	kg P eq.
Eutrophication, marine	0.02	0.02	kg N eq.
Eutrophication, terrestrial	0.17	0.17	mol N eq.
Human toxicity, cancer	$1.30\cdot10^{-8}$	$1.31\cdot10^{-8}$	CTUh
• *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
• *Human toxicity, cancer - metals*	$9.39\cdot10^{-9}$	$9.39\cdot10^{-9}$	CTUh
• *Human toxicity, cancer - organics*	$3.66\cdot10^{-9}$	$3.67\cdot10^{-9}$	CTUh
Human toxicity, non-cancer	$4.67\cdot10^{-7}$	$4.67\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$4.42\cdot10^{-8}$	$4.43\cdot10^{-8}$	CTUh
• *Human toxicity, non-cancer - metals*	$4.13\cdot10^{-7}$	$4.13\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - organics*	$1.23\cdot10^{-8}$	$1.23\cdot10^{-8}$	CTUh
Ionising radiation	5.04	5.04	kBq U-235 eq.
Land use	83.96	84.32	Pt
Ozone depletion	$1.11\cdot10^{-6}$	$1.12\cdot10^{-6}$	kg CFC11 eq.
Particulate matter	$5.13\cdot10^{-7}$	$5.17\cdot10^{-7}$	disease inc.
Photochemical ozone formation	0.05	0.05	kg NMVOC eq.
Resource use, fossils	399.02	397.82	MJ
Resource use, minerals and metals	0.00	0.00	kg Sb eq.
Water use	3.53	3.53	m3 depriv.

Table A3.5. Self-learning sensor

Name	***Impact result, without D***	***Impact result, With D***	***Unit***
Acidification	0.19	0.19	mol H+ eq.
Climate change	5.66	5.65	kg CO_2 eq.
• *Climate change - Biogenic*	0.24	0.24	kg CO_2 eq.
• *Climate change - Fossil*	5.41	5.40	kg CO_2 eq.
• *Climate change - Land use and LU change*	0.01	0.01	kg CO_2 eq.
Ecotoxicity, freshwater	318.98	312.76	CTUe
• *Ecotoxicity, freshwater - inorganics*	37.27	36.90	CTUe
• *Ecotoxicity, freshwater - metals*	283.15	277.29	CTUe
• *Ecotoxicity, freshwater - organics*	0.50	0.50	CTUe
Eutrophication, freshwater	0.01	0.01	kg P eq.
Eutrophication, marine	0.01	0.01	kg N eq.
Eutrophication, terrestrial	0.05	0.05	mol N eq.
Human toxicity, cancer	$4.30\cdot10^{-9}$	$4.16\cdot10^{-9}$	CTUh
• *Human toxicity, cancer - inorganics*	0	0.00	CTUh
• *Human toxicity, cancer - metals*	$3.75\cdot10^{-9}$	$3.61\cdot10^{-9}$	CTUh
• *Human toxicity, cancer - organics*	$5.48\cdot10^{-10}$	$5.45\cdot10^{-10}$	CTUh
Human toxicity, non-cancer	$2.37\cdot10^{-7}$	$2.27\cdot10^{-7}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$7.83\cdot10^{-9}$	$7.78\cdot10^{-10}$	CTUh
• *Human toxicity, non-cancer - metals*	$2.23\cdot10^{-7}$	0.00	CTUh
• *Human toxicity, non-cancer - organics*	$7.24\cdot10^{-9}$	0.00	CTUh
Ionising radiation	0.84	0.84	kBq U-235 eq.
Land use	14.81	14.87	Pt
Ozone depletion	$3.32\cdot10^{-7}$	3.31E-07	kg CFC11 eq.
Particulate matter	$1.69\cdot10^{-7}$	1.67E-07	disease inc.
Photochemical ozone formation	0.01	0.01	kg NMVOC eq.
Resource use, fossils	71.79	71.68	MJ
Resource use, minerals and metals	0.00	0.00	kg Sb eq.
Water use	1.15	1.14	m3 depriv.

Table A3.6. LED Driver

Name	***Impact result, without D***	***Impact result, With D***	***Unit***
Acidification	112.69	112.69	mol H+ eq.
Climate change	2403.57	2403.47	kg CO_2 eq.
• *Climate change - Biogenic*	186.60	186.60	kg CO_2 eq.
• *Climate change - Fossil*	2213.93	2213.84	kg CO_2 eq.
• *Climate change - Land use and LU change*	3.03	3.03	kg CO_2 eq.
Ecotoxicity, freshwater	23241.00	23227.5	CTUe
• *Ecotoxicity, freshwater - inorganics*	1112.11	1111.39	CTUe
• *Ecotoxicity, freshwater - metals*	$2.21\cdot10^{4}$	$2.21\cdot10^{4}$	CTUe
• *Ecotoxicity, freshwater - organics*	8.41	8.41	CTUe
Eutrophication, freshwater	3.31	3.31	kg P eq
Eutrophication, marine	1.65	1.65	kg N eq
Eutrophication, terrestrial	9.76	9.75	mol N eq
Human toxicity, cancer	$7.19\cdot10^{-7}$	$7.19\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
• *Human toxicity, cancer - metals*	$5.39\cdot10^{-7}$	$5.38\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - organics*	$1.81\cdot10^{-7}$	$1.81\cdot10^{-7}$	CTUh
Human toxicity, non-cancer	$2.53\cdot10^{-5}$	$2.52\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$2.81\cdot10^{-6}$	$2.80\cdot10^{-6}$	CTUh
• *Human toxicity, non-cancer - metals*	$2.20\cdot10^{-5}$	$2.19\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - organics*	$6.65\cdot10^{-7}$	$6.64\cdot10^{-7}$	CTUh
Ionising radiation	409.47	409.47	kBq U-235 eq.
Land use	6089.85	6089.89	Pt
Ozone depletion	$6.08\cdot10^{-5}$	$6.08\cdot10^{-5}$	kg CFC11 eq.
Particulate matter	$2.31\cdot10^{-5}$	$2.31\cdot10^{-5}$	disease inc.
Photochemical ozone formation	3.04	3.04	kg NMVOC eq.
Resource use, fossils	$3.05\cdot10^{4}$	$3.05\cdot10^{4}$	MJ
Resource use, minerals and metals	0.02	0.02	kg Sb eq.
Water use	156.80	156.76	m3 depriv.

Table A3.7. Impact results for comparison of lighting systems with an area sensor in the German grid.

Indicator	***Lighting with area sensor***	***Conventional lighting***	***Unit***
Acidification	93.19	131.24	mol H+ eq.
Climate change	2050.58	2860.40	kg CO_2 eq..
• *Climate change - Biogenic*	151.80	214.90	kg CO_2 eq.
• *Climate change - Fossil*	1896.19	2641.89	kg CO_2 eq.
• *Climate change - Land use and LU change*	2.58	3.61	kg CO_2 eq.
Ecotoxicity, freshwater	22042.00	29683.40	CTUe
• *Ecotoxicity, freshwater - inorganics*	1200.62	1552.33	CTUe
• *Ecotoxicity, freshwater - metals*	20816.90	28095.20	CTUe
• *Ecotoxicity, freshwater - organics*	101.47	127.56	CTUe
Eutrophication, freshwater	2.74	3.86	kg P eq
Eutrophication, marine	1.44	2.00	kg N eq
Eutrophication, terrestrial	8.92	12.18	mol N eq
Human toxicity, cancer	8.05	1.04E-06	CTUh
• *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
• *Human toxicity, cancer - metals*	$5.33\cdot10^{-7}$	$7.10\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - organics*	$2.73\cdot10^{-7}$	$3.32\cdot10^{-7}$	CTUh
Human toxicity, non-cancer	$2.30\cdot10^{-5}$	$3.14\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$2.84\cdot10^{-6}$	$3.78\cdot10^{-6}$	CTUh
• *Human toxicity, non-cancer - metals*	$1.97\cdot10^{-5}$	$2.70\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - organics*	$6.29\cdot10^{-7}$	$8.47\cdot10^{-7}$	CTUh
Ionising radiation	343.47	481.63	kBq U-235 eq.
Land use	5228.22	7277.12	Pt
Ozone depletion	0.00	0.00	kg CFC11 eq.
Particulate matter	0.00	0.00	disease inc.
Photochemical ozone formation	2.84	3.86	kg NMVOC eq.
Resource use, fossils	26001.90	36284.90	MJ
Resource use, minerals and metals	0.02	0.03	kg Sb eq.
Water use	184.35	235.08	m3 depriv.

Table A3.8. Impact results for comparison of lighting systems with an area sensor in the Icelandic grid.

Indicator	***Lighting with area sensor***	***Conventional lighting***	***Unit***
Acidification	2.85	3.26	mol H+ eq
Climate change	298.40	378.04	kg CO_2 eq
- *Climate change - Biogenic*	20.69	29.15	kg CO_2 eq
- *Climate change - Fossil*	174.60	202.87	kg CO_2 eq
- *Climate change - Land use and LU change*	103.11	146.02	kg CO_2 eq
Ecotoxicity, freshwater	23355.90	31544.90	CTUe
- *Ecotoxicity, freshwater - inorganics*	673.51	805.56	CTUe
- *Ecotoxicity, freshwater - metals*	23363.40	31702.90	CTUe
- *Ecotoxicity, freshwater - organics*	49.94	54.56	CTUe
Eutrophication, freshwater	0.10	0.12	kg P eq
Eutrophication, marine	0.18	0.20	kg N eq
Eutrophication, terrestrial	1.83	2.13	mol N eq
Human toxicity, cancer	5.8610^{-7}	7.3110^{-7}	CTUh
- *Human toxicity, cancer - inorganics*	0.00	0.00	CTUh
- *Human toxicity, cancer - metals*	$3.60 \cdot 10^{-7}$	$4.65 \cdot 10^{-7}$	CTUh
- *Human toxicity, cancer - organics*	$2.26 \cdot 10^{-7}$	$2.67 \cdot 10^{-7}$	CTUh
Human toxicity, non-cancer	$9.41 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$	CTUh
- *Human toxicity, non-cancer - inorganics*	$9.09 \cdot 10^{-7}$	$1.04 \cdot 10^{-6}$	CTUh
- *Human toxicity, non-cancer - metals*	$8.12 \cdot 10^{-6}$	$1.05 \cdot 10^{-5}$	CTUh
- *Human toxicity, non-cancer - organics*	$4.06 \cdot 10^{-7}$	$5.30 \cdot 10^{-7}$	CTUh
Ionising radiation	15.08	16.39	kBq U-235 eq
Land use	629.14	761.50	Pt
Ozone depletion	$8.43 \cdot 10^{-6}$	$9.67 \cdot 10^{-6}$	kg CFC11 eq
Particulate matter	$1.03 \cdot 10^{-5}$	$1.22 \cdot 10^{-5}$	disease inc.
Photochemical ozone formation	0.65	0.75	kg NMVOC eq
Resource use, fossils	1786.91	1979.06	MJ
Resource use, minerals and metals	0.02	0.02	kg Sb eq
Water use	126.72	153.43	m3 depriv.

Table A3.9. Impact results for lighting systems with and without self-learning sensor, in the German grid.

Indicator	***Lighting with 5634***	***Conventional lighting***	***Unit***
Acidification	40.23	79.94	mol H+ eq
Climate change	873.69	1719.17	kg CO_2 eq
• *Climate change - Biogenic*	65.97	131.82	kg CO_2 eq
• *Climate change - Fossil*	806.61	1585.18	kg CO_2 eq
• *Climate change - Land use and LU change*	1.10	2.17	kg CO_2 eq
Ecotoxicity, freshwater	9052.90	16966.90	CTUe
• *Ecotoxicity, freshwater - inorganics*	471.70	836.52	CTUe
• *Ecotoxicity, freshwater - metals*	8570.31	16107.30	CTUe
• *Ecotoxicity, freshwater - organics*	37.21	64.63	CTUe
• *Eutrophication, freshwater*	1.18	2.35	kg P eq
Eutrophication, marine	0.61	1.19	kg N eq
Eutrophication, terrestrial	3.70	7.10	mol N eq
Human toxicity, cancer	$3.09\cdot10^{-7}$	$5.56\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - inorganics*	0	0.00	CTUh
• *Human toxicity, cancer - metals*	$2.14\cdot10^{-7}$	$3.99\cdot10^{-7}$	CTUh
• *Human toxicity, cancer - organics*	$9.50\cdot10^{-8}$	$1.58\cdot10^{-7}$	CTUh
Human toxicity, non-cancer	$9.63\cdot10^{-6}$	$1.83\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$1.13\cdot10^{-6}$	$2.11\cdot10^{-6}$	CTUh
• *Human toxicity, non-cancer - metals*	$8.30\cdot10^{-6}$	$1.58\cdot10^{-5}$	CTUh
• *Human toxicity, non-cancer - organics*	$2.60\cdot10^{-7}$	$4.84\cdot10^{-7}$	CTUh
Ionising radiation	147.38	291.58	kBq U-235 eq
Land use	2220.43	4363.07	Pt
Ozone depletion	$2.27\cdot10^{-5}$	$4.40\cdot10^{-5}$	kg CFC11 eq
Particulate matter	$9.46\cdot10^{-6}$	$1.74\cdot10^{-5}$	disease inc.
Photochemical ozone formation	1.17	2.23	kg NMVOC eq
Resource use, fossils	11084.70	21820.10	MJ
Resource use, minerals and metals	0.01	0.02	kg Sb eq
Water use	69.18	122.09	m3 depriv.

Table A3.10. Impact results for lighting systems with and without self-learning sensor, in the Icelandic grid.

Indicator	***Lighting with 5634***	***Conventional lighting***	***Unit***
Acidification	0.92	1.34	mol H+ eq
Climate change	111.37	194.59	kg CO_2 eq
• *Climate change - Biogenic*	8.93	17.74	kg CO_2 eq
• *Climate change - Fossil*	57.60	87.22	kg CO_2 eq
• *Climate change - Land use and LU change*	44.84	89.64	kg CO_2 eq
Ecotoxicity, freshwater	9624.54	18110.20	CTUe
• *Ecotoxicity, freshwater - inorganics*	242.37	377.87	CTUe
• *Ecotoxicity, freshwater - metals*	9678.21	18323.10	CTUe
• *Ecotoxicity, freshwater - organics*	14.80	19.79	CTUe
• *Eutrophication, freshwater*	0.04	0.05	kg P eq
Eutrophication, marine	0.06	0.08	kg N eq
Eutrophication, terrestrial	0.61	0.93	mol N eq
Human toxicity, cancer	$2.14 \cdot 10^{-7}$	$3.65 \cdot 10^{-7}$	CTUh
• *Human toxicity, cancer - inorganics*	0	0	CTUh
• *Human toxicity, cancer - metals*	$1.39 \cdot 10^{-7}$	$2.48 \cdot 10^{-7}$	CTUh
• *Human toxicity, cancer - organics*	$7.48 \cdot 10^{-8}$	$1.17 \cdot 10^{-7}$	CTUh
Human toxicity, non-cancer	$3.70 \cdot 10^{-6}$	$6.41 \cdot 10^{-6}$	CTUh
• *Human toxicity, non-cancer - inorganics*	$2.90 \cdot 10^{-7}$	$4.32 \cdot 10^{-7}$	CTUh
• *Human toxicity, non-cancer - metals*	$3.25 \cdot 10^{-6}$	$5.70 \cdot 10^{-6}$	CTUh
• *Human toxicity, non-cancer - organics*	$1.63 \cdot 10^{-7}$	$2.89 \cdot 10^{-7}$	CTUh
Ionising radiation	4.51	5.85	kBq U-235 eq
Land use	219.53	361.40	Pt
Ozone depletion	$2.79 \cdot 10^{-6}$	$4.06 \cdot 10^{-6}$	kg CFC11 eq
Particulate matter	$3.50 \cdot 10^{-6}$	$5.51 \cdot 10^{-6}$	disease inc.
Photochemical ozone formation	0.21	0.32	kg NMVOC eq
Resource use, fossils	549.56	750.56	MJ
Resource use, minerals and metals	0.01	0.01	kg Sb eq
Water use	44.11	71.94	m3 depriv.