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Towards more efficient industrial lighting

– Literature review on energy efficiency improvement of industrial lighting.

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EXECUTIVE SUMMARY

This master thesis work is aimed to investigate the possibilities of achieving more efficient industrial lighting. The study is divided in four parts: 1) Industrial lighting energy efficiency measures, 2) Added value of lighting, 3) Drivers and barriers for adopting lighting efficiency measures, and 4) Applications of AI in industrial lighting.

The first part of the study explores various energy efficiency measures that could be applied in industrial lighting. The results show that using energy-efficient lighting fixtures, optimizing lighting controls, and adopting smart lighting solutions that integrate daylight in the illumination strategy and design are the most effective measures for reducing energy consumption and increasing efficiency.

In the second part, the study examines the added values or non-energy benefits of efficient industrial lighting. The findings indicate that apart from cost savings, efficient lighting leads to improvements on the quality of work environments, enhances workers health and safety conditions and improves environmental performance. Moreover, the study suggests that in many cases, the added values of lighting are not given the importance they should have and are not considered when an energy efficiency investment is planned to be done.

The third part of the study identifies the drivers and barriers for adopting lighting efficiency measures in industrial settings. The study found that factors such as cost and energy savings, energy efficiency regulations are the main drivers for implementing efficient lighting solutions. However, barriers such as lack of awareness, perceived high initial costs, technology adoption and insufficient government incentives are the main obstacles to adoption.

Finally, the study investigates the potential of artificial intelligence (AI) in industrial lighting. The results show that AI-based solutions, such as predictive maintenance and intelligent lighting control could significantly improve energy efficiency and reduce maintenance costs. Moreover, AI can bring the work environment to another level by the application of human centred and personalized lighting.

Overall, this master thesis work provides valuable insights into achieving more efficient industrial lighting by highlighting effective energy efficiency measures, identifying the added value of efficient lighting, and examining the drivers and barriers to adoption. Moreover, the study sheds light on the potential of AI in industrial lighting and its potential benefits and future challenges.

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Chapter 1. INTRODUCTION

The purpose of the following study is to increase the understanding of actual opportunities for lighting energy efficiency available in industry. Moreover, several drivers and barriers towards applying energy efficiency measures will be discussed.

1.1 Background

Regarding (United Nations, 2023) climate change is used to describe the gradual change of the earth's temperatures, precipitation patterns, and other climatic factors over decades or longer periods. The climate on Earth is naturally changing all the time, but human actions like the combustion of fossil fuels and deforestation are speeding up that shift. Rising sea levels, more frequent and intense extreme weather events, and population relocation are just a few of the detrimental effects this has had on ecosystems and human cultures. In order to reduce its impacts and prepare for the changes now taking place, climate change is an important worldwide issue that has to be addressed immediately.

In this context, energy efficiency is a key aspect to reduce the energy use and ultimately, the CO_2 emissions related to that energy production. In regard to the efforts of the EU for climate change mitigation, in 2006 the directive on energy end-use efficiency and energy services was presented in the European parliament. (European Commission, 2023).

This directive outlined the need for improving the actual energy end-use efficiency and promoted the production of energy by renewable sources. Furthermore, this directive set the main target of improving the energy efficiency at least a 9% by the ninth year of application of the Directive, which was 2016. Afterwards, in 2012 the previous directive on energy-end-use efficiency and services was repealed by the energy efficiency directive. This directive aimed to set a clear framework of measures for the promotion of energy efficiency in the EU. The main target of this directive was to improve the energy efficiency in the EU at least 20% by the year 2020 compared to 2005 levels. This directive implied that EU energy consumption must be limited to 1312 million tonnes of oil equivalent of primary energy, or 959 Mtoe of final energy. Both targets were achieved by 2020, with a final energy consumption of 907 Mtoe and a primary energy consumption of 1236 Mtoe. It has to be outlined that these values were influenced by the Covid-19 pandemic. (European Commission, 2023).

Regarding the amending directive on energy efficiency set on December 2018 (European Commission, 2023), the main target nowadays is to improve the energy efficiency at least 32.5% relative to the year 2007. Under this directive each EU member should achieve an energy saving of 0.8% of final energy consumption for the 2021-2030 period excluding Cyprus and Malta. Cyprus and Malta were excluded because they are small countries with unique energy consumption profiles that make it difficult for them to achieve the same energy savings targets as larger EU member states.

Considering the need of becoming more efficient on the one hand to comply with the new EU directives and on the other to mitigate the global issue of climate change, the industrial sector is now becoming more aware of the importance of being more efficient. This study will focus on the energy saving opportunities in industrial lighting. The potential in the industrial sector for lighting energy saving is very high due to night shifts and the lack of natural light in the halls and buildings (Kralikova et al., 2020). Moreover, industry is typically associated with spacious work environments, fixed positions, extended work hours, challenging conditions, variable lighting levels, and lighting systems that include high bay lighting and centralized controls. These factors also contribute to significant energy consumption related to lighting. Additionally, maintenance opportunities may be limited (Kralikova et al., 2015).

Support processes refer to all processes that are designed to enable the smooth functioning of key processes and overall operations of a company. Some examples of support processes in industry are air conditioning system, heating system or office equipment (Thollander et al., 2020, Chapter 3). On the other hand, production processes are a series of activities and operations that are designed to transform raw materials or components into finished goods that can be sold or used by consumers or other businesses. Industrial production processes can be highly automated and involve the use of specialized machinery, tools, and equipment, as well as the application of specific manufacturing techniques and procedures. For example, some primary production processes on the mechanical engineering industry are chip-cutting machining, plastic forming or piece-cutting machining (Thollander et al., 2020, Chapter 3).

In various industries, lighting is considered a crucial element for operations and is classified as a support process. Although its energy consumption only constitutes a small percentage of the overall energy consumption for energy-intensive businesses that primarily utilize energy for production processes, it can account for 30% or more of the total energy consumption for non-energy intensive companies with a high percentage of energy use in support processes. (Thollander et al., 2020, Chapter 9)

1.2 Problem description

As it has been mentioned before, industrial lighting can account for significant energy use in industrial companies. Therefore, it is important for a company to know the different possibilities of reducing energy use by applying energy efficiency measurements for lighting, such as lighting sensors for controlling that lights are turned on only when needed. Furthermore, energy efficiency of lighting systems can provide added value, such as increased productivity, reduced maintenance costs and safer work environment. A large part of the energy efficiency potential is not realized due to different barriers. It is important for companies to identify those barriers to really see if an investment aimed to improve the energy efficiency is worth. Finally, new technology in the form of AI can be of great interest for efficient lighting systems, but it is still not much used in the industry nowadays (Hellström & Juslén, 2022).

On the one hand, there are several studies focused on specific energy efficiency measures for industrial lighting such as (Risteiu et al., 2016) where old lighting replacement to LED lighting is proposed. Moreover, many studies have already studied the drivers and barriers for improving energy efficiency. For example, (Nehler, 2019), (Thollander et al., 2020, Chapter 15) and (Thollander et al., 2020, Chapter 16) make good research about the drivers and barriers for adopting industrial energy efficiency measures in general. Due to the considerable amount of information in these fields, this study will try to resume the most important energy efficiency measures used nowadays, and the drivers and barriers specifically for lighting will be further analysed. Furthermore, the most relevant added values of improved industrial lighting will also be explored, as extensive research has been conducted in fields such as the effect of lighting in workers safety and health, or environmental impact.

On the other hand, as in recent years there has been a significant development in the use of Artificial Intelligence technologies, and it has started to be implemented in many industrial applications, this study will try to resume the most important applications that AI can have on industrial lighting.

In resume, this study will try to make a general and comprehensive review and analysis of industrial lighting including all the aspects mentioned before.

1.3 Objectives and limitations

The main purpose of this study is to increase the understanding of existing research on how to achieve more energy efficient industrial lighting.

The following research questions will be analyzed in order to fulfill the main purpose:

1. Which are the energy efficiency measures used for industrial lighting nowadays?
2. Which is the added value of having more efficient industrial lighting?
3. Which are the main drivers and barriers for energy efficiency of industrial lighting?
4. Which are the possibilities to improve industrial lighting systems by applying Artificial Intelligence (AI)?

Concerning the limitations, firstly several documents searched by databases that were eligible for the literature review were not available online, so they have been discarded. Therefore, not all the eligible literature has been considered, reducing even more the amount of literature selected. Secondly, as the literature review has been planned to be finished in 5 months, the time available for searching for relevant literature has been limited. Considering this, just two databases have been used to search for documents, Scopus and Web of Science. Finally, a last limitation has been the lack of papers directed to the opportunities of improving lighting efficiency by the use of Artificial Intelligence. A reason for this last limitation could be the recent application of this type of technology in industrial lighting.

Chapter 2. THEORETICAL FRAMEWORK

This chapter will provide the necessary theoretical framework for the reader to understand all concepts that will be discussed in the following chapters.

2.1 Lighting characteristics

In this section the most important characteristics of lighting will be presented. When a luminaire is going to be selected for a specific function, the performance characteristics need to be evaluated to select the option that suits best.

The typical features of lighting include both photometric and colorimetric performance, which must be evaluated objectively using globally acknowledged standards like IES LM-79-08. Photometric characteristics are defined in terms of aspects such as luminous intensity values, distribution, light output, and total luminous flux of the luminaire. Meanwhile, colorimetric characteristics are measured through various parameters, including correlated colour temperature, peak wavelength, dominant wavelength, colour rendering index, red-green-blue ratio, and standard deviation colour matching. (Mangkuto & Soelami, 2017)

2.1.1 Colour Rendering Index (CRI)

The CRI, also called the R_a Index, measures how accurately a light source reproduces colours in comparison to a reference light source. The CRI uses a standard reference light source, which is an incandescent light bulb. The maximum possible CRI is 100, and lamps with CRIs above 70 are commonly used in residential and workplace settings.(Sağlam & Oral, 2010)

The CRI is determined by the extent to which a light source exhibits the full spectrum of wavelengths. A CRI slightly above 90 poses no threat of colour distortions. A CRI ranging from 80 to 85 signifies some susceptibility to changes in delicate colours, while most colours are accurately reproduced. Finally, a CRI below 70 indicates a significant risk of inadequate colour reproduction. (Thollander et al., 2020, Chapter 9)

2.1.2 Correlated Colour Temperature (CCT)

The colour temperature of a lamp refers to its warmth or coolness, as measured on the Kelvin (K) scale. A higher colour temperature indicates a cooler colour appearance. Generally, a CCT rating below 3200 K is classified as warm, whereas a rating above 4000 K is regarded as cool. (Sağlam & Oral, 2010)

In the Figure 1 the colour temperature of common light sources can be appreciated.

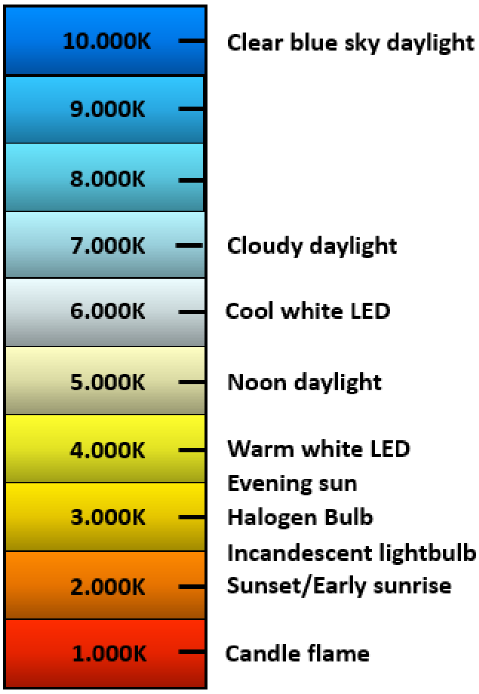

Figure 1 - Colour temperature of common light sources – Adapted from (ilumi, 2015)

2.1.3 Luminous efficacy

A lumen is a unit of measurement used to quantify the total amount of visible light emitted by a light source per second. In other words, it measures the brightness of a light source as perceived by the human eye. The higher the number of lumens, the brighter the light source. The luminous efficacy is the ratio between the light output measured in lumen (lm) and the power input measured in watts (W). Therefore, the luminous efficacy is represented in lumen per watt (lm/W).(Sağlam & Oral, 2010)

In Figure 2 the evolution of different lighting technologies in luminous efficacy can be appreciated until the year 2015 with the LED technology leading the market.

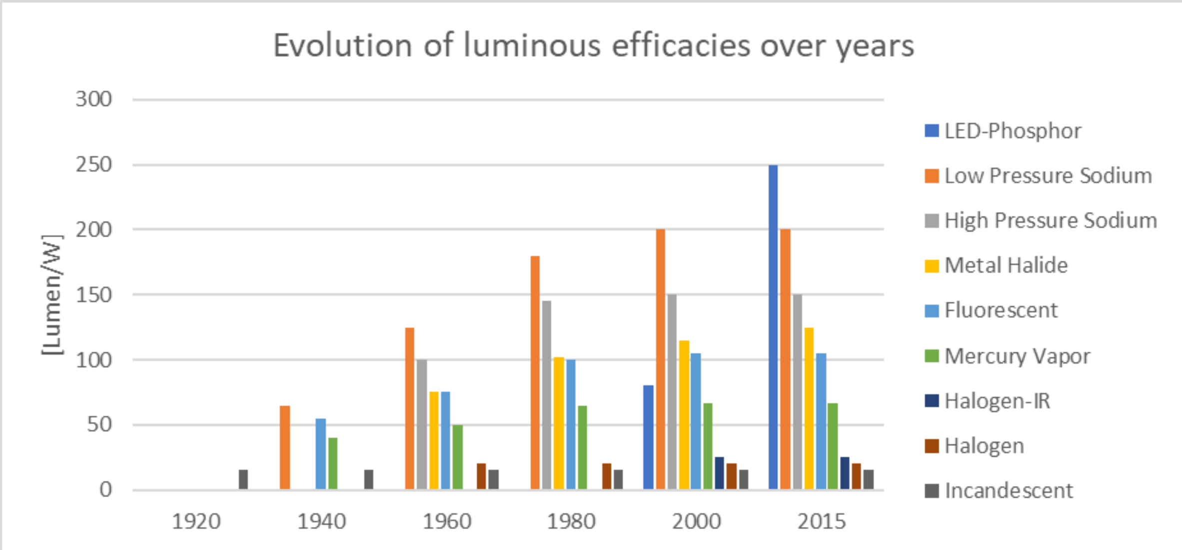

Figure 2 - Evolution of luminous efficacy of different lighting technologies – Adapted from (Cowan & Daim, 2011)

2.2 Types of lamps

A lamp is an artificial source of light. Lamps have become an indispensable aspect of our everyday routines in the last century. There are numerous types of lamps accessible in the market that operate on various principles, use different materials, and most importantly, have varying levels of energy efficiency and other lighting characteristics stated before. (Electrical4U, 2021)

In Table 1 a resume of the most relevant parameters of different types of lamps can be appreciated:

Table 1 - photometric parameters of different types of lamps (Thollander et al., 2020, Chapter 9)

Type of lamp		Efficacy (lm/W)	Colour temperature (K)	CRI	Life span (hours)
Incandescent lamps		10-30	2.500-3.500	100	1.000-4.000
Halogen lamps		20-40	3.000-3.500	80-100	2.000-5.000
Fluorescent lamps	T8	60-70	2.500-5.500	80	9.000-17.000
	T5	70-110	3.000-7.000	80	17.000-40.000
Compact fluorescent lamps		50-80	2.500-4.000	>80	10.000-20.000
High pressure sodium lamps		70-130	2.000-2.500	80	10.000-30.000
Low pressure sodium lamps		200	2.000	very low	12.000
Mercury lamps		40-60	3.000-3.700	50-60	6.000-12.000
Metal halide lamps		75-100	2.800-4.200	75-95	6.000-12.000
Ceramic metal halide lamps		90-100	3.000-4.200	90-95	9.000-15.000
Induction lamps		80-130	2.700-4.000	>80	60.000-100.000
LED		80-150	3.000-5.000	40-95	>50.000

2.2.1 Incandescent Lamps

The components of an incandescent lamp are a socket, a piston, a filler gas (commonly argon or nitrogen), and a filament, often composed of tungsten (Thollander et al., 2020, Chapter 9). Incandescent lamps operate as a result of the filament glowing because of the electric current flowing through it. Around 90% of the electrical energy used to power these lights is wasted as heat, with an efficiency ranging from 10 to 30 lm/W (Electrical4U, 2021).

The traditional incandescent light bulb, which had been in use for over a century, was prohibited in September 2012 so nowadays they are not produced within the European Union (Thollander et al., 2020, Chapter 9).

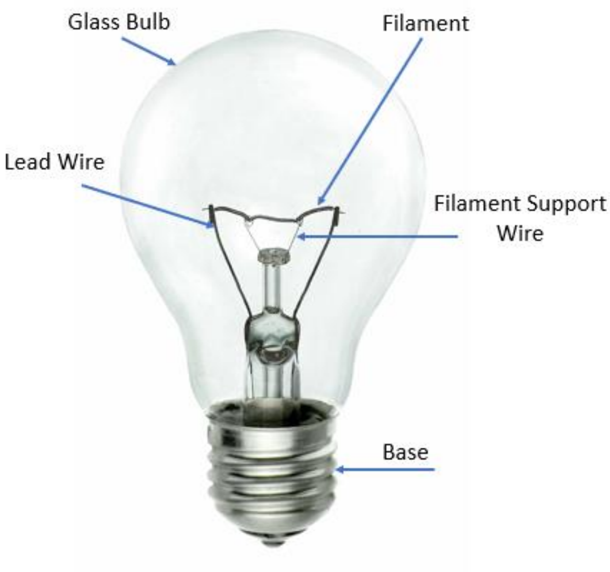

Figure 3 - Incandescent light bulb. Adapted from (Wallpaper Flare, 2023) *CC-0*

2.2.2 Tungsten Halogen Lamps

Halogen lamps use a similar technology as the incandescent lamp mentioned before, and are composed of a socket, a piston, a filler gas, and a filament. Halogen lamps were developed by incorporating a halogen gas, such as iodine, into the incandescent lamp. The reason for this is that without the halogen gas, the filament of the incandescent lamp deteriorates over time due to evaporation at high operating temperatures. As tungsten from the filament evaporates, it accumulates on the surface of the bulb, gradually obstructing the flow of lumens from the bulb. Consequently, the efficacy of the incandescent lamp, measured in lumens per watt, decreases gradually. (Electrical4U, 2021)

Halogen lamps utilize a regenerative process in which the filler gas catches the evaporated tungsten from the filament and subsequently returns it to the filament. As a result of this process, the lamp has a longer lifespan than a typical incandescent lamp. (Thollander et al., 2020, Chapter 9).

Figure 4 - Tungsten Halogen lamp. (Wikimedia Commons, 2023) *CC-0*

2.2.3 Fluorescent Lamps

A fluorescent lamp utilizes fluorescence to produce visible light and operates by energizing mercury vapor through an electric current in the gas. This results in the release of ultraviolet radiation via a discharge process, which in turn causes the phosphor coating on the inner wall of the lamp to emit visible light. Additionally, this type of lamp is characterized by its low weight and use of mercury vapor. (Electrical4U, 2021)

Historically, the most common fluorescent lamp has been the T8 that uses conventional ballast technology, which is the magnetic ballast. Nowadays, there are T8 lamps equipped with electrical ballasts or high frequency ballasts. Furthermore, the T5 fluorescent lamps represent the new generation of fluorescent lamps. This lamp can only use electrical ballasts and has better efficacy and longer lifespan than the previous T8 lamp. (Thollander et al., 2020, Chapter 9)

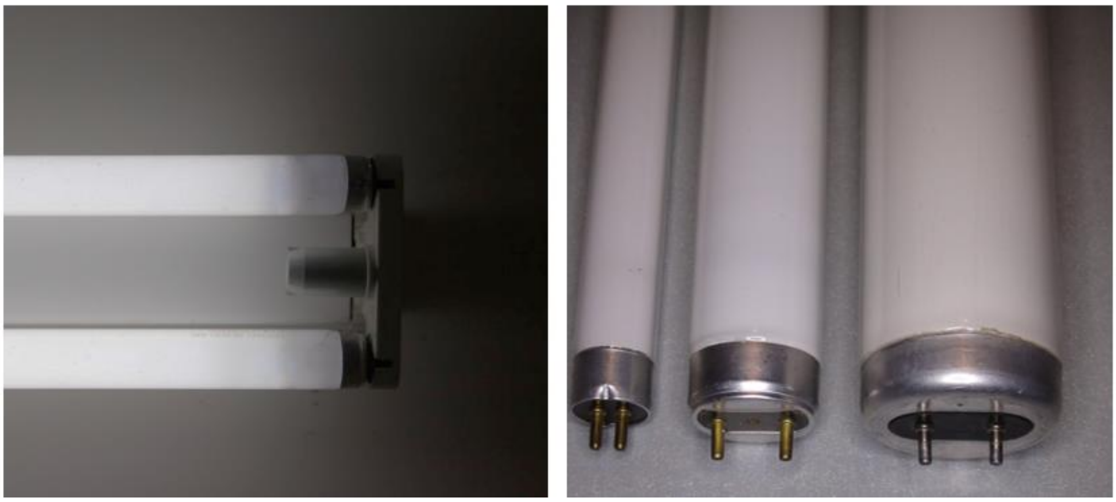

Figure 5 - Fluorescent lamps. (Wikimedia Commons, 2023), (flickr, 2023) *CC-BY-SA*

2.2.4 Compact Fluorescent Lamps

Compact fluorescent lamps employ the same technology as traditional fluorescent lamps, but the significant benefit they offer is their size, which allows them to be used as a substitute for incandescent light bulbs. (Thollander et al., 2020, Chapter 9)

Figure 6 - Compact fluorescent lamp. (Wikimedia Commons, 2023) *CC-BY-SA*

2.2.5 Mercury Vapour Lamps

Mercury lamps have been extensively used for lighting in industrial facilities during several years. However, since 2015 it is prohibited to sale them within the European Union. (Thollander et al., 2020, Chapter 9)

The operational mechanism of this device is similar to that of a fluorescent lamp. It contains two primary electrodes and a starting electrode within its arc tube. A tungsten rod is held by each primary electrode, around which a double layer of coiled tungsten wire is wound. (Electrical4U, 2021)

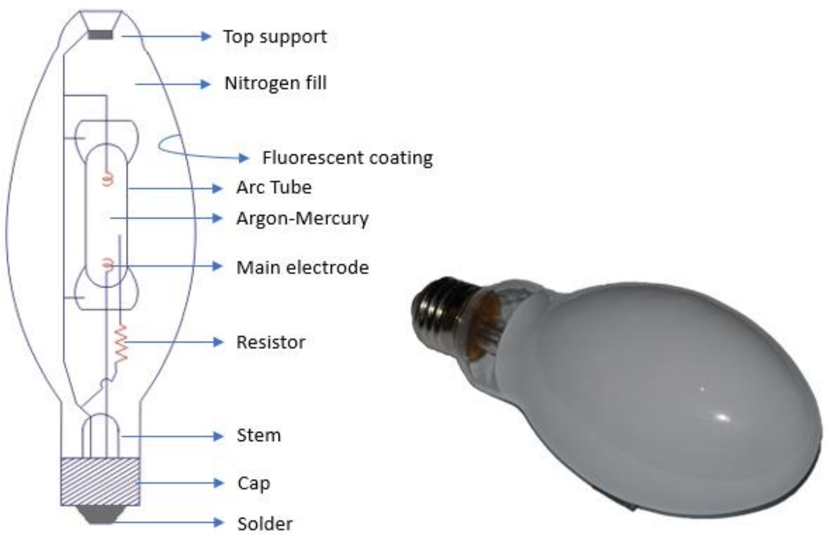

Figure 7 - Mercury vapour lamp – Adapted form (Electrical4U, 2021)

2.2.6 Metal Halide Lamps

The metal halide lamp is a special type of arch discharge technology lamp. It can be considered as a development of the mercury lamp with improved efficiency and CRI. (Thollander et al., 2020, Chapter 9)

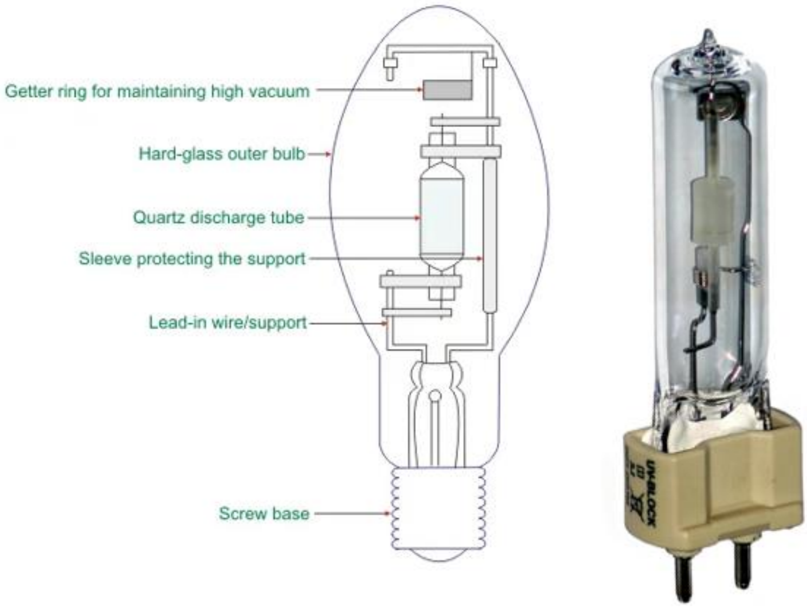

Figure 8 - Metal halide lamp – Adapted from (Electrical4U, 2021)

2.2.7 High Pressure Sodium Vapour Lamps

High-pressure sodium lamps, also referred to as HPS lamps, are a form of sodium lamp that has gained widespread use in industrial lighting as well as many public outdoor areas, such as parking lots, roadways, and security zones, where colour rendering requirements are not very high. Their high efficiency is a major factor driving their adoption, as they can produce around 100 lumens per Watt when evaluated under photopic lighting conditions. Some high-power lamps (>600 Watt) can even achieve efficacies of approximately 150 lumens per Watt. However, the production of high-pressure sodium lamps presents a significant challenge due to the difficulty of finding materials that are resistant to corrosion in the presence of high temperatures and pressures of sodium vapor. (Electrical4U, 2021)

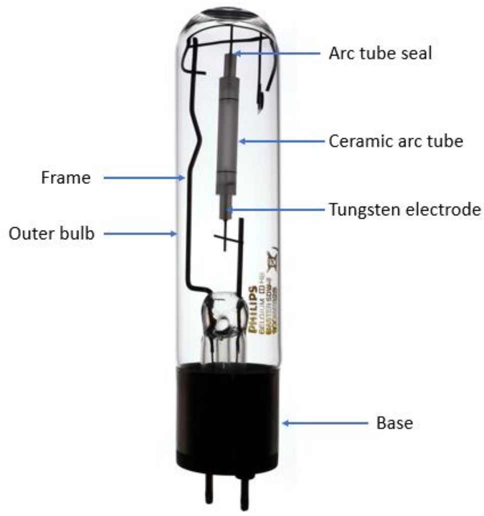

Figure 9 - High Pressure Sodium Vapour lamp. (Wikimedia Commons, 2023) *CC-0*

2.2.8 Low Pressure Sodium Vapour Lamps

The Low-Pressure Sodium Vapor lamp, also known as an LPSV lamp, is considered a "miscellaneous discharge lamp" due to its combination of characteristics from both High-Intensity Discharge (HID) lamps and fluorescent lamps. (Electrical4U, 2021). This type of lamp has a very high lighting efficacy. However, the CRI is very low as it is considered monochromatic.

LPSV lamps are a cost-effective option for road and security lighting, particularly in situations where colour rendering is not critical. These lamps are especially well-suited for use in foggy weather conditions. (Electrical4U, 2021)

Figure 10 - Low Pressure Sodium Vapour lamp warming up. (Wikimedia Commons, 2023) *CC-BY-SA*

2.2.9 LED Lamps

White Light Emitting Diodes, or White LEDs, represent a significant advance in the field of lighting technology. Previously, LEDs were limited to applications such as indicators, displays, and emergency lighting. However, with the development of white light emitting

LEDs, they are now widely used in almost all lighting contexts, from indoor and street lighting to flood lighting. (Electrical4U, 2021)

The term solid state lighting refers to the mechanism of light generation and specifically encompasses LED (light emitting diode) and LED-related technologies. A LED is considered solid state due to its absence of movable components or gas for light production. Solid-state lighting produces light with less heat output compared to incandescent and fluorescent lamps. This is achieved through the use of a semi-conducting material that directly converts electricity into light, resulting in a highly energy-efficient source of illumination. (Sağlam & Oral, 2010)

Figure 11 - LED lamp. (Wikimedia Commons, 2023) *CC-BY-SA*

2.3 Lighting controls

Lighting controls are an effective technique to improve the flexibility of a lighting system apart from reducing the total energy consumption by reducing the light output or turning off light when it is not needed.

2.3.1 Manual dimming

Manual dimming controls provide the ability for people in a room to modify the brightness or amount of light produced. This can lead to a reduction in energy usage by decreasing the amount of input power needed. It can also be useful for lowering the peak power demand, while also providing greater flexibility in lighting. Slide switches are a straightforward form of manual control that allow for adjustments across the full range of light output.(Sağlam & Oral, 2010)

Figure 12 - Manual dimmer. (Wikimedia Commons, 2023) *CC-BY-SA*

2.3.2 Photosensors

Photosensors are used to automatically modify the amount of light produced by a lighting system by detecting the level of illuminance in a given area. Certain photosensors are capable not only of turning lights on and off, but also adjusting the brightness level. By automatically dimming lights, these sensors can aid in lumen maintenance, which involves dimming lighting fixtures when they are initially installed in order to avoid over-design and wasteful energy use. As the lamp ages and its brightness decreases, the power supplied to it can be gradually increased to compensate for the loss in light output over time. (Sağlam & Oral, 2010)

2.3.3 Occupancy sensors

Occupancy sensors have the ability to switch lights on and off by sensing motion in a given area. When paired with dimming controls, some sensors can prevent lights from turning off entirely when a space is unoccupied. This type of control system may be suitable for instances where occupancy sensors regulate separate zones within a large area, such as a laboratory or an open office space. In such situations, the lights can be dimmed to a pre-determined level when the space is unoccupied. (Sağlam & Oral, 2010)

There are three types of occupancy sensors:

- Passive infrared

Passive infrared (PIR) sensors detect the presence of a heat-emitting object moving within their viewing area. PIR occupancy sensors that are designed like wall boxes are most appropriate for confined areas such as individual offices. These sensors can replace traditional wall light switches. (Sağlam & Oral, 2010)

- Ultrasonic

Ultrasonic sensors emit sound patterns that are not audible to the human ear and then detect changes in the reflected sound pattern. They are more effective than most infrared sensors at detecting even the slightest motion. As a result, they are suitable for use in areas such as restrooms with stalls, where the field of view may be obstructed. (Sağlam & Oral, 2010)

- Dual technology (Hybrid)

Occupancy sensors that utilize dual-technology employ both passive infrared and ultrasonic technologies to reduce the chance of false triggering, which means that lights are turned on when space is unoccupied. (Sağlam & Oral, 2010)

2.3.4 Clock switches or timers

Clock switches or timers are used to manage lighting for a predetermined duration as they have an internal clock. The user can set the specific times for turning the lights on and off. Clock switches can be utilized alongside photosensors. (Sağlam & Oral, 2010)

2.3.5 Centralized controls

Building automation systems or centralized building controls can be utilized to automatically manage electric lighting throughout a building, including turning lights on and off, or dimming them. If an office setting is analysed, in the morning, the central control system can activate lights before employees arrive, while during times of high-power demand, the same system can dim lights. Additionally, at the end of the day, the lights can be automatically turned off. By implementing a centralized lighting control system, there can be a notable reduction in energy consumption in buildings where lights are habitually left on unnecessarily. (Sağlam & Oral, 2010)

2.3.6 Intelligent control systems

A system that has an intelligent control system merges various methods from control engineering to create self-governing systems that can perceive, reason, plan, learn and behave intelligently. This type of system should be capable of maintaining the desired performance even when faced with unpredictable circumstances. Intelligent control systems are composed by three main subsystems. Firstly, the perception subsystem aimed to collect information from the environment and adapt it into a suitable form by signal processing. Secondly, the cognition subsystem aimed to carry out a decision-making process under conditions of uncertainty. Lastly, the actuation subsystem aimed to act following the signals from the cognition subsystem in order to achieve the desired conditions in the plant. (Sağlam & Oral, 2010)

2.4 Artificial Intelligence (AI)

The ability to learn is a fundamental indication of intelligence. A technology that lacks the ability to learn cannot be deemed intelligent. When a system or component of a system can learn autonomously, without dependence on a human programmer or user, it can be referred to as self-learning or machine learning. By employing software algorithms for learning and data-based predictions, artificial intelligence can be implemented in control mechanisms. Therefore, three prerequisites are necessary for the active application of artificial intelligence in control: data, intelligent software, and reactive technology. (Hellström & Juslén, 2022)

2.5 Added values

Added values are often called Non-Energy Benefits (NEB) as they describe all the good consequences that applying an energy efficiency solution may bring apart from the ones directly connected to energy savings or cost reductions. Improvements in productivity, improved product quality, reduction of errors, improved workers morale or improved environmental performance can all be considered added values (Nehler, 2019).

For instance, the improvement of the lighting system of a factory can result in higher productivity and fewer mistakes in manufacturing even if the main objective of the lighting improvement was to lower the energy use and costs related to energy. Similarly, implementing a more efficient air conditioning could create a more comfortable work environment, which may boost employee health and morale.

Non-energy benefits are often overlooked in the decision-making process for energy efficiency projects because they are more difficult to quantify and value than energy savings or cost savings. However, they can be significant and should be considered when evaluating the overall impact and value of energy efficiency measures. (Nehler & Rasmussen, 2016)

2.6 Energy policies for improved energy efficiency

The implementation of policies aimed at improving energy efficiency plays a crucial role in addressing market barriers and failures related to energy consumption. There exist three distinct approaches for implementing such policy interventions: (Thollander et al., 2020, Chapter 16)

- Economic policies
- Administrative policies
- Information policies

Apart from the three aforementioned categories, there exists a fourth category that deals with research and development. The primary objective of this category is to promote technological advancement, enabling the launch of new products and services in the free market at a later stage. In practice, policies typically consist of a combination of these four categories. (Thollander et al., 2020, Chapter 16)

2.6.1 Economic policies

Economic policies can be implemented through subsidies and taxes. In many cases, policies consist of a mixture of different types of measures such as energy and carbon taxes, as well as subsidized energy audit programs that comprise both an economic component, i.e., subsidies, and an informational aspect, such as the energy audit report delivered to the company. The use of economic policy instruments provides price signals that can alter economic incentives and steer the behaviour of both individuals and companies in a desired direction. (Thollander et al., 2020, Chapter 16)

2.6.2 Administrative policies

Administrative or regulatory policies refer to a set of measures that include laws, technology standards, performance standards, and management standards. The last type, also known as enforced self-regulation or management-based regulation, mandates firms to have management systems in place, with the firms being responsible for determining the specifics of the management systems themselves. The key distinction between administrative and economic policy instruments lies in their approach to achieving a specific goal. Administrative policies specify the means and methods to be employed in reaching the goal, whereas economic instruments focus on signalling the goal without prescribing the specific strategies or approaches to be used. An example of an administrative policy is the European Industrial Emission Directive, which prescribes BAT (Best Available Technology) documents for various sectors. (Thollander et al., 2020, Chapter 16)

2.6.3 Information policies

Information can be utilized as a policy tool to directly influence the creation of knowledge, attitudes, and user behaviour. Additionally, information can be a vital supplement to financial and administrative policies. For instance, energy services can only have an impact if companies are informed about the conditions and regulations that are applicable. Information policies comprise voluntary guidelines, manuals, and training, while non-compulsory energy audit programs are also categorized under this group. (Thollander et al., 2020, Chapter 16)

Chapter 3. METHOD

Literature reviews play a crucial role in research by anchoring investigations in the relevant knowledge domains, identifying areas where further knowledge is needed, and avoiding duplication of efforts in addressing previously answered research questions.

3.1 Selection of a Literature Review Method (LRM)

In order to structure literature review projects, many Literature Review Methods (LRM) have been created. Using a proven methodology guarantees high standards, rigor, transparency, applicability, and repeatability.(Brendel et al., 2020)

In Table 2 a comparison of the most common Literature Review Methods can be appreciated.

Table 2 - Different literature review method comparison – Adapted from (Brendel et al., 2020)

META STEPS (VOM Brocke et al. 2009)	Bandara et al. (2015)	Boell and Cecez-Kecmanovic (2014)	Churchill (1979)	Fettke (2006)	Levy and Ellis (2006)	Kitchenham and Charters (2004, 2007)	Okoli and Schabram (2010)	Webster and Watson (2002)	Wolfswinkel et al. (2013)
1.Definition of Review Scope	1.Identification of Relevant Literature	1.Initial Ideas	1.Specify Domain of Construct 2.Generate Sample of items	1.Problem Formulation	1.Input	1.Planning the Review	1.Identify Purpose 2.Protocol and Training	1.Define Topic 2.Set Boundaries	1.Define Scope
2.Conceptualiza-tion of Topic									
3.Literature Search		2.Search and Acquisition	3.Collect Data 4.Purify Measure 5.Collect Data	2.Literature Search	2.Know Literature 3.Comprehend Literature 4.Apply	2.Identification 3.Selection 4.Assessment 5.Extraction	3.Search Literature 4.Screen	3.Search Literature 4.Backward and Forward Search	2.Search Literature 3.Refine Sample
4.Literature Analysis and Synthesis	2.Organization of analysis 3.Coding and Analysis	3. Analysis and Interpretation	6.Assess Reliability 7.Assess Validity	3.Literature Analysis 4.Interpretation	5.Analyse 6.Synthesize 7.Evaluate	6.Synthesis	5.Quality Appraisal 6.Data Extraction 7.Synthesis	5.Theory Development 6.Theory Evaluation 7.Discussion	4.Open Coding 5.Axial Coding 6.Selective Coding
5.Research Agenda	4.Write-up and Presentation		8. Develop Norms	5.Presentation	8.Output	7.Report	8.Write Review		7.Present

After analysing several methods for the literature review such as (Webster & Watson, 2002), (Vom Brocke et al., 2009) and (Wolfswinkel et al., 2013) it has been concluded that the best method for carrying out this work is the one proposed by (Brendel et al., 2020) where different aspects of the previous cited documents are included and it mainly adapts the structure of the method from (Vom Brocke et al., 2009). This method provides a comprehensive understanding of the research area by following a systematic approach to identify, select, and evaluate relevant literature. This method is timesaving, rigorous, and transparent.

This LRM by (Brendel et al., 2020) is suitable for conducting this literature review as it takes the method of (Vom Brocke et al., 2009) which has a certain level of abstraction, and makes it more detailed by splitting the literature analysis and synthesis into two different parts. Moreover, it maintains a good balance on displaying an emphasis on different parts of a literature review. Some methods are more concerned with the literature search process, such as (Bandara et al., 2015) while others are more focused on the effective way of summarizing and displaying the results of the analysis, for example (Webster & Watson, 2002) and (Wolfswinkel et al., 2013). Therefore, this method has been chosen as it has a lower level of abstraction than other methods and maintains a good balance, giving similar importance to each part of the literature review process. In Figure 13 the steps that have been followed for carrying out the literature review can be appreciated.

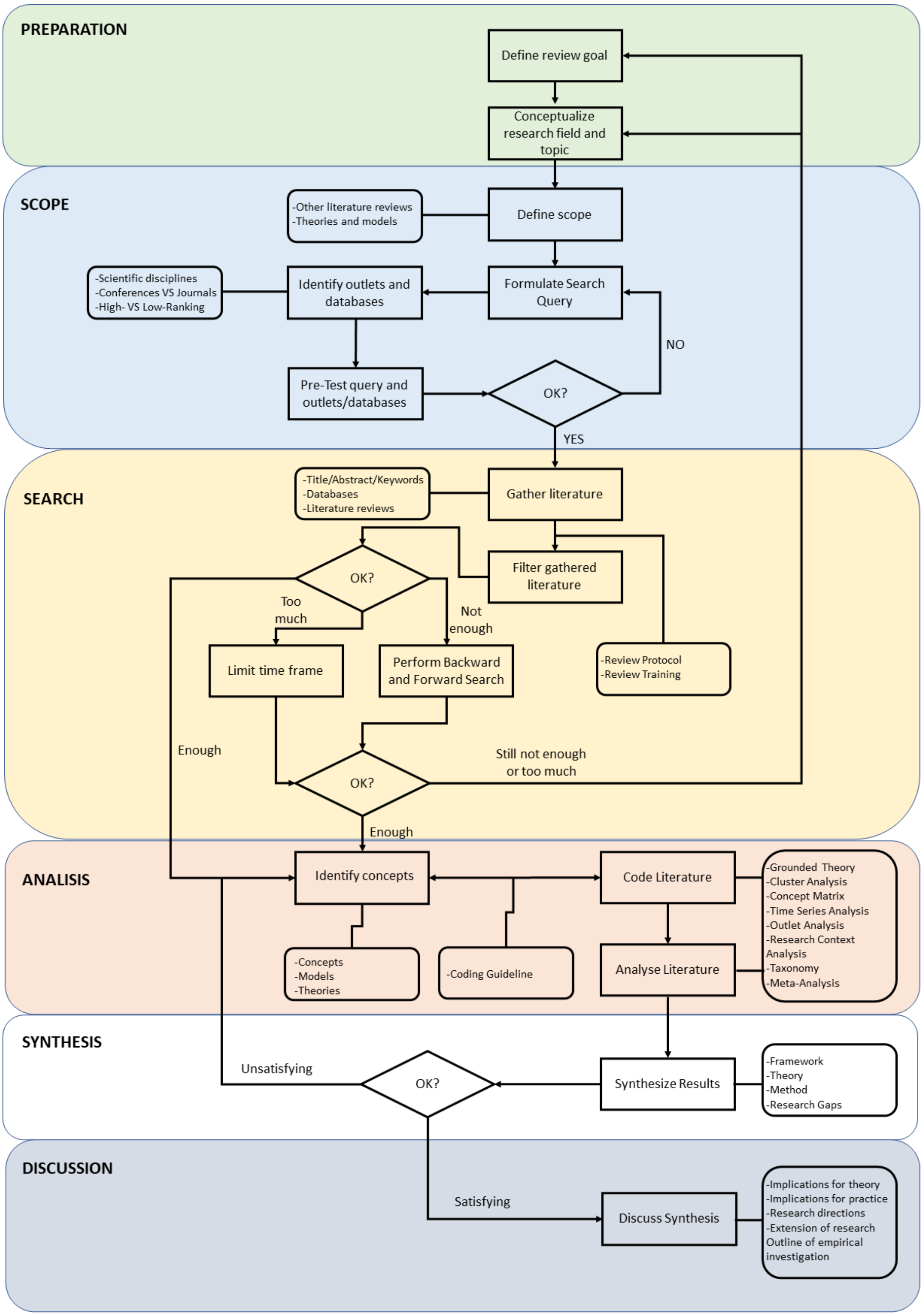

Figure 13 - Selected Literature Review Method schematic - Adapted from (Brendel et al., 2020)

In this study, the preparation and the scope parts have been added on the introduction part, with a contextualization of the research field and the topic on the background and problem descriptions. The main scope of the study has been defined in the objectives and limitations part, as well as the search query. The literature search has been included in the next part, inside the method chapter. The literature analysis has also been included in the method part. The synthesis of the literature has been considered the most relevant part of this research and it has been included under the results chapter. Finally, the discussion part has been added in the final chapters.

3.2 Literature search

The searching part of the literature review has been based on a systematic search where academic journals published in peer-reviewed journals that are relevant to the topic have been searched by key words. The key words have been selected based on the research questions. For the search, the scholarly databases Scopus and Web of Science have been used in order to assure the reliability of the documents selected.

In the following table the result from the first search for literature can be appreciated:

Table 3 - First literature search in Scopus and Web of Science

Database	Keywords	Hits	Excluded by title and abstract	Not available online	Older than 2000	Repeated	Selected
Scopus	industrial lighting **AND** efficiency	236	156	19	16	0	45
	Lighting **AND** AI	24	23	1	0	0	0
	Lighting **AND** Added Value	12	11	0	0	0	1
Web of Science	industrial lighting **AND** efficiency	16	6	3	0	0	7
	industrial lighting	241	203	17	0	8	13
	Lighting **AND** AI	31	29	2	0	0	0
	Lighting **AND** Added Value	4	4	0	0	0	0
						TOTAL	**66**

Firstly, a broad search with the general key words “industrial lighting” and “efficiency” has been made so that a wide range of journals could be searched and selected depending on their relevance for the research questions. Afterwards, a grouping of the documents gathered has been made to evaluate how much documents were selected for each research questions.

The documents related to lighting energy efficiency measures and drivers and barriers for applying energy efficiency measures were considered enough for the literature review after the first search by keywords was finished. However, there were not so many documents related to added values and Artificial Intelligence, so more search was done with the key words related to the topics of added value and AI as it can be seen in Table 3. Furthermore, a backwards citation search was done with the few papers focusing on added values and artificial intelligence.

The total amount of selected papers on the first search was up to 66. However, a stricter exclusion criterion was set. Due to the fast growing of the lighting technology in recent years, especially in LED lighting, the publishing time period for papers was reduced. For the first search the time period was framed between the years 2000-2023. After an extensive search on the internet and several papers, it has been concluded that the time period should be framed from 2010-2023. This is due to the fact that LED technology started to become a real alternative for industrial lighting around the year 2010.

During 2010, white LEDs were recorded to have luminous efficacies ranging from 150 to 250 lm/W, with numerous companies reporting exceptionally high efficiencies. On the other hand, LED replacement light bulbs were introduced in 2010 and became available in stores all over the world. Additionally, especially in Europe, by 2010 Philips was already selling LED light bulbs with much better lighting efficacies than incandescent lamps and competing with other existing technologies such as fluorescent.(Cho et al., 2017)

Finally, after excluding papers before 2010 and excluding some papers that after a second read were not considered enough relevant for the topic, a total of 50 papers have been selected for the literature review. The grouping of the literature can be seen in the following table:

Table 4 - Grouping of the selected literature.

Groups	Papers
Cost-effective measures	18
Drivers and barriers	13
Added value	11
Introduction of AI in lighting	8
Total	**50**

It must be noted that some documents classified in one specific group may be useful for another group too, but they have been classified in a specific group due to their main focus.

3.3 Literature analysis

For the analysis of the previously selected literature, the best option has been considered to firstly identify the key concepts on the literature selected for each research question as it is stated in Figure 13 on the literature analysis section. For that, the concept matrix has been considered the best alternative based on the literature review method of (Webster & Watson, 2002). An example of the concept matrix that has been used for identifying key concepts from industrial lighting energy efficiency measures can be seen in Table 5.

Table 5 - Concept matrix of industrial lighting energy efficiency measures

CONCEPT MATRIX							
INDUSTRIAL LIGHTING ENERGY EFFICIENCY MEASURES							
ARTICLES	**CONCEPTS**						
	DAYLIGH USAGE	CONTROL SYSTEMS	IMPORTANCE OF LIGHTING DESIGN	REPLACEMENT OF LAMPS	CARRYIGN OUT AN ENERGY AUDIT	ENERGY PERFORMANCE EVALUATION	MAINTENANCE
1				X			
2		X					
3		X					
4				X			X
5				X			
6	X		X				
7	X	X	X				
8				X			
9		X		X	X		X
10	X	X		X			X
11						X	X
12	X	X	X				
13		X	X	X			X
14		X	X	X			
15	X						
16		X					
17				X			X
18			X	X			X

For the first and the last research question a separate concept matrix has been built for each one due to the diversity of concepts from each question. In the case of papers related to added values and drivers and barriers to lighting energy efficiency, several papers from each research question have common concepts so the concept matrix has been unified for the second and third research questions.

After identifying the key concepts, these concepts have been used to define the structure of the literature review depending on the number of papers connected to each concept and connecting some less mentioned concepts under bigger concepts.

All the concept matrixes are showed in the appendix section.

Chapter 4. RESULTS

In the following chapter the results from the literature review will be presented.

4.1 Industrial lighting energy efficiency measures

As mentioned before in the introductory chapters, energy efficiency has become an increasingly important issue in the industrial sector, as it has a direct impact on the operational costs, and it contributes to create a "green" image of a company. One of the processes that requires a big share of the energy consumption in industrial facilities is lighting. Therefore, implementing cost-effective measures to reduce the energy consumption of industrial lighting can have an important impact on the overall energy consumption and electricity costs of a factory. This section aims to investigate different energy efficiency measures that are applied nowadays in industrial lighting.

After analysing literature from several sources, it has been found that in order to have an efficient industrial lighting, firstly it is crucial to have a deep knowledge of the workplace so that a detailed design of an adequate lighting system can be drawn by the implementation of the most cost-effective measures. The paper (Kralikova & Wessely, 2016) highlights the crucial role of design in achieving industrial lighting efficiency. Efficient lighting not only saves energy but also improves productivity and safety in the workplace.

The sort of work being done, the size and form of the area, and the properties of the lighting technology employed are all variables that proper lighting design takes into consideration. Designers may construct lighting systems that offer the appropriate amount of light where it is required, while minimizing energy loss and lowering glare and eye strain, by optimizing these characteristics. Investing in high-quality lighting design increases office productivity and employee well-being while also saving money on energy bills.

For a better understanding of the workplace a lighting audit could be applied. The paper (Khalid et al., 2012) highlights the significance of a lighting audit in identifying areas where lighting energy consumption can be reduced. The audit can help determine lighting efficiency, energy usage patterns, and opportunities to upgrade or replace lighting systems.

4.1.1 Improved daylight usage

The use of daylight, which is a valuable natural resource, may enhance lighting conditions in a variety of contexts, including industrial structures. A lot of research has been carried out throughout the years to investigate how daylight affects energy efficiency and illumination quality in industrial settings. Utilising information from a few carefully chosen research publications, the purpose of this section is to discuss the advantages of utilising daylight for better lighting in industrial settings.

Daylight can provide substantial quantity of energy that can be used to reduce the need for electric lighting in a facility. The electric lighting control strategy is crucial for developing a unified lighting system. It is essential to take into account the amount of natural light available in each area of the building and organise the lighting fixtures accordingly in order to design an optimum lighting system. An automated control system can be implemented to dim or switch on a specific group of luminaries depending on the daylight influence (Parise & Martirano, 2013).

For an efficient design that includes daylight effect, two main cases need to be considered. On the one hand, the design should identify the best options for assuring the necessary illuminance in night-time. On the other hand, for daytime an evaluation of all daylight impact on the illuminance of the area should be made and a lighting system modulation should be implemented accordingly. Most of the time, a lighting control system must be able to independently dim or switch tiny interior space sectors in order for daylighting to be successful. However, in most cases the general criteria adopted in lighting design only considers a condition of “night-time” without considering the presence of natural daylight. (Parise & Martirano, 2013)

One of the main advantages of daylight is its contribution to the energy efficiency of industrial buildings. The study (Kralikova et al., 2015) explores different energy efficiency techniques for industrial lighting including the use of daylight. The study concludes that incorporating daylight into industrial lighting systems can reduce the energy costs and consumption significantly.

Similarly, the research (Kousalyadevi & Lavanya, 2019) shows the possible use of daylight simulations for the optimization of the energy efficiency of industrial lighting. The paper carries out a simulation-based experiment in a facility located in Coimbatore, India in order to evaluate the impact of daylight use in the energy consumption of the industrial building. The illuminance simulation of the facility is done by Velux daylight visualizer, which is a lighting simulation tool for the analysis of the daylight conditions in a building usually used in early stages of the design of the building to evaluate the impacts of design choices in daylight performance.

Daylighting also has the potential to improve the standard of lighting in industrial building spaces. The research (Katunský et al., 2018) illustrates how daylight should be used to improve the working environment. The study has been carried out in a textile factory located in the eastern part of the Slovak republic. The study firstly points out that if all the needs in the facility are not considered daylight can affect negatively the visual performance of the facility by creating shadows, causing discomfort by dazzling eyes and causing unpleasant scattering in the interior. The study finally concludes that if an optimal combination of natural light and artificial light is achieved the standard of lighting can be optimized.

4.1.2 Lighting Control systems implementation

Control systems have become an essential part of modern industrial lighting, offering companies the ability to optimize their lighting energy use to unprecedented levels. Moreover, this optimization implies a reduced carbon footprint and reduced energy costs. By the integration of several technologies such as dimmers, photosensors, occupancy sensors or centralized control systems, industrial lighting can now be managed more efficiently.

The study (Lesko et al., 2018) presents a luminaire with variable light distribution as an example of efficient lighting control system specially for industrial workplaces where different activities are carried out within the same visual space. These luminaires are able to adjust their light output dynamically based on environmental needs by the use of advanced optics and power electronics. By focusing light on areas where workers are located in a warehouse with high ceilings, luminaires can reduce energy waste and improve visibility.

Occupancy sensors are also essential for industrial lighting control. These sensors detect the presence of people in a room or area and adjust the lighting accordingly. In a large factory or warehouse, this can result in significant energy savings by ensuring that lighting is only used when and where it is needed. Occupancy sensors have frequently been touted as one of the most affordable solutions for retrofitting commercial lighting systems, with average estimated energy savings potential from one-fourth to more than one-half of lighting energy. The paper (Von Neida et al., 2001) provides strong scientific basis for several conclusions related to occupancy sensors. The main conclusion is that occupancy sensors are much more efficient for managing lighting than occupants using switches.

According to (Khalid et al., 2012) in order to implement an effective lighting control system, it is essential to conduct a lighting audit to determine the current usage and identify areas where energy savings can be made. This audit can be used to determine the best control system for each case, starting from simple occupancy sensors to centralized control systems or the use of AI. Good practices for efficient industrial lighting, such as the use of LED lighting and minimizing glare, should also be taken into account during the audit. A study on energy conservation through lighting audits revealed that effective lighting audits can result in energy savings of up to 40%

Designing an efficient lighting control system requires a methodical approach, considering factors such as the type of work being done, the size and layout of the space, and the required light levels. Energy-efficient Velux daylighting simulation software can also be used to optimize the use of natural daylight in industrial buildings and create an holistic approach for using the best combination of artificial and natural light to assure certain illuminance level during the day.(Kousalyadevi & Lavanya, 2019)

Finally, the study from (Kralikova & Wessely, 2016) presents a methodical procedure of how an efficient lighting system should be designed, including the control system. After analysing the energy consumption of the original system and a detailed analysis of the space that needs to be illuminated, a selection of lighting system is done by the selection of the luminaires and control system. In Figure 14 a diagram of the procedure to select an optimum control system can be appreciated.

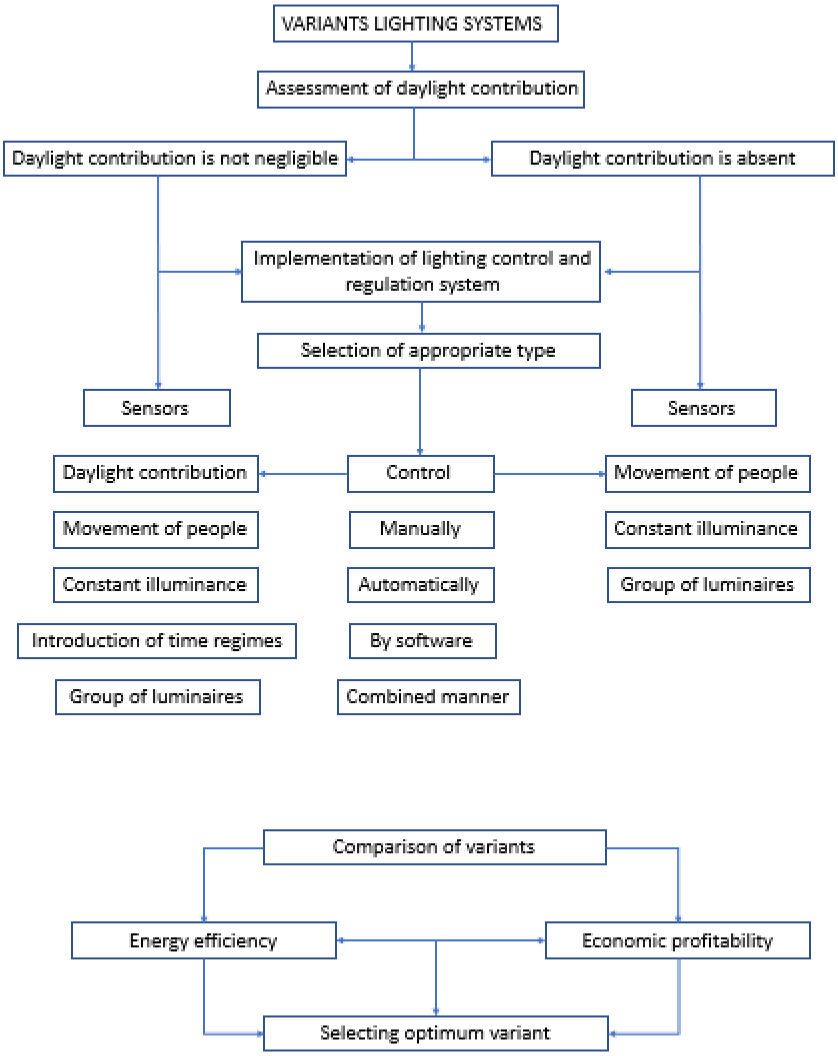

Figure 14 - Optimum control system selection - Adapted from (Kralikova & Wessely, 2016)

4.1.3 Maintenance of lighting

It is well known that maintenance plays a crucial role in maintaining the lighting system in optimal conditions, preventing lumen depreciation, and maintaining energy efficiency. Several studies about the effects of maintenance in industrial lighting energy efficiency have been analysed and the main findings will now be presented.

The study (Preston & Woodbury, 2013) concluded that retrofitting existing lighting systems of poor performance with energy-efficient alternatives can result in a significant energy saving. However, the energy savings will always be dependent on regular maintenance, which includes the replacement of failed lamps and ballasts. The study also presents the lumen maintenance value. This value is defined as the ratio between the mean lumen output and the initial lumen output. Therefore, it is a measurement that can be used to evaluate the decrease in lumen output of a bulb over time. When a retrofitting project is carried out, this value is crucial as the lamp with the greater starting lumen output may have a rapid lumen output decline, resulting in a mean lumen output that is actually lower than the lamp with the lower initial lumen output.

In the same way, the paper (Khalid et al., 2012) and (Kralikova et al., 2015) remark the importance of regular maintenance for reassuring the good performance of lighting systems. The paper recommends implementing a lighting audit program including periodical inspections, replacement of malfunctioning lamps and cleaning to guarantee the optimal performance and energy efficiency of lighting.

Finally, the studies (Kralikova & Wessely, 2016) and (Shailesh, 2017) also supports the idea that maintenance is a key factor for ensuring lighting energy efficiency and it suggests that the early phase of the design of an efficient lighting system should take into account maintenance factors such as simplicity of the replacement of lamps and the accessibility of fixtures in order to ensure the maximum maintenance efficiency.

4.1.4 Replacement of inefficient lamps

The use of inefficient lamps for industrial lighting usually leads to an increased energy consumption and higher maintenance costs. Moreover, old lamps can lead to poor working conditions due to lumen depreciation through time specially when there has been a lack of a well-designed maintenance program. Therefore, the replacement of inefficient lamps with new energy-efficient alternatives such as LED lighting is an approach that is becoming popular in several industrial facilities for improving energy efficiency.

A study has been conducted to determine what type of lamp is the best nowadays for the replacement of old inefficient lamps in industrial facilities. The study (Perdahci et al., 2018) which makes a comparative study of fluorescent and LED lighting in industrial facilities found that LED lamps are more energy-efficient and cost-effective than fluorescent lamps, due to their higher luminous efficacy and longer lifespan. The study also argues that in many cases fluorescent lamps are still preferred in several facilities due to their accessibility in open market. These two lighting technologies are the most used nowadays for replacing old lighting due to their luminous efficacy and short payback period.

In Table 6 main advantages and disadvantages of LED lighting technology are presented.

Table 6 - Advantages and disadvantages of LED lighting – Adapted from (Cowan & Daim, 2011)

Advantages of LEDs
Efficiency: LEDs can produce more light per watt than incandescents and many fluorescent bulbs. Their theoretical maximum efficiency is higher than any other current lighting technologies. Shape and size does not affect efficiency, unlike fluorescent bulbs. LEDs also radiate very little heat compared to incandescents and fluorescents.
Lifetime: LEDs useful operating lives are estimated between about 25,000 to 50,000 hours today to 100,000 hours or more in the future. Incandescent light bulbs last only about 1,000–2,000 hours, while most fluorescents last about 8,000 to 10,000 hours. LEDs also tend to slowly grow dimmer over time, rather than abruptly failing, like most other lighting technologies.
Color: LEDs can produce colored light without the use of filters. Most current LEDs tend to produce cooler colors, however, than traditional light sources, leading some people not to choose LEDs for general illumination.
Cycling: LEDs can be turned on and off very quickly, and frequently cycling them does not cause premature failure, the way it does with fluorescents.
Low Toxicity: LEDs do not contain toxins like mercury that are found in fluorescent bulbs. This makes recycling easier.
Disadvantages of LEDs
Efficiency: Although LED's theoretical maximum efficiencies are very high, currently fluorescent bulbs are more efficient at producing light in the commonly desired daylight spectrum ranges.
High Purchase Price: The initial price of LED lighting is still considerably more expensive than other lighting technologies, however costs are projected to fall rapidly.
Light Quality: The color spectra produced by LEDs can differ significantly from sunlight or incandescent light. The color of the light tends to be cooler and more blue. Although advances are being rapidly made to develop LEDs which produce natural light colors, it is unclear when such changes may occur.

On the other hand, the paper (Preston & Woodbury, 2013) which makes a cost-benefit analysis of retrofitting high-intensity discharge factory lighting with energy-saving alternatives explores different options for the most cost-effective solution. In this case LED lighting is not considered for the replacement of old metal halide and high-pressure sodium lamps. The study finally concludes that although new pulse-start metal halide lamps could be used for retrofitting the old ones with a reduced investment cost, the best alternative is to use the T5 type fluorescent lamps. The retrofit with this fluorescent lamp would represent an average 3% deterioration in lumen output and a payback period of between 5.6 and 6.5 years. Afterwards, a yearly saving of 50$ per base case fixture relative to maintaining the pulse-start metal halide lamps is estimated. It has to be noted that these values are from 2013 and nowadays, there are more cost-effective options in the market with more energy efficient fluorescent lighting and LED technology.

In order to select the most suitable energy-efficient lamp it is crucial to consider several criteria including colour rendering, colour temperature and luminous efficacy. The study (Paul et al., 2017) highlights the importance of choosing luminaires that have high colour rendering index to reassure an accurate colour reproduction and visual clarity within the workplace. These parameters for different lighting system can be appreciated in Table 1.

In short, the replacement of inefficient lamps with new energy-efficient alternatives such as LED or T5 fluorescent is a simple solution to reduce the energy consumption in a company. The low payback period of implementing these technologies should make the investment worth in most cases and extra benefits such as better working conditions could be achieved if the technology is supported by a suitable control system.

4.2 Added values of lighting

Apart from providing visibility, lighting is a key aspect of any industrial facility and serves to multiple purposes. A good lighting system should enhance safety, comfort, productivity, and energy efficiency in a workplace. Additionally, a well-designed lighting system can help to reduce human errors and accidents and increases employee morale and well-being. On the other hand, as it has been cited several times in this document, energy efficient lighting is able to promote sustainability and reduce energy use and electricity costs which is key for a company to comply with environmental regulations. Therefore, added values of lighting should be always considered when new investments related to lighting are going to be done.

Conducting a lighting audit can be a good opportunity to identify non-energy benefits as building owners and managers can focus on areas where a more efficient lighting equipment can have other benefits apart from the economic such as enhanced productivity and safety. For instance, installing task lighting in work areas can improve visibility, reduce eye strain, and enhance worker comfort, leading to increased productivity.(Khalid et al., 2012)

Although added values could also be considered as drivers towards implementing more efficient industrial lighting, in this study drivers and added values have been included in separated chapters as one of the main objectives of this study is to explore in detail the different added values of having more efficient industrial lighting and how they are considered in decision making processes.

4.2.1 Improved safety

Industrial lighting is a key aspect of a workplace safety. A good lighting system can reduce accidents, enhance productivity, and improve the work environment in general.

The main benefit of a good lighting can be considered the improved visibility. For example, in hazardous environments, it is crucial that workers have a clear vision of the surrounding environment. Considering the study (Peck et al., 2011) effective lighting can help workers with the identification of potential hazards as for example moving machinery, different obstacles or similar dangers that can be usual in an industrial setting. Moreover, effective lighting should improve the visibility of warning signs and therefore avoid accidents. The paper from (Peck et al., 2011) also claims that the recent adoption of LED technology instead of HID (High Intensity Discharge) has significantly improved lighting for applications in hazardous locations in terms of safety, light quality and reliability, mainly due to their high CRI index, good lumen maintenance and low maintenance need during a prolonged lifetime.

The research paper (Jayawardena et al., 2016) examines the impact that lighting has on workers safety and well-being in a very precise way. The study finally concludes that a proper lighting can reduce accidents within a workplace and enhance productivity. If the entire study is analysed, firstly, it claims that safety is the primary reason for investing in more efficient lighting, but many attributes of lighting that have a real impact on safety are often overlooked. Therefore, it argues that safety centric solutions require a human centric product design for any application as research has shown that different attributes of lighting have an impact on visual and non-visual human performance.

The paper also presents several facts about the effects of improved lighting and presents LED technology as a way to reduce occupational hazards due to improved visual performance and low maintenance requirements. One of the effects of improved lighting is the statistical evidence that lighting quality improvements have reduced roadway accidents by 12-30%. Moreover, studies have indicated that controlling light exposure can lead to enhanced alertness and better sleep quality for nurses working night shifts in hospitals. This, in turn, would decrease fatigue and lower the risk of human error. While some of the research cited pertains to non-industrial settings, the underlying visual processes are similar, suggesting that similar benefits may be achievable by improving lighting quality in industrial environments.

The study finally claims that there is limited knowledge on the correlation of lighting quality and reduction in occupational hazards in industrial environments and that many times lighting is lumped along with other environmental stress factors that have demonstrated strong correlation with occupational injuries in industrial environments. In Table 7 the study tries to develop a lighting quality framework that combines occupational injuries, visual attributes and lighting quality metrics.

Table 7 - Relation between occupational injury, visual attributes and lighting quality metrics - Adapted from (Jayawardena et al., 2016)

Occupational injury incident	Key visual attributes	lighting quality metrics
Fatigue induced human error	Circadian entrainment Alertness	Circadian light stimulus
Slip, trip and fall	Supra-threshold visual performance	Relative visual performance (RVP)
	Color discrimination	Color rendering index (CRI)
	Glare	Unified glare rating (UGR)
	Efficient light distribution	Application Efficacy - LASE
Roadway/ Transportation accidents	On-axis-vision-threshold Visual performance	Small target visibility (STV)
	Off-axis vision	Mesopic luminance
Contact with objects/ equipment	Efficient light distribution	Application Efficacy - LASE
	Supra-threshold visual performance	Relative visual performance (RVP)
	Stroboscopic effect	Flicker index
Perception of personal safety	Brightness	Brightness efficiency function

If the framework from Table 7 is taken as a guideline, industrial facilities could use it for calculating lighting metrics and relate the metrics with the visual attributes that they should improve to avoid certain accident. Moreover, this framework can be considered as effective in evaluating lighting technologies, luminaires, and lighting installations in relation to their impact on occupational safety. The lighting quality metrics from the previous table are described in the paper (Jayawardena et al., 2016).

On the other hand, the paper from (Leong & Seaver, 2015) emphasizes the importance of safety considerations on industrial settings. In this study the authors discuss the negative effects that old and inefficient lighting fixtures can have, such as reduced productivity, eye strain or accidents derived from poor lighting, and make suggestions on how to improve lighting and minimize risks within the work environment. The study also highlights the significance of industry type and environmental conditions in determining the extent to which accidents and hazards can be averted. Moreover, the paper emphasizes the necessity of appropriate lighting levels, accurate colour rendering, and the avoidance of glare and shadows. Regular maintenance and inspections are also underscored as key factors in reducing accidents. The implementation of these recommendations can foster safer and more efficient work environments for employees in industrial facilities.

The type of lighting used in the facility also plays a key role on preventing accidents. The study (Leong & Seaver, 2015) argues that it is usual to have multiple lamp failures in the same area of a facility, rising the risk of accidents due to poor illumination. Considering this, it is important to note that lighting technologies such as LED need less maintenance compared to traditional incandescent lamps. Moreover, LED lamps have a much larger life span, so the needed relamping is much lower than other technologies and the exposure of maintenance workers into hazards such as elevated work is reduced as it can be seen in Figure 15.

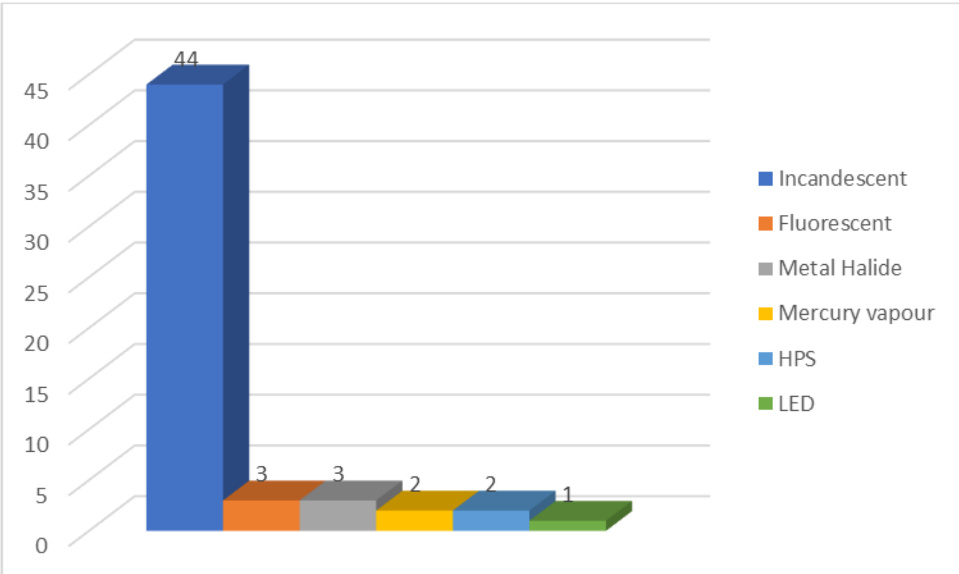

Figure 15 - Relamping occurrences in a 5 year period – based on (Leong & Seaver, 2015)

In conclusion, by combining the rapid technological advances in LED technology with the use of systems such as advanced controllers or remote monitoring, intelligent lighting solutions will provide enhanced security conditions in future workplaces, bringing more control and predictability.

4.2.2 Impact on health

Several studies have already concluded the significant impact of industrial lighting on employee health and well-being. Such studies have examined the effects of lighting on many aspects of human health such as thermal and visual comfort, cognitive performance, non-visual effects, emotional state, and safety.

The research conducted by (Cheong et al., 2020) introduces a methodology supported by simulations to enhance the comfort of both temperature and visual aspects while promoting energy efficiency in building structures. This design approach encompasses three distinct stages. The initial phase entails creating a virtual representation of the indoor environment. Subsequently, the second phase involves employing light transport simulations to assess the lighting conditions within the indoor space. Lastly, the third phase incorporates computational fluid dynamics (CFD) simulations to evaluate the thermal conditions, including heat transfer. The study finally shows that inadequate lighting can cause discomfort and results in increased energy consumption. The ability to accurately predict lighting conditions is crucial nowadays for human health-centred design optimization in a modern world where speed and precision is especially important.

In contrast, the publication by (Zauner & Plischke, 2021) examines the impact of different lighting conditions on the physical and mental wellness of individuals working night shifts. Research indicates that when night shift workers experience disturbances in their natural sleep patterns and are exposed to artificial illumination, they face higher susceptibility to health concerns, including cardiovascular diseases, diabetes, and weight-related problems. The researchers emphasize the importance of creating lighting conditions that support the human body's natural circadian rhythms.

The study presents the term non-visual lighting. While conventional lighting has traditionally been focused on providing illumination for visual tasks, non-visual light sources are the ones designed to improve aspects such as human physiology and behaviour. It is recommended to use non-visual light design principles that take into account the effects of light on the human body beyond mere perception, such as exposure time, intensity and colour temperature.

The study presents a case study of an industrial production line where non-visual lighting design principles were applied, resulting in improved employee satisfaction and a reduction in production errors. The research found non-visual lighting to improve night shift workers health. An example of non-visual lighting could be the use of specific wavelengths of light to stimulate alertness and regulate circadian rhythms without directly influencing visual perception. This can be achieved by employing blue-enriched light during certain periods of the night shift to promote wakefulness and enhance cognitive performance, while minimizing disruption to the natural sleep-wake cycle. The study also highlighted the need for further study and practical application of non-visual design principles. Overall, the paper emphasizes the important role of lighting conditions in supporting the health and performance of workers, particularly those working night shifts.

In the study (Hawes et al., 2012) which analyses the effects of four workplaces lighting technologies on parameters such as perception, cognition and affective state, the researchers found that different lighting technologies can have a significant effect on the affective state and cognitive performance of workers. Some examples of that effect are the improvement of cognitive performance by lighting that mimics natural daylight and the increased alertness and reduced fatigue by blue-enriched lighting. Additionally, high colour temperature LEDs generally increase arousal states and have lower rated depression relative to the lower temperatures lighting such as the traditional fluorescent technology.

In conclusion, industrial lighting has a significant impact on human health, and studies have highlighted the importance for businesses to invest in quality lighting systems to ensure the health and safety of the personnel. Moreover, it has been demonstrated that production quality of night shifts can also be improved by correct lighting, specially when LED technology is used.

4.2.3 Improved production quality

Proper lighting can play a crucial role in reducing human errors and improving product quality. This is due to the fact that adequate lighting enhances visibility, which is critical in identifying and rectifying errors in manufacturing processes.

The study (Hawes et al., 2012) that has been presented before, which analyses the effects that different lighting technologies can have on perception, cognition and affective state, also emphasizes the improvement of high colour temperature lighting in several aspects related to production quality. On the one hand, on the tests accomplished for colour recognition performance, improvement was shown by higher colour temperatures. This affects product quality directly as colour recognition can be key in order to realize small errors in the production. This result can be related to an improved visual acuity. On the other hand, higher colour temperature lighting was also proven to improve reaction time, which can be important for product quality checks, especially when there is limited time.

The study (Hossain & Ahmed, 2012) examines the effect of illumination on work efficiency in garment factories in the tropics. One of the key findings of the study was the relationship between illumination conditions and production errors. This study examines very accurately the implications of inadequate illumination in the production errors. The study suggests that production errors are increased due to the fact that workers require good visibility to perform their tasks according to the established quality standards. Inadequate illumination may cause visual discomfort, reduces visibility and finally, causes eye strain and fatigue. All these factors play a crucial role in production errors.

The main recommendation of the paper is to use adequate lighting levels in order to reduce the production errors in garment factories. In this case, the use of LED lighting is recommended for these types of factories due to the bright and consistent illumination they provide. Finally, a last recommendation would be the use of task lighting to be able to provide focused illumination on specific work areas in order to provide the necessary lighting levels in each case.

In conclusion, the study highlights the importance of proper illumination conditions in reducing production errors in garment factories. Adequate lighting can improve visibility, reduce eye strain and fatigue, and enhance worker performance, ultimately leading to higher productivity and better product quality. As such, garment factory owners and managers should prioritize the implementation of proper lighting systems to ensure optimal production outcomes.

Finally, it can be said that LED lighting is the best option for improving production quality in an industrial environment as it usually has higher colour temperatures and CRI, which enables a better visual acuity and faster reaction time for workers performing quality-related tasks.

4.2.4 Improved environmental performance

It is well-known that industrial lighting is a key factor for ensuring the safe and efficient operation of all type of industrial facilities. However, traditional lighting that is still widely used nowadays such as incandescent lamps can be energy-intensive, producing a big share of greenhouse gas emissions in a factory. Nowadays, there is a growing need of shifting towards energy-efficient lighting solutions, specially driven by the growing awareness of companies towards being more sustainable and comply with policies and regulations that are becoming stricter over the years. This rise of awareness has been highly influenced by the need to mitigate climate change. In this context, the added value of improved environmental impact should always be considered in decision making processes, as depending on the context of policies and regulations, it can even be more relevant than the cost savings.

As an starting point, the paper (Bergesen et al., 2016) investigates several possible environmental advantages, limitations, and risks associated with the use of energy-efficient lighting as a solution for reducing global greenhouse gas emissions in the short and long term. To achieve this, a life cycle assessment (LCA) is conducted to compare various light source technologies based on a wide range of environmental indicators. The paper first highlights that lighting represents a significant source of energy consumption worldwide and is responsible for a large share of greenhouse gas emissions. Because of that, there is a need to develop and adopt more energy-efficient lighting technologies to reduce energy consumption and mitigate the environmental impact of lighting.

The authors emphasize that embracing energy-efficient lighting technologies, like light-emitting diodes (LEDs), holds great promise for substantially diminishing both energy consumption and greenhouse gas emissions. LED lighting stands out by consuming significantly less energy and having longer lifespans compared to conventional lighting technologies. This translates to reduced energy usage, lowered operational expenses, and decreased waste. Furthermore, the implementation of LED lighting can also contribute to decreased reliance on air conditioning since they generate less heat compared to traditional lighting. This dual benefit further drives down energy consumption and the corresponding greenhouse gas emissions.

LED lamps and fixtures are becoming more common in homes, offices, and industrial and commercial buildings, as they are replacing traditional incandescent and fluorescent lamps and fixtures. A luminaire is a full lighting system that includes one or more lamps, their housing, and necessary drivers, or ballasts. Fluorescent lamps require a ballast to regulate their operation, while LED technology needs an integrated control gear and driver in the base. In Table 8 the market penetration scenario for new solid-state lighting can be appreciated until the year 2050.

Table 8 - Shares of energy consumption for a conservative scenario of solid-state lighting market penetration – Adapted from (Bergesen et al., 2016)

Market type	Light source	Commercial and industrial (%)			Residential (%)		
		2010	2030	2050	2010	2030	2050
OECD	Incandescent lamps	7	0	0	85	0	0
	CFLs	4	0	0	9	40	25
	LED lamps	<1	0	0	<1	40	55
	FL luminaires	88	50	30	6	10	5
	LED luminaires	<1	50	70	<1	10	15
Non-OECD	Incandescent lamps	20	0	0	61	0	0
	CFLs	3	0	0	9	40	25
	LED lamps	0	0	0	0	40	55
	FL luminaires	77	50	30	2	10	5
	LED luminaires	0	50	70	0	10	15
	Kerosene lamps	0	0	0	28	0	0

In Table 8 CFLs refers to compact fluorescent luminaires. On the other hand, OECD stands for Organization for Economic Cooperation and Development, which is a platform in which the governments of 37 democracies with economies based on markets work together to create guidelines for policies that encourage long-lasting economic expansion.

The paper also explores the environmental implications of manufacturing and disposal of energy-efficient lighting technologies. While the production of LED lighting requires a higher initial investment, the long-term energy and cost savings outweigh the environmental impacts of the manufacturing process. Moreover, LED lighting can be recycled, and their disposal has less environmental impact than traditional lighting technologies. Finally, as they have much longer life span compared to other technologies, LED lighting fixtures need lower replacements, which decreases the waste generation greatly.

According to this analysis, solid state LED light sources, CFLs, and fluorescent luminaires have environmental and natural resource benefits when compared to traditional incandescent light sources. Over time, the life cycle impacts resulting from these light sources are expected to decrease. However, in the short term, replacing inefficient light sources with efficient ones may require additional metal resources due to the materials needed for the lamps' electronics and phosphors. In the future, electricity generation scenarios that emit fewer greenhouse gases may require more metals and materials. Therefore, advancements in technology that improve the efficiency of light sources' materials or enable recycling and metal recovery may become more important.

The study (Wu & Su, 2021) examines the environmental impact of a specific LED low bay luminaire which will be manufactured in China and sold in the UK market. A low bay luminaire is a light that is intended for use in a ceiling under 20 feet from the floor. The luminaire is designed to be used in industrial environments. In this study, the luminous flux of a product's lifetime has been chosen as the functional unit because it allows for fair evaluation between luminaires with varying luminous flux. To achieve consistency in measurements, the functional unit for this study has been established as a luminaire that offers 40,000 hours of lighting service.

The paper presents a comprehensive analysis of the environmental impact of an industrial luminaire. Using the product environmental footprint (PEF) method, the study evaluated the luminaire's life cycle stages, including material extraction, manufacturing, transportation, use, and end-of-life. The results for different impact categories sorted by life cycle stages can be appreciated in Figure 16.

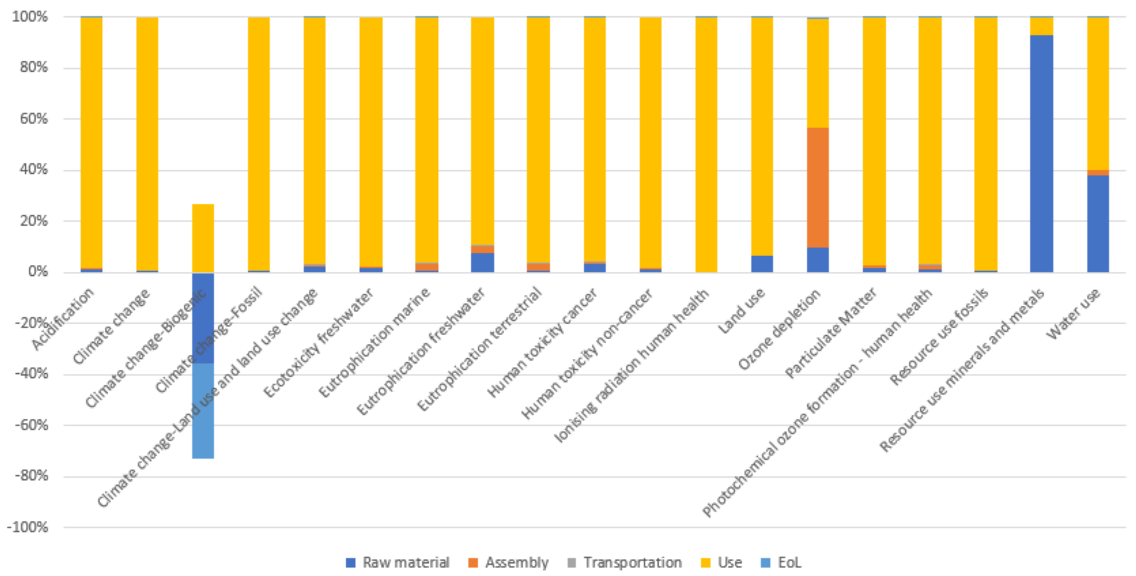

Figure 16 - Relative contribution of each life cycle stage of a LED luminaire manufactured in China and sold in the UK market in several impact categories – Adapted from (Wu & Su, 2021)

The results indicate that the major contributor for most of the impact categories is the use phase, where the electricity generation from the UK has been considered. In the UK, the use of biofuels for electricity production accounts for 7.85% of total electricity consumption. However, despite this relatively low consumption, it generates a significant 26.53% of the total environmental impact specially in the categories that include land use. In comparison, electricity generation from wind and hydro sources contributes negligibly to environmental impact, with only 0.03% and 0.002%, respectively. The worst environmental performance is shown by oil power, which accounts for a staggering 36.12% of total impacts with the 34.502% of the electricity contribution.

Regarding the Raw material extraction phase, it has by far the biggest contribution in resource use related to minerals and metals (92.9%) and relatively high contribution in water use (38%). The study suggests that using sustainable materials and energy-efficient manufacturing processes can significantly reduce the luminaire's environmental impact.

Considering the results from the Figure 16, it can be concluded that although producing new energy efficient luminaires has a considerable impact on the depletion of resources like minerals and metals and water use, the use of more energy-efficient luminaires in the use phase can severally reduce most of the impact categories analysed before. Therefore, changing towards efficient LED lighting technology reduces the overall environmental impact of the lighting system. In the future, new materials and optimized ways for recycling scarce resources should be used in order to reduce the impact on material depletion.

4.2.5 Implications of added values in energy efficiency investments on lighting

Nowadays, investing in energy efficiency has become a priority for companies in every sector in order to reduce their ecological impact and decrease energy expenses, often driven by imposed government regulations. When an energy efficiency investment is being considered, organizations tend to concentrate only on the operational cost savings they will have. However, it is important to also consider the added values that these investments can yield. These added values include enhanced worker productivity, improved safety, and an overall commitment to environmental sustainability The mentioned advantages should always be considered as they have the potential to influence a company’s performance and profitability greatly. In this context, the following text will explore the implications of added values when making an energy efficiency investment in order to optimize their investments.

In light of the research conducted by (Thollander et al., 2020, Chapter 14), empirical studies have concluded that the financial benefits derived from added values, also known as Non-Energy Benefits (NEBs), are approximately 2.5 times more substantial than the savings obtained through energy cost reduction alone. This emphasizes how important these extra values are compared to simple energy cost savings. It can be challenging to precisely quantify all the additional values, which makes it challenging to clearly see how they affect financial consequences. However, when determining the right payback time, it becomes essential to take into account the financial factors connected with these additional benefits in order to ensure informed energy efficiency investments and smart decision-making.

The paper (Nehler & Rasmussen, 2016) examines how firms consider non-energy benefits when making energy efficiency investments. This research indicates that firms have varying levels of awareness regarding added values of lighting and their importance. Some companies may prioritize non-energy benefits in their decision-making process, whereas others may overlook them entirely. This discrepancy can be a consequence of several factors, like the nature of the investment, the company's financial situation, the overall goals, or the implication of the top management on energy efficiency.

Moreover, the research paper highlighted the difficulty faced by companies in accurately measuring and quantifying the added values, thereby posing a challenge in integrating them into financial assessments. Consequently, companies may make investment choices that inadvertently overlook the potential financial advantages associated with these added values.

Nevertheless, the study reveals a positive trend, as companies are nowadays more aware of the importance of added values than some years ago. As most organizations are willing to improve their environmental sustainability and embrace social responsibility, they are increasingly acknowledging the substantial influence these added values can have on their overall achievements and financial well-being.

Overall, this research highlights the importance of considering the added values when making energy efficiency investments. While quantifying these added values can be difficult, it is essential for businesses to consider them in their decision-making process in order to make informed investment choices that optimize their overall sustainability and financial returns.

It is well known that improved lighting could improve work environment and workers health. According to the study (Nehler & Rasmussen, 2016), where several firms from the Swedish manufacturing sector are interviewed concerning added values in energy efficiency investments, all the company representatives surveyed considered work environment and health to be important. If an investment had the potential to improve the work environment, it was frequently included in investment proposals. However, none of the respondents expressed that they assigned a monetary value to non-energy benefits associated with work environment or health. Additionally, none of the respondents believed that it was possible to put a monetary value on health benefits.

On the other hand, regarding (Jayawardena et al., 2016) poorly planned and implemented lighting that is integrated into the work environment may raise the probability of human errors, leading to safety concerns. Research indicates that the average social cost of a workplace injury between 1992-2002 was USD 831,000 (in 2003 USD), which is now valued at USD 1,066,000. However, the cost saved by avoiding workplace injuries is not recognized as a benefit when assessing the investment in a lighting setup. As a result, there is a need for lighting measurements that can measure the safety benefits delivered by a specific application.

4.3 Drivers and barriers for adopting lighting efficiency measures

Efficient lighting practices have emerged as a key strategy to reduce energy consumption and curb greenhouse gas emissions. However, the adoption of lighting efficiency measures in various settings faces both drivers and barriers. Understanding these factors is crucial for policymakers and businesses looking to implement sustainable lighting solutions. On the one hand, drivers such as energy and cost savings, increased productivity, and improved lighting quality can incentivize organizations to adopt efficient lighting measures. On the other hand, barriers like lack of awareness, upfront costs, and complex regulations can hinder the widespread adoption of efficient lighting practices. In this context, it is important to explore the drivers and barriers to adopting lighting efficiency measures in different settings and devise strategies to overcome these barriers to promote the widespread adoption of efficient lighting solutions.

The study (Kralikova et al., 2015) argues that in many cases, the implementation and use of energy-efficient lighting systems is not considered a top priority, as the available budget is typically allocated towards production-related activities such as the operation and modernization of production processes.

On Table 9 the most common driving factors for adopting energy efficiency measures are presented.

Table 9 - Main driving factors for adopting energy efficient lighting technologies – based on (Cowan & Daim, 2011)

Behavioral category		Technology Acceptance & Use Factors
Performance Expectancy	Relative Advantage & Outcome Expectations	Implementation Cost
		Energy Savings
		Payback Time
		Maintenance Cost
		Total Cost of Ownership
	Perceived Usefulness & Fitness for Purpose	Brightness
		Light Color
		Start-up Speed
		Flicker
Effort Expectancy	Ease of Operation	Ease of Use
		Ease of Maintenance
		Ease of Recycleability
Social Influences	Subjective Norms & Image	Perceived Greeness of Product
		Social Status/Significance of Adoption
		Importance of Recyclability
Facilitating Conditions	Compatibility	Standards/Compatibility
		Recycling Infrastructure
	Perceived Behavioral Control	Taxes of Tariffs
		Energy Prices
		Incentives or Promotional Policies
		Public Environmental Consciousness

Although several important driving factors are stated in the previous table, such as ease of operation and compatibility, under this section the energy and cost savings and the enforced policies have been analysed as main drivers and the implementation costs and lack of knowledge have been analysed as main barriers.

4.3.1 Drivers

In the following section the main drivers towards adopting energy efficiency measures in industrial lighting will be analysed.

4.3.1.1 Energy and cost reductions

The adoption of energy-efficient lighting measures has proven to be highly effective in reducing energy consumption and lowering electricity expenses across diverse industrial facilities. Numerous research papers have emphasized the advantages and potential presented by energy-efficient lighting solutions.

Improving energy efficiency can yield several benefits, even though they may not manifest immediately. Regarding (Adewunmi et al., 2019) among these benefits, the primary advantage is a reduction in energy costs, particularly in buildings where old inefficient lighting fixtures can be replaced. Additionally, other benefits include lower maintenance costs and improved comfort levels.

Similarly, according to a paper by (Grinbergs, 2013) industries heavily reliant on electrical lighting tend to consume a significant amount of energy, particularly when inefficient lighting practices are in place. Nonetheless, substantial energy savings can be achieved through the adoption of energy-efficient lighting technologies, the utilization of effective illumination sensors, optimized system design, and fostering increased awareness of energy conservation among workers. Apart from the electricity bill cost savings, the proper and efficient utilization of electric lighting can minimize heat gains, resulting in energy savings within air conditioning systems and improved thermal comfort. Furthermore, a study by (Kralikova et al., 2020) also supports the notion that minimizing energy consumption requires a controlled use of light, employing the appropriate amount only when necessary.

As an example of the potential effect that more efficient lighting can have on reducing electricity costs, the paper (Cowan & Daim, 2011) presents a good overview of the share of electricity consumption for lighting on the United States. Table 10 provides a summary of the electricity usage across three key categories of lighting users in the United States, where lighting accounted for roughly 17% of total electricity consumption in 2008, which is a considerable amount.

Table 10 - Percentage of electrical use for lighting by sector in the United States – adapted from (Cowan & Daim, 2011)

	Electrical Use by Sector (GWh/yr)	% of Electrical Use by Sector for Lighting	Total Electrical Use for Lighting (GWh/yr)	% of Total US Electrical Use for Lighting
Residential	1,390,650	16%	222,504	6%
Commercial	1,343,200	25%	335,800	9%
Industrial	1,003,750	7%	70,263	2%
Total Usage	**3,737,600**		**628,567**	**17%**

Although the residential sector had the largest total electricity consumption, only around 16% of this was used for lighting. In contrast, the commercial sector used a much higher percentage, with roughly one quarter of its electricity consumption going toward lighting. The industrial sector consumed about 3 to 5 times less electricity for lighting than the commercial and residential sectors, even though its total electricity usage was similar. This is due to the energy-intensive processes that are carried out in industrial settings. Given the amount of electricity used for lighting in these three sectors, new energy-saving lighting technologies have the potential to significantly reduce overall electricity consumption, being the new highly efficient LED technology one of the most promising.

In a broader sense, incorporating energy-efficient lighting solutions in industrial settings yields substantial reductions in energy consumption and cost. Nevertheless, it is crucial for policymakers and industry stakeholders to meticulously evaluate all the drawbacks and advantages associated with diverse approaches to promote energy efficiency, so that not only energy and cost savings are considered. This evaluation needs to consider both, financial and non-financial factors for ensuring a comprehensive understanding of the multifaceted implications involved.

4.3.1.2 Policy and regulatory framework

The policy and regulatory framework related to industrial lighting could be a complex area to understand. In order to make an evaluation of the enforced policies it is required to consider numerous factors such as the type of company they are directed to, and the extent to which they help companies to shift towards more efficient lighting options. Several studies have explored the effects of different policies and utility rebate programs related to industrial lighting, and the most representative will be now presented.

The paper (Grinbergs, 2013) argues that the main regulatory institutional barriers include a lack of government attention, insufficient enforcement of policies, a shortage of skilled personnel, and a focus on increasing supply instead of reducing consumption.

On the other hand, the study (Thollander et al., 2020, Chapter 16) provides a comprehensive overview of energy policy programs for promoting energy efficiency. The literature review reveals that energy policy programs are critical in promoting the adoption of energy-efficient technologies in different sectors, including industry, commercial, and residential settings.

(Thollander et al., 2020, Chapter 16) highlights the need for policy interventions that address the various barriers to energy efficiency, such as lack of awareness, high initial costs, and market failures. The book emphasizes that energy policy programs should be tailored to specific sectors and regions, taking into account their unique characteristics and challenges.

The study suggests that financial incentives, such as subsidies and tax credits, are effective in promoting energy efficiency by reducing the initial costs of adopting energy-efficient technologies or preventing companies from using inefficient energy intensive procedures. However, the effectiveness of financial incentives depends on the level of subsidy and the sector targeted. A good example of these economic policies are energy and carbon dioxide taxes. By implementing taxes on energy and carbon dioxide emissions, the expenses associated with energy consumption and emissions are raised. This increase in costs serves as a signal to industrial firms, urging them to adopt measures for improving energy efficiency. Another good example is the EU Emissions Trading Scheme (EU ETS), which was established in 2005 as a measure to decrease greenhouse gas emissions. Under the EU ETS, every EU company operating boilers, furnaces, etc., with a capacity exceeding 20 MW, is required to possess emission allowances equivalent to their greenhouse gas emissions. If a company requires additional emission permits or has surplus permits, they can be bought or sold in the market where emission rights are traded. The EU progressively reduces the quantity of emission allowances available within the EU ETS on an annual basis.

The study also discusses the importance of regulatory support in promoting energy efficiency. Regulations, such as building codes and appliance standards, can mandate the use of energy-efficient technologies and promote market transformation. The paper notes that regulatory support should be coupled with enforcement mechanisms to ensure compliance. Two good examples of effective administrative policies that are being used in Sweden are The Swedish Environmental Code, which states that the Best Available Technology (BAT) must be applied, and the law on energy audits for large companies.

Education and awareness-raising programs are also highlighted as important components of energy policy programs. These programs can increase public awareness of energy efficiency and promote behaviour change. The study suggests that education and awareness-raising programs should target different stakeholders, including consumers, businesses, and policymakers.

As far as specific policies for lighting are concerned, the paper (Shook & Choi, 2022) explores the use of machine learning techniques to forecast the effectiveness of utility lighting rebate programs in promoting industrial energy efficiency. The study focuses on the impact of these programs on lighting-related energy savings in the industrial sector. By utilizing historical data from previous rebate programs, the author develops predictive models to estimate the potential energy savings that can be achieved through such initiatives. The paper highlights the potential of machine learning as a valuable tool for policymakers and utility companies to optimize the design and implementation of energy efficiency programs in the industrial sector and emphasizes the importance of financial incentives on driving adoption of energy-efficient lighting technologies.

Another policy specific to lighting is presented in the paper (Frondel & Lohmann, 2011), which explores the impact of the European Commission's light bulb decree. This decree aims to phase out inefficient incandescent light bulbs in favour of more energy-efficient alternatives. The research suggests that while the regulation is costly, it has led to significant energy savings and reduced greenhouse gas emissions.

Overall, these studies demonstrate the importance of a policy and regulatory framework that supports the adoption of energy-efficient lighting technologies in industrial settings. This framework should include financial incentives, regulatory support, and educational programs aimed at increasing awareness and understanding of the benefits of energy-efficient lighting. Moreover, it must be noted that apart from the policies and regulations stated before, many companies are driven towards adopting more efficient industrial lighting due to economic factors such as increased price of electricity.

4.3.2 Barriers

On the following section, the main drivers for adopting energy efficiency measures for industrial lighting will be analysed.

4.3.2.1 Investment cost of lighting efficiency measures

The paper (Adewunmi et al., 2019) states that several companies prefer the use of energy efficient lighting equipment and ventilation, as they represent a relatively low investment cost compared to other measures such as the change of a boiler. Regarding the study, the primary barrier to implementing an energy-efficient strategy is the initial investment required, as companies are reluctant to accept short-term financial losses in exchange for long-term returns on investment from energy-efficient practices. For example, in the context of the South African facilities management sector, the main factor that makes firms invest in energy efficiency can be considered the immediate feedback of cost reduction in bills. Investments that require long term payback periods and have added values that cannot be immediately noticed such as improved health, are considered of secondary importance although still significant. This indicates that facilities managers acknowledge the significance of energy-efficient factors but may lack the necessary resources or means to implement them.

Many studies suggest that measures that imply high investment costs are not as attractive for companies as the low-cost ones even though they may represent a greater savings in the long-term. In the study (Thollander et al., 2020, Chapter 16) American IAC, which is the largest energy audit program globally, is analysed and it is found that approximately half of the recommended measures were implemented, with a preference for low-cost measures.

In the same line, the paper (Shook & Choi, 2022), highlights that companies often face significant upfront expenses when adopting energy-efficient lighting technologies and systems. This cost factor can deter businesses from pursuing such measures, as they may prioritize short-term financial considerations over long-term energy savings. The paper explores the use of utility lighting rebate programs as a potential solution to mitigate this barrier by providing financial incentives to offset the investment costs and encourage industrial energy efficiency initiatives.

On the other hand, the paper (Frondel & Lohmann, 2011) which analyses the European Commission's light bulb decree from 2009 refers to the relatively high initial investment cost as a psychological barrier rather than a lack of resources. The Commission's reasoning for banning incandescent light bulbs is that consumers have not adequately shifted towards more energy-efficient alternatives, despite the fact that these alternatives cost significantly less over their entire lifespan. This is because the price difference between traditional incandescent bulbs and more efficient options creates a psychological barrier, even though the higher initial investment pays off within a year and leads to substantial savings in the long run (though these savings are less visible). Therefore, the Commission sees the regulation as a necessary solution to correct the market's failure to adapt, implying that households are behaving irrationally.

4.3.2.2 Technology adoption

The study (Cowan & Daim, 2011) introduces the concept of technology adoption. The process of adopting a new technology involves several stages, according to the study. It begins with knowledge about the technology and progresses to persuasion, decision-making, implementation, and confirmation. At any point in this process, an individual or decision-making unit can choose not to adopt or even disadopt the innovation. Disadoption is particularly relevant for energy efficiency technologies, which often require ongoing commitment from users to reap the benefits. While simple interventions like weatherproofing a building may not require much effort, advanced energy efficiency products demand larger investments, time for learning and customization, and a willingness to accept performance trade-offs for energy savings. However, many energy efficiency technologies offer the advantage of rapid adoption, sometimes as quickly as replacing a light bulb. Sometimes, the adoption cannot be done so quickly, and high investment costs are needed, for example when implementing a centralized control system for lighting.

4.3.2.3 Lack of knowledge of energy-efficient options

The paper (Nehler, 2019) argues that energy efficiency measures typically arise from the completion of an energy audit within an industrial company, where a thorough examination and analysis of energy usage in various processes and areas of the firm are conducted. The energy audit enables the mapping and evaluation of information regarding the specific methods and locations where energy is consumed within the organization. Without carrying out an energy audit it is very difficult for a company to make a good decision towards investments on energy efficiency measures. Because of that, small companies that are not forced to carry out energy audits and have other priorities tend to overlook the benefits of energy efficiency.

The paper (Grinbergs, 2013) states that there are various challenges associated with the adoption of technologies, including limited knowledge, availability and a scarcity of qualified experts. Similarly, the study (Thollander et al., 2020, Chapter 15) presents several empirical barriers to energy efficiency in the Swedish industry from a questionary made to several Swedish companies. Several barriers related to information are presented in the study. One big barrier was the cost of obtaining information about the energy consumption of purchased equipment, especially when the information comes from equipment suppliers. Another important barrier was considered the lack of staff awareness as companies stated that staff members in general, did not pay attention to energy efficiency and its potential. Finally, although energy audits had been carried out, six out of eight respondents considered that they had poor information quality regarding energy efficiency opportunities.

As an example of the importance of the lack of knowledge, the paper (Adewunmi et al., 2019) states that South Africa is a developing nation that has witnessed substantial growth in its heavy industry sector, which inherently demands high energy consumption. However, there seems to be a lack of awareness and knowledge regarding energy-efficient strategies, and the South African industry and consumers are unaware of the existence of the strategies. The Energy Efficiency Strategy of the Republic of South Africa, released in 2005, highlights the opportunities for energy efficiency, but these have largely been overlooked. Consequently, it appears that energy consumption is being taken for granted in South Africa, likely due to the neglect of existing strategies.

Moreover, the study mentioned before (Adewunmi et al., 2019) argues that obstacles to implementing energy-efficient practices in organizations can arise from the level of education and training received by facilities managers during their academic and professional development. The commitment of facilities managers to energy efficiency is crucial and the education received from the manager can have a direct impact on that motivation.

Informative policies can be effective in helping companies to find energy efficiency improvement opportunities. Two main informative policy programmes applied in Sweden are presented on the study (Thollander et al., 2020, Chapter 16).

On the one hand, the energy audit policy program for SMEs can help small and medium size companies to identify areas that should be improved. The primary objective of this policy is to furnish the industrial sector with precise and tailored information regarding energy consumption and strategies for enhancing energy efficiency.

On the other hand, in the program for energy efficiency networks aimed at SMEs, approximately 400 participating companies are categorized into 40 customized networks. Each network comprises around 10 companies, working together under the guidance of a network coordinator and an energy specialist. The program commences with the companies conducting an energy audit, followed by regular meetings over a span of 3 to 4 years.

4.4 Application of AI in industrial lighting

The rapid advances in technology in recent years have made the application of AI in industrial lighting a real alternative offering new possibilities. The study (Jha, 2020) suggests that the process of transitioning to LED lighting technology occurred before the widespread implementation of Internet of Things (IoT) applications in the lighting industry. This sequence of events had the consequence of slowing down the adoption of artificial intelligence (AI) in the industry. In other words, the focus on transitioning to LED lighting took precedence over integrating IoT applications, which in turn delayed the advancement of AI technologies within the lighting industry. The study also suggests that there is a huge opportunity for AI in improving industrial lighting as the capability to learn characteristic is not present in today's lighting solutions.

4.4.1 Lighting optimization

On the one hand AI can be used for lighting optimization in real-time. Intelligent sensors can detect the presence of workers in a specific area and adjust the illumination based on that. The lighting could be reduced or turned off when there are no workers in the area which could save energy and reduce electricity costs. For that, (Jha, 2020) argues that self-learning algorithms and Machine Learning (ML) possess the capability to facilitate the adoption of adjustable lighting. By incorporating lighting and associated sensors throughout a building, they can serve as the foundation for smart buildings.

4.4.2 Customed lighting systems

AI can be used for creating a lighting system that is personalized depending on the needs and preferences of each worker and the type of activity that is carried out in each specific area. This can also improve the comfort and productivity of workers, which are some added values mentioned previously in this document.

The study (Jha, 2020) suggests that with an increased amount of data, the design emphasis will shift from the building itself to the individuals who inhabit it. This shift will be advantageous for all users, resulting in improved buildings that ultimately yield greater financial benefits for building owners. Moreover, (Jha, 2020) states that AI can play a crucial role in enhancing lighting experiences for end users. Through supervised learning, AI can learn and understand user preferences by analysing their selections. By gathering data from various sources, AI can automatically adjust lighting settings to meet the specific needs of users and even provide personalized lighting recommendations.

Without AI, it is possible to ensure adequate illumination above standard norms by selecting appropriate lighting solutions, assuming the environment and needs remain unchanged. However, since needs often evolve, users may develop different requirements over time. To address this, user interfaces can be implemented to allow users to modify lighting conditions according to their preferences. It has been noticed that individuals are willing to tolerate less than optimal lighting conditions prior to assuming control, indicating that depending exclusively on users for lighting regulation may not be adequate.

AI has revolutionized various industries, and one area where it has made significant strides is in the development of customized lighting systems. In the paper (Koh et al., 2011), the authors explore the use of AI in creating intelligent and energy-efficient lighting solutions.

Similar to the previous study, the paper (Koh et al., 2011) argues that customized lighting systems have gained popularity due to their ability to enhance user experience, improve energy efficiency, and provide a tailored environment for different applications. Traditional lighting systems often rely on manual adjustments or simple timers, which may not fully meet the diverse needs of users. AI-powered lighting systems, on the other hand, offer a more intelligent and flexible approach.

The paper proposes the use of AI algorithms to optimize lighting control in a low voltage DC grid powered smart LED lighting system. By leveraging AI techniques, the lighting system can adapt to changing conditions and user preferences in real-time. This level of adaptability ensures that the lighting system operates at maximum efficiency while meeting the specific requirements of different environments. AI algorithms can learn from user feedback and behaviour patterns to adjust lighting settings accordingly. For instance, the system can learn when and where users require brighter or dimmer lighting, automatically adjusting the intensity and colour temperature to create a more comfortable and productive environment.

4.4.3 Predictive maintenance

Predictive maintenance is one of the most innovative and interesting applications that AI is bringing to the world of industrial lighting. The AI can be used to monitor the lighting systems to identify possible issues and malfunctions. This enables a facilities manager to spot minor issues before they turn into more complicated and expensive issues.

The paper (Segovia-Muñoz et al., 2022) focuses on enhancing current fault detection procedures in LED street lighting through the implementation of a telemanagement system and predictive maintenance using software tools. Telemanagement, also known as telecommunication management, refers to the process of managing and overseeing various aspects of telecommunication systems and networks within an organization. It involves the administration, monitoring, and control of telecommunication resources, services, and devices to ensure their efficient operation and optimal utilization.

The paper emphasizes the importance of effective fault detection in LED street lighting systems to minimize downtime and maintenance costs. Traditional maintenance approaches often rely on reactive measures, where faults are identified after they occur. However, this approach can lead to delays in repairing faults and result in extended periods of inefficient lighting.

To address these challenges, the paper proposes the use of a telemanagement system, which allows for remote monitoring and control of street lighting. By utilizing software tools, the system enables real-time data collection and analysis, facilitating the detection of faults and malfunctions more efficiently.

Predictive maintenance plays a crucial role in this approach. The system utilizes data from various sensors installed in the LED street lighting infrastructure to monitor performance parameters such as temperature, power consumption, and light output. By analysing this data, the software tools can identify patterns and deviations that indicate potential faults or deterioration in the system.

The paper highlights that the predictive maintenance approach allows for proactive intervention and timely repairs. Instead of waiting for a fault to occur, maintenance personnel can be alerted in advance, enabling them to take necessary actions promptly. This approach minimizes the impact of faulty lighting on public safety and reduces overall maintenance costs by addressing issues before they escalate.

Furthermore, the software tools employed in the telemanagement system provide additional benefits. They enable centralized monitoring and control, allowing operators to remotely adjust lighting levels, schedule maintenance activities, and optimize energy consumption. The ability to remotely access and control the street lighting system enhances operational efficiency and reduces the need for physical inspections.

In Figure 17 the predictive maintenance plan proposed by the study can be appreciated.

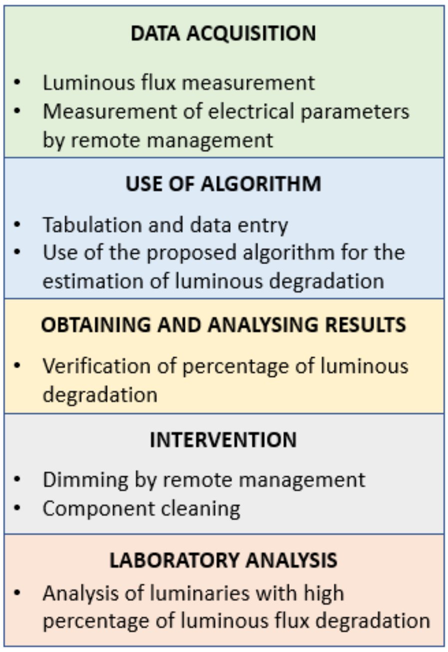

Figure 17 - Proposed predictive maintenance plan from (Segovia-Muñoz et al., 2022)

Similarly, the paper (R.Berlanga-Llavori & D.María Llidó, 2018) focuses on the implementation of a predictive maintenance approach for outdoor lighting systems using a Smart Outdoor Light Desktop Central Management System. Predictive maintenance plays a crucial role in ensuring the optimal performance and longevity of outdoor lighting systems. Traditionally, maintenance activities for such systems have been conducted on a fixed schedule or in response to reported faults. However, these approaches often lead to inefficiencies, unnecessary costs, and delays in addressing issues.

The paper proposes a more proactive and efficient approach to maintenance through the implementation of a Smart Outdoor Light Desktop Central Management System. This system utilizes advanced technologies and data analysis to predict and detect potential faults or failures in the lighting infrastructure before they occur.

By leveraging data collected from various sensors and monitoring devices, the system continuously analyses performance parameters such as energy consumption, light intensity, and temperature. Machine learning algorithms and predictive analytics are applied to this data to identify patterns, anomalies, and potential indicators of imminent failures. The predictive maintenance approach offers several benefits. It enables maintenance personnel to receive timely alerts and notifications about potential issues, allowing them to intervene proactively. This reduces the risk of complete system failure and optimizes maintenance schedules and resource allocation.

Additionally, the Smart Outdoor Light Desktop Central Management System can generate detailed reports and analytics, providing valuable insights into the performance and condition of the outdoor lighting infrastructure. These insights can inform decision-making processes, optimize maintenance strategies, and improve the overall efficiency of the lighting system.

The studies that have been analysed in this section focus on street lighting systems instead of industrial lighting systems. It has been considered that the results from the street lighting analysis in predictive maintenance can be extrapolated to industrial lighting.

4.4.4 Integration of AI in Building Management System (BMS)

Another new possibility is the integration of AI in the BMS of a facility. This enables lighting systems to work coordinated with other systems for the energy optimization and security improvement of a building. For example, if a smoke detection system detects a fire in a specific area, the AI can adjust the lighting to guide workers to emergency exits.

Moreover, the integration of AI in Building Management Systems (BMS) has brought significant advancements in optimizing visual comfort and energy consumption, particularly through the utilization of natural light. In the context of the paper (Zhang et al., 2019) AI techniques, specifically Particle Swarm Optimization (PSO), are employed to achieve these objectives.

By incorporating AI algorithms into BMS, the system becomes capable of dynamically adjusting lighting levels and optimizing the utilization of natural light sources. AI algorithms can analyse real-time data from various sensors, such as light intensity and occupancy, to determine the optimal amount of natural light to be used at any given time. This ensures that the visual comfort of occupants is maintained while minimizing the reliance on artificial lighting and reducing energy consumption.

The PSO algorithm, specifically used in the paper, is a computational optimization technique inspired by the behaviour of a swarm of particles. It enables the BMS to find the most suitable lighting settings based on defined objectives, such as maximizing visual comfort or minimizing energy consumption. The AI algorithm iteratively explores and updates the lighting parameters to achieve the desired optimization goals. For that, the algorithm based on PSO controls the curtains used to let the daylight enter in the building depending on the daylight available and the visual comfort conditions. Another goal of the control system apart of reducing lighting energy consumption, is to optimize the air conditioner energy consumption (ACEC), which is also highly influenced by the daylight entering to the building.

4.4.5 Challenges of using AI for industrial lighting

The study (Jha, 2020) identifies three main challenges. On the one hand, the challenge for humans lies in the fact that Artificial Intelligence (AI) is primarily based on mathematics and computer science. While advancements in computational and algorithmic efficiency have made it more accessible, AI still remains limited to a specialized community of scientists.

On the other hand, the challenge related to data is crucial. In order to develop reliable AI-based solutions, the availability and quality of data is very important. When considering the integration of AI solutions into an existing portfolio, the initial analysis heavily relies on the available data. However, the quality of the analysis greatly depends on the interpretability of the data.

Finally, the challenge related to privacy arises when implementing AI-based solutions that aim to enhance user experience. These solutions inevitably involve the use of user data to some degree. However, it is crucial to ensure that the collection of data does not infringe upon the privacy of any individual.

Chapter 5. CONCLUSIVE DISCUSSION

On the following chapter the most relevant conclusions from the study will be presented and discussed. This discussion will be separated in two sections, firstly the method will be discussed and secondly, the results.

5.1 Method discussion

In general, the method used for the literature search and the synthesis has been proved to be time-saving and rigorous. The use of the databases Scopus and Web of Science has assured the quality of the papers used for the literature review. However, it can be considered that the search has been limited to a certain number of papers, and many relevant papers that could give more insights about industrial lighting may have been overlooked in case they were not included in these databases. Moreover, papers from 2010 to 2023 have been considered for the study. Therefore, some papers were up to 13 years old, so they may be outdated to some extent due to the rapid advances in lighting technologies.

Regarding the synthesis of the literature selected, a concept matrix provides a structured approach to organizing and synthesizing information. It allows you to categorize and sort the literature based on key concepts, themes, or variables, making it easier to identify connections and patterns. Moreover, it gives you the possibility to present how the synthesis has been done in a visual way, for example, in a table. However, the most relevant limitations of using this matrix are the risk of oversimplification and subjectivity. On the one hand, depending solely on predefined categories or variables may lead to the omission of important details or subthemes. On the other hand, the process of categorizing and filling in a concept matrix involves subjective judgments. Different researchers may interpret concepts or assign them to different categories in varying ways.

5.2 Results discussion

In this section the results presented on the previous chapter will be discussed. The study has been separated into four different research areas. Firstly, the energy efficiency measures for lighting that are used nowadays have been explored. The objective of this first chapter is to resume the most important technologies and measures that are used to reduce the energy use of lighting in industrial environments. A large number of papers have been considered in this part as extensive research has been done during recent years about the available measures to reduce the energy consumption in lighting. The main measures that have been further analysed are improving daylight usage, the use of advanced control systems in order to use light just when it is necessary and integrate daylight in the lighting strategy, set an effective maintenance plan for preventing the lumen degradation of lighting fixtures, and finally, replace old inefficient lamps for new LED or fluorescent lamps. After analysing all the literature, for now the change of old inefficient lamps for efficient LED lighting seems to be the most cost-efficient alternative for industrial companies. However, in the near future the use of intelligent control systems based on dimmable LED lighting will be widely used given that the adoption of this technology will become more affordable.

Afterwards, the added values of efficient lighting have been highlighted. Firstly, the most considerable added values have been analysed in detail, which are enhanced safety, improved health, improved production quality and improved environmental performance. It has been demonstrated that the type of lighting used for the industrial illumination has a direct impact on the health and well-being of workers, especially for the ones working in night shifts. Moreover, it can be said that illumination also plays a key role in preventing several types of accidents in industrial facilities for example by enhancing workers alertness so that there is less probability of suffering an accident in case of any machinery failure or similar hazards related to industrial environments. The relation of lighting with production errors has also been proved. The use of LED lighting is recommended for reducing production errors due to the bright and consistent illumination they provide. Finally, the driver of the environmental implications of using efficient lighting has been presented. In this regard, it has been concluded that the use of new LED technology for lighting is far more beneficial for the environment than keeping using old traditional incandescent lamps. LED lighting has a longer lifespan than incandescent lamps, so less waste is generated, and lower maintenance is needed. Furthermore, during the use phase, as LED lighting consumes less power than other lamps for generating the same lumen output, it generates far less environmental impacts related to electricity production. This effect is even more notorious in territories that are producing electricity through fossil fuels and non-renewable sources such as oil and gas.

Regarding the considerations of added values in lighting energy efficiency investments, it has been concluded that added values are often overlooked by companies due to the fact that it is very difficult to make a monetary quantification of them. However, some studies claim that non-energy benefits bring more substantial savings than the ones obtained through energy cost reduction alone. Therefore, it is crucial to consider the added values when a decision is going to be made regarding any energy efficiency investment, for example by listing all the added values that any energy efficiency measure will imply and classify them by the importance that the companies are giving to them.

On the other hand, several drivers, and barriers towards adopting energy efficiency measures in lighting have been presented. Firstly, the most obvious driver has been presented, which is the energy and cost savings.

Another factor towards adopting energy efficiency measures has been considered policy. This factor can be considered a driver or a barrier depending on the level in which they promote energy efficiency. In several places the policies are considered insufficient for adopting efficiency measures whereas in other places they are having a great impact. Some studies suggests that financial incentives, such as subsidies and tax credits, are effective in promoting energy efficiency by reducing the initial costs of adopting energy-efficient technologies or preventing companies from using inefficient energy intensive procedures. A good example of effective policies are carbon dioxide taxes, which have pushed several companies to adopt energy efficiency measures to cut the costs related to emissions.

On the other hand, several barriers towards adopting lighting energy efficiency measures have also been discussed such as the high initial cost of measures, the difficulties for technology adoption and the lack of knowledge towards energy efficiency options. In many studies the initial investment cost of measures has been considered a psychological barrier more than a lack of resources. Even though measures that require bigger investment costs will have big benefits in the long run, companies tend to adopt energy efficiency measures that require lower investment costs and short payback periods. Economic policies can play a key role towards facilitating the adoption of more costly efficiency measures such as installing a centralized control system for the lighting and heating of a building. Furthermore, the barrier of the lack of knowledge of available energy efficiency measures has also been considered relevant as several companies do not have the necessary resources for conducting energy audits to identify areas that could potentially be improved. This problem is more common in SMEs as they do not usually have a specific position for defining the energy plan of the company and they are not able to afford external contributions. In order to solve this lack of information, informative policies can play a key role. For example, the energy audit policy program for SMEs offers subsidies for companies to carry out energy audits in order to facilitate tailored information regarding energy consumption and energy efficiency opportunities.

Finally, the opportunities to use Artificial Intelligence (AI) for industrial lighting have been analysed in detail. The study concluded that AI could be of great interests in applications such as predictive maintenance and personalized lighting, but it is still not widely used nowadays due to the high initial cost of the integration of AI in the industrial lighting system, and the current priority of replacing inefficient lamps for LED lighting. Furthermore, there are several challenges related to AI such as limited access on the market, the need of quality data for the well-functioning of the system and the privacy of personal data.

Chapter 6. FUTURE RESEARCH

In the following chapter several research areas related to industrial lighting that have not been explored in this document will be presented, as they have been considered important in case any future research around industrial lighting is going to be conducted.

On the one hand, it would be interesting to analyse the recyclability of different lighting technologies and perform a comparison between them. Furthermore, different techniques for recycling lighting fixtures could be presented and improvements could be suggested in order to recycle the maximum number of materials. This research area is especially interesting as there is a growing concern about material depletion and near future lighting technologies will probably be dependent on scarce materials.

On the other hand, a further analysis of the effectiveness of the policies related to industrial lighting that EU have put in place in recent years should be conducted in order to give valuable insight for policy makers for the creation of future policy programmes. Furthermore, this analysis should also be given a broader perspective, as the advances in lighting energy efficiency are much slower in developing countries compared to countries from Western Europe. Therefore, it would be interesting to make a comparison related to the adoption of energy efficient lighting technologies between multiple countries with different economic situations.

Finally, the challenges of the application of AI for industrial lighting could be further analysed, and how these challenges could be addressed in the future should be suggested, making a detailed plan.

Chapter 7. BIBLIOGRAPHY

Adewunmi, Y. A., Alister, A., Phooko, B., & Nokukhanya, T. (2019). Energy efficiency practices in facilities management in Johannesburg. *Journal of Facilities Management*, *17*(4), 331–343. https://doi.org/10.1108/JFM-11-2018-0067

Bergesen, J. D., Tähkämö, L., Gibon, T., & Suh, S. (2016). Potential Long-Term Global Environmental Implications of Efficient Light-Source Technologies. *Journal of Industrial Ecology*, *20*(2), 263–275. https://doi.org/10.1111/jiec.12342

Brendel, A. B., Marrone, M., Trang, S., Lichtenberg, S., & Kolbe, L. M. (2020). What to do for a literature review? - A synthesis of literature review practices. *26th Americas Conference on Information Systems, AMCIS 2020*, *May*.

Cheong, K. H., Teo, Y. H., Koh, J. M., Acharya, U. R., & Man Yu, S. C. (2020). A simulation-aided approach in improving thermal-visual comfort and power efficiency in buildings. *Journal of Building Engineering*, *27*(February 2019), 100936. https://doi.org/10.1016/j.jobe.2019.100936

Cho, J., Park, J. H., Kim, J. K., & Schubert, E. F. (2017). White light-emitting diodes: History, progress, and future. *Laser and Photonics Reviews*, *11*(2). https://doi.org/10.1002/lpor.201600147

Cowan, K. R., & Daim, T. U. (2011). *Understanding Adoption of Energy Efficiency Technologies : Applying Behavioral Theories of Technology Acceptance & Use to Understand the Case of LED Lighting for Commercial , Residential , and Industrial End-Users*.

Electrical4U. (2021). *Different Types of Lamps And Their Applications*. https://www.electrical4u.com/lamps-types-and-performance-comparison/

European Commission. (2023). *Energy efficiency directive*. Energy Efficiency Directive. https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficiency-targets-directive-and-rules/energy-efficiency-directive_en#content-heading-0

flickr. (2023). *No Title*. https://www.flickr.com/photos/russellstreet/7412970228

Frondel, M., & Lohmann, S. (2011). The European Commission's light bulb decree: Another costly regulation? *Energy Policy*, *39*(6), 3177–3181. https://doi.org/10.1016/j.enpol.2011.02.072

Grinbergs, K. (2013). Energy efficient electricity usage and lighting solutions for industrial plants. *Civil Engineering. International Scientific Conference. Proceedings (Latvia)*, *VO - 4*, *4*, 356–362. http://libezproxy.iyte.edu.tr:81/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsagr&AN=edsagr.LV2013000799&site=eds-live

Hawes, B. K., Brunyé, T. T., Mahoney, C. R., Sullivan, J. M., & Aall, C. D. (2012). Effects of four workplace lighting technologies on perception, cognition and affective state. *International Journal of Industrial Ergonomics*, *42*(1), 122–128. https://doi.org/10.1016/j.ergon.2011.09.004

Hellström, L., & Juslén, H. (2022). *Lighting meets Artificial Intelligence (AI)*. https://helvar.com/artificial-intelligence-lighting/

Hossain, M. M., & Ahmed, K. S. (2012). Illumination condition and work efficiency in the tropics : Study on production spaces of ready-made garments factories in dhaka. *Proceedings - 28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs - Towards an Environmentally Responsible Architecture, PLEA 2012*, *September 2014*. https://doi.org/10.13140/RG.2.1.1846.2880

ilumi. (2015). *COLOR TEMPERATURE and CRI*. LIGHT READING. https://ilumi.co/blogs/pulse/86601543-light-iq-color-temperature-and-cri

Jayawardena, A., Duffy, D., & Manahan, J. (2016). Impact of light on safety in industrial environments. *Record of Conference Papers - Annual Petroleum and Chemical Industry Conference*, *2016-March*. https://doi.org/10.1109/PCICON.2015.7435087

Jha, A. (2020). *AI & ML Application for LED Lighting*. *June*.

Katunský, D., Dolníková, E., & Dolník, B. (2018). Daytime lighting assessment in textile factories using connected windows in Slovakia: A case study. *Sustainability (Switzerland)*, *10*(3). https://doi.org/10.3390/su10030655

Khalid, M. U., Gul, M., Aman, M. M., & Hashmi, A. (2012). Energy conservation through lighting audit. *PECon 2012 - 2012 IEEE International Conference on Power and Energy*, *May*, 840–845. https://doi.org/10.1109/PECon.2012.6450335

Koh, L. H., Tan, Y. K., Wang, Z. Z., & Tseng, K. J. (2011). An energy-efficient low voltage DC grid powered smart LED lighting system. *IECON Proceedings (Industrial Electronics Conference)*, 2883–2888. https://doi.org/10.1109/IECON.2011.6119610

Kousalyadevi, G., & Lavanya, G. (2019). Optimal investigation of daylighting and energy efficiency in industrial building using energy-efficient velux daylighting simulation. *Journal of Asian Architecture and Building Engineering*, *18*(4), 271–284. https://doi.org/10.1080/13467581.2019.1618860

Kralikova, R., Andrejiova, M., & Wessely, E. (2015). Energy saving techniques and strategies for illumination in industry. *Procedia Engineering*, *100*(January), 187–195. https://doi.org/10.1016/j.proeng.2015.01.357

Kralikova, R., Koblasa, F., Wessely, E., Pinosova, M., & Dzunova, L. (2020). Opportunities of energy saving lighting for sustainable development. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, *31*(1), 44–48. https://doi.org/10.2507/31st.daaam.proceedings.006

Kralikova, R., & Wessely, E. (2016). Methodical procedure for designing of efficient lighting systems. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, *27*(1), 66–73. https://doi.org/10.2507/27th.daaam.proceedings.010

Leong, M. F., & Seaver, S. (2015). Lighting Safety Considerations. *IEEE Transactions on Industry Applications*, *51*(5), 4233–4238. https://doi.org/10.1109/TIA.2015.2429125

Lesko, M., Rózowicz, A., Baran, K., & Wachta, H. (2018). A luminaire with variable light distribution. *E3S Web of Conferences*, *49*, 1–9. https://doi.org/10.1051/e3sconf/20184900066

Mangkuto, R. A., & Soelami, F. X. N. (2017). Photometric and Colorimetric Measurements of Luminaires Using Goniometer and spectrophotometer in a Dark Chamber. *Procedia Engineering*, *170*, 226–233. https://doi.org/10.1016/j.proeng.2017.03.054

Nehler, T. (2019). *Non-Energy Benefits of Industrial Energy Efficiency Roles and Potentials* [Linköping University]. https://doi.org/10.3384/diss.diva-156297

Nehler, T., & Rasmussen, J. (2016). How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry. *Journal of Cleaner Production*, *113*, 472–482. https://doi.org/10.1016/j.jclepro.2015.11.070

Parise, G., & Martirano, L. (2013). Daylight impact on energy performance of internal lighting. *IEEE Transactions on Industry Applications*, *49*(1), 242–249. https://doi.org/10.1109/TIA.2012.2229454

Paul, B., Kamath, V., & Mathew, M. (2017). Lighting audit and energy efficient LED based lighting scheme for a pharmaceutical industry. *2017 Innovations in Power and Advanced Computing Technologies, i-PACT 2017*, *2017-Janua*, 1–5. https://doi.org/10.1109/IPACT.2017.8245136

Peck, J., Ashburner, G., & Schratz, M. (2011). Solid state led lighting technology for hazardous environments; Lowering total cost of ownership while improving safety, quality of light and reliability. *2011 European Conference on Electrical and Instrumentation Applications in the Petroleum and Chemical Industry, PCIC EUROPE*.

Perdahci, C., Akin, H. C., & Cekic, O. (2018). A comparative study of fluorescent and LED lighting in industrial facilities. *IOP Conference Series: Earth and Environmental Science*, *154*(1). https://doi.org/10.1088/1755-1315/154/1/012010

Preston, D. J., & Woodbury, K. A. (2013). Cost-benefit analysis of retrofit of high-intensity discharge factory lighting with energy-saving alternatives. *Energy Efficiency*, *6*(2), 255–269. https://doi.org/10.1007/s12053-012-9179-1

R.Berlanga-Llavori, & D.María Llidó. (2018). *Smart Outdoor Light Desktop Central Management System*. *1995*, 58–68.

Risteiu, M., Marc, G., & Ileana, I. (2016). Study of improving artificial lighting in industrial environments. *Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VIII*, *10010*(December 2016), 100102X. https://doi.org/10.1117/12.2245291

Sağlam, Ş., & Oral, B. (2010). Modern lighting sources and controls for energy efficient lighting and a smart control algorithm application. *WSEAS Transactions on Systems*, *9*(10), 1098–1108.

Segovia-Muñoz, D., Serrano-Guerrero, X., & Barragan-Escandon, A. (2022). Predictive maintenance in LED street lighting controlled with telemanagement system to improve current fault detection procedures using software tools. *Renewable Energy and Power Quality Journal*, *20*(20), 379–386. https://doi.org/10.24084/repqj20.318

Shailesh, K. R. (2017). Technology options for DSM in interior lighting. *Proceedings of the 3rd IEEE International Conference on Advances in Electrical and Electronics, Information, Communication and Bio-Informatics, AEEICB 2017*, *1*, 491–496. https://doi.org/10.1109/AEEICB.2017.7972362

Shook, P., & Choi, J. K. (2022). Predicting the Impact of Utility Lighting Rebate Programs on Promoting Industrial Energy Efficiency: A Machine Learning Approach. *Environments - MDPI*, *9*(8). https://doi.org/10.3390/environments9080100

Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). *Introduction to Industrial Energy Efficiency*. Elsevier. https://doi.org/10.1016/C2018-0-01452-8

United Nations. (2023). *What is climate change?* Climate Change. https://www.un.org/en/climatechange/what-is-climate-change

Vom Brocke, J., Simons, A., Niehaves, B., Riemer, K., Plattfaut, R., & Cleven, A. (2009). Reconstructing the giant: On the importance of rigour in documenting the literature search process. *17th European Conference on Information Systems, ECIS 2009*, *December 2013*.

Von Neida, B., Manicria, D., & Tweed, A. (2001). An analysis of the energy and cost savings potential of occupancy sensors for commercial lighting systems. *Journal of the Illuminating Engineering Society*, *30*(2), 111–125. https://doi.org/10.1080/00994480.2001.10748357

Wallpaper Flare. (2023). *No Title*. https://www.wallpaperflare.com/bulb-close-up-electric-light-filament-glass-glass-bulb-wallpaper-anibu

Webster, J., & Watson, R. T. (2002). Analyzing the Past to Prepare for the Future: Writing a Literature Review. *MIS Quarterly*, *26*(2), xiii–xxiii. https://doi.org/10.1.1.104.6570

Wikimedia Commons. (2023). *No Title*. https://commons.wikimedia.org/wiki/Main_Page

Wolfswinkel, J. F., Furtmueller, E., & Wilderom, C. P. M. (2013). Using grounded theory as a method for rigorously reviewing literature. *European Journal of Information Systems*, *22*(1), 45–55. https://doi.org/10.1057/ejis.2011.51

Wu, Y., & Su, D. (2021). LCA of an industrial luminaire using product environmental footprint method. *Journal of Cleaner Production*, *305*, 127159. https://doi.org/10.1016/j.jclepro.2021.127159

Zauner, J., & Plischke, H. (2021). Designing light for night shift workers: Application of nonvisual lighting design principles in an industrial production line. *Applied Sciences (Switzerland)*, *11*(22). https://doi.org/10.3390/app112210896

Zhang, Y., Zhong, Y., Gong, Y., & Zheng, L. (2019). The optimization of visual comfort and energy consumption induced by natural light based on PSO. *Sustainability (Switzerland)*, *11*(1). https://doi.org/10.3390/su11010049

APPENDIX

1. CONCEPT MATRIX

CONCEPT MATRIX

INDUSTRIAL LIGHTING ENERGY EFFICIENCY MEASURES

ARTICLES	CONCEPTS						
	DAYLIGH USAGE	CONTROL SYSTEMS	IMPORTANCE OF LIGHTING DESIGN	REPLACEMENT OF LAMPS	CARRYIGN OUT AN ENERGY AUDIT	ENERGY PERFORMANCE EVALUATION	MAINTENANCE
1				X			
2		X					
3		X					
4				X			X
5				X			
6	X		X				
7	X	X	X				
8				X			
9		X		X	X		X
10	X	X		X			X
11						X	X
12	X	X	X				
13		X	X	X			X
14		X	X	X			
15	X						
16		X					
17				X			X
18			X	X			X

CONCEPT MATRIX

DRIVERS AND BARRIERS AND NON-ENERGY BENEFITS

ARTICLES	CONCEPTS								
	FINANCIAL SAVINGS	REDUCED ENERGY CONSUMPTION	IMPORTANCE OF THE INVESTMENT COST	LACK OF KNOWLEDGE OF ENERGY-EFFICIENT OPTIONS	POLICY AND REGULATORY FRAMEWORKS	ENVIRONMENTAL IMPLICATIONS OF EFFICIENT LIGHTING	OTHER DRIVERS AND BARRIERS	LACK OF KNOWLEDGE OF HOW TO QUANTIFY NON-ENERGY BENEFITS	COMMON NON-ENERGY BENEFITS: SAFETY, HEALTH, QUALITY...
19						X			X
20	X	X	X	X			X		
21	X	X	X				X		
22	X	X	X	X	X		X		
23					X				
24					X				
25		X							X
26		X				X			
27	X	X	X		X				
28							X		X
29		X	X		X	X			
30	X	X	X	X	X	X			
31						X			
32									X
33									X
34									X
35								X	X
36	X	X	X	X				X	X
37									X
38									X
39								X	X
40									X
41	X	X	X	X			X	X	X
42									X

CONCEPT MATRIX

AI APPLICATION IN INDUSTRIAL LIGHTING

ARTICLES	CONCEPTS				
	LIGHTING OPTIMIZATION	CUSTOMED LIGHTING DESIGN	PREDICTIVE MAINTENANCE	INTEGRATION OF AI IN BMS	OTHER APPLICATIONS OF AI
43	X	X			
44	X	X		X	
45	X		X		
46	X				
47	X				X
48	X				
49	X		X		X
50	X			X	

2. LIST OF REFERENCES

Number	Article	Research Question
1	Perdahci, C., Akin, H. C., & Cekic, O. (2018). A comparative study of fluorescent and LED lighting in industrial facilities. *IOP Conference Series: Earth and Environmental Science*, *154* (1). https://doi.org/10.1088/1755-1315/154/1/012010	
2	Lesko, M., Rózowicz, A., Baran, K., & Wachta, H. (2018). A luminaire with variable light distribution. *E3S Web of Conferences*, *49*, 1–9. https://doi.org/10.1051/e3sconf/20184900066	
3	Von Neida, B., Manicria, D., & Tweed, A. (2001). An analysis of the energy and cost savings potential of occupancy sensors for commercial lighting systems. *Journal of the Illuminating Engineering Society*, *30* (2), 111–125. https://doi.org/10.1080/00994480.2001.10748357	
4	Preston, D. J., & Woodbury, K. A. (2013). Cost-benefit analysis of retrofit of high-intensity discharge factory lighting with energy-saving alternatives. *Energy Efficiency*, *6* (2), 255–269. https://doi.org/10.1007/s12053-012-9179-1	
5	Eltamaly, A. M., Alolah, A. I., Malik, N. H., Bawah, U., & Yousef, M. J. (2011). Criteria for comparison of energy efficient lamps. *Proceedings - ISIE 2011: 2011 IEEE International Symposium on Industrial Electronics*, 1017–1022. https://doi.org/10.1109/ISIE.2011.5984299	
6	Parise, G., & Martirano, L. (2013). Daylight impact on energy performance of internal lighting. *IEEE Transactions on Industry Applications*, *49* (1), 242–249. https://doi.org/10.1109/TIA.2012.2229454	
7	Katunský, D., Dolníková, E., & Dolník, B. (2018). Daytime lighting assessment in textile factories using connected windows in Slovakia: A case study. *Sustainability (Switzerland)*, *10* (3). https://doi.org/10.3390/su10030655	
8	Paul, B., Kamath, V., & Mathew, M. (2017). Lighting audit and energy efficient LED based lighting scheme for a pharmaceutical industry. *2017 Innovations in Power and Advanced Computing Technologies, i-PACT 2017*, *2017 -Janua*, 1–5. https://doi.org/10.1109/IPACT.2017.8245136	
9	Khalid, M. U., Gul, M., Aman, M. M., & Hashmi, A. (2012). Energy conservation through lighting audit. *PECon 2012 - 2012 IEEE International Conference on Power and Energy*, *May*, 840–845. https://doi.org/10.1109/PECon.2012.6450335	
10	Kralikova, R., Andrejiova, M., & Wessely, E. (2015). Energy saving techniques and strategies for illumination in industry. *Procedia Engineering*, *100* (January), 187–195. https://doi.org/10.1016/j.proeng.2015.01.357	**Energy Efficiency Measures**
11	Parise, G., & Martirano, L. (2013). Daylight impact on energy performance of internal lighting. *IEEE Transactions on Industry Applications*, *49* (1), 242–249. https://doi.org/10.1109/TIA.2012.2229454	
12	Petrinska, I., Ivanov, D., & Pavlov, D. (2018). Good Practices for Efficient Industrial Lighting. *2018 7th Balkan Conference on Lighting, BalkanLight 2018 - Proceedings*, 8–11. https://doi.org/10.1109/BalkanLight.2018.8546976	
13	Kralikova, R., & Wessely, E. (2016). Methodical procedure for designing of efficient lighting systems. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, *27* (1), 66–73. https://doi.org/10.2507/27th.daaam.proceedings.010	
14	Kralikova, R., Sobotova, L., & Badidová, A. (2017). Methodological procedure of energy saving and efficient industrial illumination. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM*, *17* (62), 691–698. https://doi.org/10.5593/sgem2017/62/S27.088	
15	Kousalyadevi, G., & Lavanya, G. (2019). Optimal investigation of daylighting and energy efficiency in industrial building using energy-efficient velux daylighting simulation. *Journal of Asian Architecture and Building Engineering*, *18* (4), 271–284. https://doi.org/10.1080/13467581.2019.1618860	
16	Shankar, A., Vijayakumar, K., Babu, B. C., & Durusu, A. (2020). Smart LED lighting system for energy efficient industrial and commercial LVDC nanogrid powered buildings with BIPV. *SEST 2020 - 3rd International Conference on Smart Energy Systems and Technologies*, *November* https://doi.org/10.1109/SEST48500.2020.9203067	
17	Risteiu, M., Marc, G., & Ileana, I. (2016). Study of improving artificial lighting in industrial environments. *Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies VIII*, *10010* (December 2016), 100102X. https://doi.org/10.1117/12.2245291	
18	Shailesh, K. R. (2017). Technology options for DSM in interior lighting. *Proceedings of the 3rd IEEE International Conference on Advances in Electrical and Electronics, Information, Communication and Bio-Informatics, AEEICB 2017*, *1*, 491–496. https://doi.org/10.1109/AEEICB.2017.7972362	
19	Henriques, C. O., Coelho, D., & Cardoso, H. (2017). A multidimensional assessment of efficient lighting technologies in the industrial sector. *Energy and Sustainability in Small Developing Economies, ES2DE 2017 - Proceedings*. https://doi.org/10.1109/ES2DE.2017.8015341	
20	Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). *Introduction to Industrial Energy Efficiency*. Elsevier. https://doi.org/10.1016/C2018-0-01452-8 - Chapter 15	
21	Adewunmi, Y. A., Alister, A., Phooko, B., & Nokukhanya, T. (2019). Energy efficiency practices in facilities management in Johannesburg. *Journal of Facilities Management*, *17* (4), 331–343. https://doi.org/10.1108/JFM-11-2018-0067	
22	Grinbergs, K. (2013). Energy efficient electricity usage and lighting solutions for industrial plants. *Civil Engineering. International Scientific Conference. Proceedings (Latvia) VO - 4*, *4*, 356–362. http://libezproxy.iyte.edu.tr:81/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsagr&AN=edsagr.LV2013000799&site=eds-live	
23	Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). *Introduction to Industrial Energy Efficiency*. Elsevier. https://doi.org/10.1016/C2018-0-01452-8 - Chapter 16	
24	Franceschini, S., & Alkemade, F. (2016). Non-disruptive regime changes—The case of competing energy efficient lighting trajectories. *Environmental Innovation and Societal Transitions*, *21*, 56–68. https://doi.org/10.1016/j.eist.2016.04.003	
25	Kralikova, R., Koblasa, F., Wessely, E., Pinosova, M., & Dzunova, L. (2020). Opportunities of energy saving lighting for sustainable development. *Annals of DAAAM and Proceedings of the International DAAAM Symposium*, *31* (1), 44–48. https://doi.org/10.2507/31st.daaam.proceedings.006	**Drivers and Barriers**
26	Bergesen, J. D., Tähkämö, L., Gibon, T., & Suh, S. (2016). Potential Long-Term Global Environmental Implications of Efficient Light-Source Technologies. *Journal of Industrial Ecology*, *20* (2), 263–275. https://doi.org/10.1111/jiec.12342	
27	Shook, P., & Choi, J. K. (2022). Predicting the Impact of Utility Lighting Rebate Programs on Promoting Industrial Energy Efficiency: A Machine Learning Approach. *Environments - MDPI*, *9* (8). https://doi.org/10.3390/environments9080100	
28	Peck, J., Ashburner, G., & Schratz, M. (2011). Solid state led lighting technology for hazardous environments; Lowering total cost of ownership while improving safety, quality of light and reliability. *2011 European Conference on Electrical and Instrumentation Applications in the Petroleum and Chemical Industry, PCIC EUROPE*.	
29	Frondel, M., & Lohmann, S. (2011). The European Commission's light bulb decree: Another costly regulation? *Energy Policy*, *39* (6), 3177–3181. https://doi.org/10.1016/j.enpol.2011.02.072	
30	Cowan, K. R., & Daim, T. U. (2011). *Understanding Adoption of Energy Efficiency Technologies : Applying Behavioral Theories of Technology Acceptance & Use to Understand the Case of LED Lighting for Commercial , Residential , and Industrial End-Users*.	
31	Wu, Y., & Su, D. (2021). LCA of an industrial luminaire using product environmental footprint method. *Journal of Cleaner Production*, *305*, 127159. https://doi.org/10.1016/j.jclepro.2021.127159	
32	Cheong, K. H., Teo, Y. H., Koh, J. M., Acharya, U. R., & Man Yu, S. C. (2020). A simulation-aided approach in improving thermal-visual comfort and power efficiency in buildings. *Journal of Building Engineering*, *27* (February 2019), 100936. https://doi.org/10.1016/j.jobe.2019.100936	
33	Zauner, J., & Plischke, H. (2021). Designing light for night shift workers: Application of nonvisual lighting design principles in an industrial production line. *Applied Sciences (Switzerland)*, *11* (22). https://doi.org/10.3390/app112210896	
34	Hawes, B. K., Brunyé, T. T., Mahoney, C. R., Sullivan, J. M., & Aall, C. D. (2012). Effects of four workplace lighting technologies on perception, cognition and affective state. *International Journal of Industrial Ergonomics*, *42* (1), 122–128. https://doi.org/10.1016/j.ergon.2011.09.004	
35	Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). *Introduction to Industrial Energy Efficiency*. Elsevier. https://doi.org/10.1016/C2018-0-01452-8 - Chapter 14	
36	Nehler, T., & Rasmussen, J. (2016). How do firms consider non-energy benefits? Empirical findings on energy-efficiency investments in Swedish industry. *Journal of Cleaner Production*, *113*, 472–482. https://doi.org/10.1016/j.jclepro.2015.11.070	
37	Hossain, M. M., & Ahmed, K. S. (2012). Illumination condition and work efficiency in the tropics : Study on production spaces of ready-made garments factories in dhaka. *Proceedings - 28th International PLEA Conference on Sustainable Architecture + Urban Design: Opportunities, Limits and Needs - Towards an Environmentally Responsible Architecture, PLEA 2012*, *September 2014*. https://doi.org/10.13140/RG.2.1.1846.2880	**Added Values**
38	Jayawardena, A., Duffy, D., & Manahan, J. (2016). Impact of light on safety in industrial environments. *Record of Conference Papers - Annual Petroleum and Chemical Industry Conference*, *2016 -March*. https://doi.org/10.1109/PCICON.2015.7435087	
39	Thollander, P., Karlsson, M., Rohdin, P., Wollin, J., & Rosenqvist, J. (2020). *Introduction to Industrial Energy Efficiency*. Elsevier. https://doi.org/10.1016/C2018-0-01452-8 - Chapter 7	
40	Leong, M. F., & Seaver, S. (2015). Lighting Safety Considerations. *IEEE Transactions on Industry Applications*, *51* (5), 4233–4238. https://doi.org/10.1109/TIA.2015.2429125	
41	Nehler, T. (2019). *Non-Energy Benefits of Industrial Energy Efficiency Roles and Potentials* [Linköping University]. https://doi.org/10.3384/diss.diva-156297	
42	Meshberg, G., & DiLouie, C. (2019). What can data do for me? Networked lighting controls promise added value. *Lighting Design and Application: LD and A*, *49* (9), 24–28.	
43	Koh, L. H., Tan, Y. K., Wang, Z. Z., & Tseng, K. J. (2011). An energy-efficient low voltage DC grid powered smart LED lighting system. *IECON Proceedings (Industrial Electronics Conference)*, 2883–2888. https://doi.org/10.1109/IECON.2011.6119610	
44	Jha, A. (2020). *AI & ML Application for LED Lighting*. *June*.	
45	Segovia-Muñoz, D., Serrano-Guerrero, X., & Barragan-Escandon, A. (2022). Predictive maintenance in LED street lighting controlled with telemanagement system to improve current fault detection procedures using software tools. *Renewable Energy and Power Quality Journal*, *20* (20), 379–386. https://doi.org/10.24084/repqj20.318	
46	Sağlam, Ş., & Oral, B. (2010). Modern lighting sources and controls for energy efficient lighting and a smart control algorithm application. *WSEAS Transactions on Systems*, *9* (10), 1098–1108.	
47	Mahdavian, M., & Wattanapongsakorn, N. (2014). Multi-objective optimization of PID controller tuning for greenhouse lighting control system considering RTP in the smart grid. *2014 International Computer Science and Engineering Conference, ICSEC 2014*, 57–61. https://doi.org/10.1109/ICSEC.2014.6978129	**Applications of AI**
48	Baniya, R., Maksimainen, M., Sierla, S., Pang, C., Yang, C. W., & Vyatkin, V. (2014). Smart indoor lighting control: Power, illuminance, and colour quality. *IEEE International Symposium on Industrial Electronics*, *November 2015*, 1745–1750. https://doi.org/10.1109/ISIE.2014.6864878	
49	R.Berlanga-Llavori, & D.María Llidó. (2018). *Smart Outdoor Light Desktop Central Management System*. *1995*, 58–68.	
50	Zhang, Y., Zhong, Y., Gong, Y., & Zheng, L. (2019). The optimization of visual comfort and energy consumption induced by natural light based on PSO. *Sustainability (Switzerland)*, *11* (1). https://doi.org/10.3390/su11010049	