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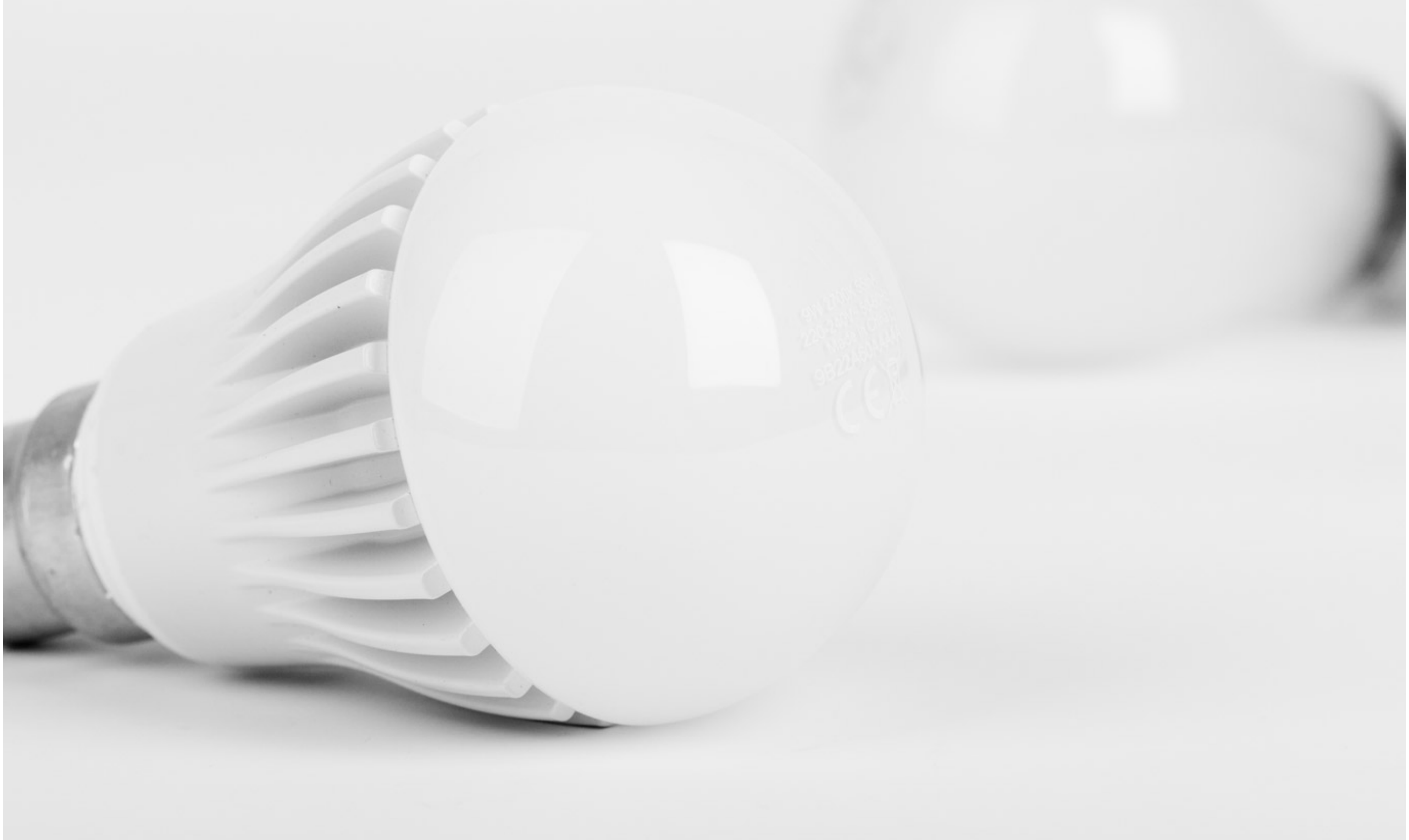

Energy Efficient Lighting in Buildings

COPENHAGEN CASE STUDY ON A SUSTAINABLE TRANSITION TO ENERGY EFFICIENT LIGHTING IN BUILDINGS

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SYNOPSIS

Buildings are the most energy-demanding sector in cities and for that reason are the targets of many energy saving initiatives. In order to comply with its goal of becoming carbon neutral by 2025, Copenhagen Municipality launched a set of targets. One of them consists in reducing in 40% its buildings energy consumption, in comparison with values from 2010. In this context, the Municipality has been developing a pilot project - Copenhagen Efficient Light Project (CELP) - which consists on retrofitting the lighting system of all municipal buildings by installing new highly energy efficient LED luminaires.

Inspired by the pilot project the Municipality is carrying out, this report aims at understanding the benefits a transition to LED lighting system in the municipal buildings could bring to the City of Copenhagen. In this way, three distinguish studies have been performed in this report: (1) cost-benefits analysis of the implementation of CELP in four different groups of municipal buildings; (2) estimation of the total energy savings if the special LED luminaires designed for CELP would replace the luminaires in every building in the City of Copenhagen; (3) two cost-benefit analyses of the lighting system retrofitting at a private household by (a) replacing the luminaires by the new ones designed for CELP and (b) by replacing only the light bulbs by LED bulbs that could be found at a Danish supermarket.

Further, concepts from the Multi-Level Perspective theory are used, together with the results from the three studies conducted in this report, in order to understand if a sustainable transition within the indoor lighting field could be triggered by CELP, and how.

The results from this project suggest that considerable amounts of electricity could be saved if indoor LED lighting would be implemented at a large scale. However, with the LED bulbs available nowadays at the market, when lights are used for few hours per day (in households), LED bulbs represent high advantages only over halogen lamps, but not yet over compact fluorescent lamps.

Nevertheless, this report concludes that, due to its high potential for electricity savings, indoor lighting is an important field to research.

Preface

This problem-based learning Master's Thesis was written as part of the fourth semester of the master's programme in Sustainable Cities, Department of Development and Planning at Aalborg University Copenhagen. It accounts 30 ECTS points and has been carried out in the period from 1 February 2016 to 5 September 2016 (because of change of project topic postponement). This report has been written by Joana Neves with the supervision of Iva Ridjan.

This project aims to explore the energy savings benefits a transition to LED lighting could bring to the City of Copenhagen. The pilot project Copenhagen Municipality is developing, in order to replace all luminaires in municipal buildings by new LED luminaires, served as an inspiration for studying a subject that otherwise I would not have considered as important. With this work I hope to inspire further people to look into buildings lighting as a field with high potential for electricity savings.

References style

The references have been arranged in accordance with the Harvard reference style.

Acknowledgements

Foremost I would like to offer my sincere gratitude to Iva Ridjan for offering her supervision for this report, and throughout the majority my study time at Aalborg University. Her support and advices helped to motivate me and to develop my skills along the way. I would also like to thank to Anders Lyngtorp, the project manager of Copenhagen Efficient Light Project at Copenhagen Municipality, who gave me the opportunity to work closely with this project by providing me information and data needed for my report. I also thank Michael Mogensen, who worked closely with Anders Lyngtorp on the referred project and with whom I could discuss the data provided and some calculation methods used by the Municipality. And last, but not least I would like to thank the Development and Planning Department at Aalborg University for having created the master's programme in Sustainable Cities that enabled me to have a great time while developing my academic career.

Thank you.

Copenhagen, September 2016

Joana Neves

List of Abbreviations

CBA – Cost-Benefit Analysis

CELP - Copenhagen Efficient Light Project

CFL - Compact Fluorescent Lamps

GHG – Greenhouse Gases

EU – European Union

FL – Fluorescent Lamp

HL – Halogen Lamp

IL – Incandescent Lamp

LED - Light-Emitting Diode

NPV – Net Present Value

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1 Introduction

Nowadays, around half of the World's population already lives in cities. According to United Nations projections, this number will rise to 70% until 2050 (Managan et al. 2012), with developing countries contributing to 94% of this increase (ESMAP 2016). The global increase in urban population will create extra environmental pressure in a World where cities are already responsible for more than 60% of the global energy demand and contribute for more than two-thirds of the World's greenhouse gas (GHG) emissions (ESMAP 2016). The rapid growth of urban areas, together with the improvement of life conditions in developing countries, will create a massive rise in global energy demand in the near future. Nevertheless, the same way cities are part of the problem, they can be seen as part of the solution as well, since it is within urban areas that measures to reduce energy consumption can have the biggest impacts.

In Europe, 80% of the population lives in cities and thus they are a priority for the European Union (EU) when looking for solutions to save energy (ICLEI 2016). From all the measures municipalities can apply to reduce energy consumption, energy efficiency actions are some of the most cost effective in order to secure the cities' energy supply and reduce GHG emissions at the same time (EC 2011a; ESMAP 2016).

In a global scale, studies have shown that energy efficiency measures could help achieving two-thirds of the global CO_2 emissions reduction needed to avoid major climate changes (Managan et al. 2012).

According to the European Commission (EC), the definition of **energy efficiency** means "*using less energy inputs while maintaining an equivalent level of economic activity or service"* (EC 2011, p. 2). In this sense, '*energy efficiency*' and *'energy saving'* might become difficult to distinguish and according to the EC's definition, *'energy saving' relates to a "broader concept (of energy efficiency) that also includes consumption reduction through behaviour change or decreased economic activity"* (EC 2011, p. 2). Both concepts are adopted in the present report and will be used interchangeably.

1.1 Energy Efficiency in Buildings

Within cities, the building sector (which encompasses residential, public and commercial buildings) is the most energy demanding and in 2010 it accounted for 32% of the global energy consumption (Lucon et al. 2014). In the EU, 40% of the total final energy consumption is used in buildings (Næss-Schmidt et al. 2012).

As the global energy demand in buildings is expected to increase rapidly, especially due to the forecasted growth and modernization of cities in developing countries, buildings represent unparalleled opportunities for energy savings (Lucon et al. 2014). In fact, from all sectors, buildings hold the greatest energy saving potential (EC 2011a). According to some studies, until 2035 there will be a higher potential for reducing the global energy consumption in the building sector (41% reduction) than in the industrial sector (24%) or in the transport sector (21%) (ESMAP 2014).

Climate change mitigation solutions can be found within the building sector as well, not only by reducing the energy consumption in buildings but also by reducing the embodied energy in building's construction materials, increasing renewable energy use and low-carbon fuels and by decreasing non-CO_2 GHG emissions (Lucon et al. 2014). However, from all the possible measures to reduce energy consumption, improving energy efficiency in buildings represents the most cost-effective, wide and diverse mitigation opportunity in this sector (Levine et al., 2007).

In the commercial and residential sectors, most of the energy is used precisely in buildings: in ventilation, temperature control, water heating, refrigeration, electric appliances, cooking and lighting (Laustsen 2008; ESMAP 2014). Thus, energy efficiency measures should be applied to all these areas in order to significantly reduce the total energy consumption in buildings.

1.2 Energy Efficiency in Copenhagen Municipality's Buildings

Copenhagen Municipality launched its Climate Plan 2025[1] in 2012, where several goals were set in order to significantly reduce CO_2 emissions and energy consumption until 2025 (CPH 2012). One of the goals set by the Danish capital is to be the first **carbon neutral city by 2025** by reducing its energy demand until that year (CPH 2012). This is a very ambitious goal since most of Copenhagen's energy demand is still relying on fossil fuels and in 2010 the City had a carbon footprint of around 110 thousand tonnes of CO_2 eq. (CPH 2012).

The success of Climate Plan 2025 depends on the integrated implementation of initiatives in four different themes: energy consumption, energy production, green mobility and city administrative initiatives. Energy saving measures alone could already reduce the city's CO_2 emissions by 7% at the same time that could bring economic savings as well, since it would be possible to reduce the investment in energy production capacity in new power plants. However, there is no way Copenhagen Municipality can achieve its ambitious target of carbon-neutrality without reaching the goals within all of the four themes in a holistic way (CPH 2012).

As mentioned before, energy efficiency measures are some of the most cost effective actions a city can implement in order to reduce its carbon footprint. Within the four themes set by Copenhagen Municipality, actions related with energy savings in the public building sector belong to the city *administration initiatives* theme, which has the target of reducing in 20 thousand tonnes of CO_2 eq. the city's carbon footprint until 2025. Due to the great potential of energy savings in buildings, **50% of that target** will be reached with actions within the building sector. The remaining emissions will be avoided with actions within the transport sector (37%) and street lighting (13%) (CPH 2012).

In fact, Copenhagen Municipality spends most of its energy running its buildings (CPH 2012). Thus, one of the city administrative initiatives is to **reduce energy consumption in Municipality's properties by 40% up to 2025**, in comparison with values from 2010 (CPH 2012). The plan is to retrofit municipal buildings by implementing long-term energy saving measures. One of the projects starting soon and that goes in that direction is the idea of a massive retrofitting of the municipal building's lighting system in order to implement more energy efficient alternatives (Copenhagen Municipality personal communication 2016), which will be referred in this report as **Copenhagen Efficient Light Project (CELP).**

Approximately 6% of the total building area in the city is owned by Copenhagen Municipality, which equals to 2.2 million m^2 (CPH 2012). Although the percentage of buildings owned by the Municipality is very low, the city administration initiatives are crucial in order to set Copenhagen as an example and stimulate the energy efficient building market. This market stimulation is particularly important to encourage private owners retrofitting their buildings and it is essential to make sure that energy efficient measures are applied from the design stage of new buildings - until 2025 Copenhagen's population is forecasted to increase in 110 thousand inhabitants, implying that 6.8 million m^2 of new buildings will be built (CPH 2012).

All energy efficient measures will be important not only to achieve Copenhagen's goals but also to maintain the Danish Capital carbon neutral even after 2025, and at least until 2035, which is the deadline for Denmark becoming fossil fuel independent (CPH 2012).

1.3 Energy Efficiency Lighting in Buildings

According with a UNEP report, 15% of the global electricity consumption is used in lighting purposes, which accounts for approximately 5% of the CO_2 emissions worldwide. If the trends continue, it is expected that until 2030 the energy consumption for lighting will increase in 60% (Conway et al. 2015).

One way of saving energy in buildings is by optimizing the use of daylight and by integrating sensors in the lighting system in order to switch off or reduce the intensity of electric lighting when it is not needed (Dubois & Blomsterberg 2011). This practice together with the use of more efficient lighting devices, such as light bulbs, ballasts or luminaires, could reduce the energy consumption for lighting proposes in 75% to 90% (Levine et al. 2007).

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[1] Copenhagen Climate Plan 2025 is a holistic plan that joins specific goals in four different areas: energy consumption;, energy production, green mobility and city administration. The aim of this plan is to guide actions in this four areas in order to Copenhagen Municipality become carbon neutral by 2025 (CPH 2012).

Some countries took already action in order to discontinuing the commercialization of inefficient incandescent lamps (IL) in order to replace them with more energy efficient products, such as compact fluorescent lamps (CFL) and light emitting diodes (LED) bulbs, which has been proven as the most cost effective measure to reduce CO_2 emissions within the building's lighting field (Conway et al. 2015; Dubois & Blomsterberg 2011). This is the case of the EU Members States that since September 2012 have adopted measures to ban the commercialization of IL. This single action is expected to save 10% to 15% of electricity within the EU (Aman et al. 2012), where 14% of the energy consumption is used in lighting purposes (EC 2011b). If a global transition to energy efficient lights in all sectors would take place until 2030, it would be possible to reduce in more than 32% the electricity demand for lighting and avoid the emission of around 3.5 Gt of CO_2 without reducing the quality of light (Conway et al. 2015; UNEP 2012).

As Humphreys (2008) points out, the highly energy inefficiency of IL (5%) and some CFL (20%) contrast heavily with the high energy efficiency of other domestic appliances; such as electric ovens and toasters (70%) and electric fans (90%) (Humphreys 2008). *"There is therefore much more potential for large energy savings from lighting than from most other appliances. Indeed, lighting is so inefficient, and it consumes so much energy, that there is probably more potential for large energy savings in this field than in any other area"* (Humphreys 2008, p. 459).

Denmark case

Around 20% of the total electricity consumption in Denmark is used for lighting purposes. This figure is even higher in schools and other educational institutions, where it is estimated that 50% of the electricity consumed is used in lighting. Studies show that these numbers could be reduced to half of their value by using efficient lighting systems at the same time that would reduce pollution and costs in new power plants (AA Danmark 2016).

According with data from the Danish website Energy Wiki (2013), there is potential for considerable savings in the total electricity consumption in some sectors in Denmark if the electricity spent in lighting is reduced. The energy savings could be higher in the buildings that spend more electricity in lighting, as it is the case of schools, and the buildings used by the administration and business sector, as it is shown in Figure 1.

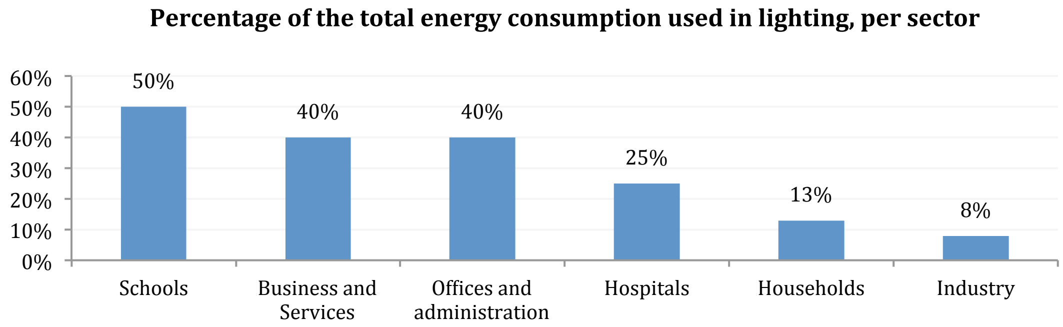


Figure 1: Percentage of the total energy consumption used in lighting in each sector in Denmark (Energy Wiki 2013).

Assuming that Figure 1 is representative of the City of Copenhagen as well, energy efficient lighting systems in municipal buildings could make a considerable contribution on the reduction of the total energy consumption at the Municipality.

1.4 Light Technologies Overview

A lighting system consists of several elements, such as: light bulbs[2], luminaires[3] (including ballast[4], driver, transformer, etc.) and regulating devices such as dimmers, light or movement sensors, etc. (Dubois & Blomsterberg 2011).

[2] Light bulb, sometimes called lamp, is the light-emitting device.

[3] Luminaire is the electrical appliance where the light bulb is attached.

Nowadays, there are basically three types of light bulbs available in the domestic lighting market: Incandescent lamps (IL); Discharge Lamps and LED bulbs (Aman et al. 2012). These three groups differ greatly in the way they generate light:

- **Incandescent lamps** have a glass bulb that seals a tungsten filament. When electric current passes through the wire it resists the current and emits visible light and heat. This lighting technology is considered highly inefficient since 90% of the input energy is lost as heat (Aman et al. 2012). A variant of these light bulbs are the halogen lamps (HL), which contain halogen gas inside the glass bulb. This gas allows the tungsten filament to last longer, increasing the lifetime of the light bulb (Aman et al. 2012).
- **Discharge Lamps**, also known as fluorescent lamps (FL), consist of a glass tube, which is coated inside with phosphorus and contains mercury gas. When an electrical discharge arcs through that gas, it emits ultra-violet light which in turn makes the phosphorus react and emit visible light (UNEP 2012; Aman et al. 2012). FL and CFL differ basically in their glass tube shapes, while FL are linear light sources, CFL are point light sources (Aman et al. 2012). Discharge lamps have to be used together with ballasts, which consume electricity while limiting the amount of current from the supply and providing the starting voltage needed to turn on the light bulb (NLPIP 2000). Electromagnetic or electronic ballast can be used with FL while with CFL only electronic ballasts are used (Aman et al. 2012).
- **LED bulbs** contain semiconductor materials that when excited by electrical current emit light of specific wavelengths, such as blue light (the most commonly available in the market) that in turn makes phosphorus react and emit white light (UNEP 2012). A LED bulb comprises several electrical components such as the light emitting element and a LED driver (Aman et al. 2012).

Figure 2 shows how the luminous efficiency of the different type of lamps evolved during the years.

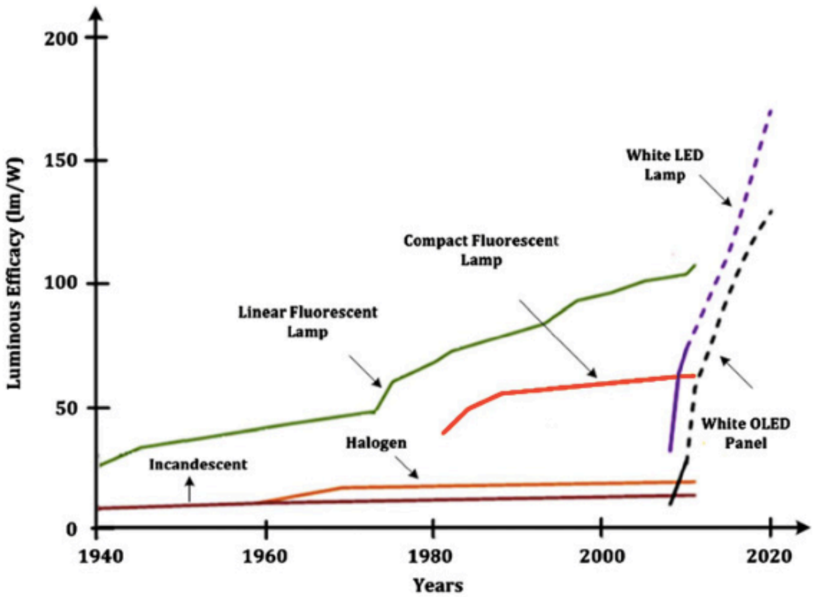


Figure 2: Historical development and forecast of luminous efficiency of different lamps (Aman et al. 2012)

As Figure 2 shows, LED lamps are still in their early development stage, when compared with the other lamps type. However LED lights are expected to revolutionize the field of lighting in the near future and soon they will become much more efficient than any other available light source in the market allowing significant energy savings (EC 2011b). Besides, recent advances in LEDs have improved their cost-effectiveness and their longevity (Levine et al. 2007).

The following table summarizes the main differences between the three lamp types.

[4] Ballast is an electronic component used together with some light bulbs types (discharge lamps and LED) in order to provide the electric current conditions needed to turn on those light bulbs. Sometimes the ballast is integrated in the luminary, other times is embedded inside the light bulb. The ballasts for LED are commonly called drivers.

Table 1: Characteristics of the main three lamp types[5]

Lamps	***Incandescent***	***Discharge***	***Light Emitting Diode***
Initial Cost	IL - Very low HL - Low to medium	Low to medium	High to very high
Lifetime	IL - up to 1,000 h HL – 2,000 to 4,000 h	FL – up to 50,000 h CFL – 30,000 to 35,000 h	35,000 to 50,000 h
Luminous Efficacy	IL - up to 12 lm/W HL – up to 15 lm/W	FL – 25 to 118 lm/W CFL – 50 to 70 lm/W	Up to 120 lm/W
Compatibility with existing luminaires	Yes	CFL - Most are compatible	Some may not fit in all luminaires

The amount of light emitted from a light source is measured in **lumens** (lm). **Luminous efficacy** of light bulbs is a measure of the amount of lumens output for a given electrical power input and it is measured in lm/Watts (Aman et al. 2012).

The **lifetime** of a lamp is measured in hours and represents the amount of hours it can be turned on until the light output is reduced to 50% of its initial lumens. In the case of IL, there is no **lumens depreciation** during its lifetime, and thus their lifetime represents the amount of hours until they stop emitting light at all. However, for the other two types of lamps there might occur lumens depreciation before they stop working (Aman et al. 2012).

Although LED bulbs seem to be more beneficial in terms of energy savings, the initial cost inherent to their use has been one of the biggest barriers to a wide penetration of these lamps in the market (Jensen 2014; Navigant & Stober 2015). Not only the cost of these lamps is higher, in comparison with the others energy efficient light bulbs, but also the fact that they do not fit all luminaires in use might increase the initial costs for the need of replacing those devices (UNEP 2012).

1.5 Benefits of LEDs over Compact Fluorescent Lamps

Although in terms of energy efficiency and lifetime compact fluorescent lamps and LEDs are currently similar and could possibly be used in the same environments and luminaires, LED bulbs present some extra benefits.

Environmental benefits

As discharge lamps contain mercury gas, which is a hazardous substance, they require extra measures in their disposal (UNEP 2012; Schleich et al. 2014). There is a risk of contamination only if the glass tube breaks. The mercury content in these lamps is usually very low, 4 to 5 mg, and does not represent a direct risk for human health if it is released from a broken glass tube (UNEP 2012). However, the accumulation of this gas in the environment can create damages in the ozone layer and can be bio-accumulated in higher concentrations in fish for human consumption (Aman et al. 2012).

On the other hand, LEDs are made from non-toxic substances and their materials can be recycled (Waide et al. 2006; EC 2011b; Smink et al. 2015). In addiction, unlike some DL, LED bulbs do not emit ultraviolet light, which can damage materials and fade colours (Waide et al. 2006).

Health benefits

The health benefits of a moderated Sunlight exposure have been known already for a long time (Neves 2011). The use of Sunlight in offices, for instance, is associated with better health and higher productivity, which some authors argue that can have a higher value than the potential energy savings from using natural light instead of electric light (Waide et al. 2006). Within all domestic light bulbs available in the marked nowadays, LED bulbs are the ones that better mimic the therapeutic characteristics of Sunlight without emitting harmful ultraviolet radiation (Waide et al. 2006). Some studies indeed show that the natural light conditions LED lamps can generate contribute to wellbeing and concentration, can create better learning and working conditions (important in schools and offices), and positively influences people's vitality (important in care institutions) (EC 2011b).

[5] Adapted from UNEP (2012) and Aman et al. (2012).

Versatile and adaptable to innovation

Most discharge lamps are not dimmable (UNEP 2012) and they might take a short time before attaining full light output (Aman et al. 2012), which makes them a bad choice for lighting systems regulated with daylight sensors.

In contrast, LEDs are compatibility with dimming controls so their light intensity can be easily regulated (EC 2011b; UNEP 2012; Smink et al. 2015). Because their brightness is proportional to the passing electric current (Bao et al. 2015) it is possible to turn on and off LED lights so fast that it is imperceptible to the human eye (Gupta et al. 2016). This characteristic enables new and innovative ways of using LEDs, such as in data transmission. An emerging technology called Light Fidelity (Li-Fi) uses the visible light spectrum from LED bulbs instead of radio waves (such as does Wi-Fi) for transmitting data (Gupta et al. 2016). By codding the way LED bulbs turn on and off it is possible to emit binaural signals to a photo-detector in a much faster way than data is transmitted through Wi-Fi (Bao et al. 2015; Tsonev et al. 2013).

Although Li-Fi cannot completely substitute the use of Wi-Fi, due to its limitation of not passing through walls, it is forecasted that it will be the future communication technology in offices since it offers many advantages at indoor scenarios (for instance: due to its limitation it can represent a safer way of transmitting data) (Bao et al. 2015; Tsonev et al. 2013). Even though the use of Li-Fi would be limited to specific scenarios, by combining the function of illumination and communication with LEDs it would be possible to reduce costs and the carbon footprint in offices for the fact that the electricity used for communication would be almost zero since it would use an already installed technology (lights) (Tsonev et al. 2013).

1.6 Copenhagen Efficient Light Project

As part of the initiative to reduce in 40% the energy consumption in municipal buildings, Copenhagen Municipality is currently studying the possibility of retrofitting the lighting system of all of its buildings with its Copenhagen Efficient Light Project. From personal communications with Anders Lyngtorp and Michael Mogensen, both involved in this project, it was possible to learn how the Municipality is approaching the case and how the project's budget is being estimated.

The idea is to replace all the light bulbs, ballasts and luminaires from the entire building area owned by the Municipality (2.2 Million m^2), plus the area rented from private owners (0.4 Million m^2), by more energy efficient devices (Copenhagen Municipality personal communication 2016). Simply exchanging the existing light bulbs by LED bulbs would not be enough, not only for the fact that LED bulbs might not fit the majority of the existing luminaires but also for the fact that the Municipality wants to reduce costs in maintenance as well, by installing a new design of luminaires where the LED bulbs and the ballasts could be easily replaced by the users, without the need of hiring an electrician (Copenhagen Municipality personal communication 2016). Besides, some luminaires, that contain electromagnetic ballasts, are very old and still contain capacitors maid with PCB (polychlorinated biphenyl) (Copenhagen Municipality personal communication 2016), a persistent organic pollutant that can have carcinogenic effects on human health and that is forbidden in Europe since 1985 (EC 2001).

A luminaire where the users could easily detach their basic components does not exist in the market and for that reason the Municipality has to develop its own line of energy efficient luminaires, LED bulbs and drivers (Copenhagen Municipality personal communication 2016). One of their goals is to develop a more efficient and cheap LED bulb in comparison with the ones found in the market nowadays. Further, the driver should be a separate device and not an integrated part of the LED bulb as it happens in most of the cases (Copenhagen Municipality personal communication 2016). In this way, when the LED bulb needs to be replaced, the driver can be saved and vice-versa. The City aims at saving money not only on energy consumption, but also on procurements and labour for the luminaires maintenance (Copenhagen Municipality personal communication 2016).

With CELP, the Municipality has in view the opportunity for innovation as well. The new luminaires' design should allow the connection to a software management to regulate all public building's luminaires remotely (Copenhagen Municipality personal communication 2016). This could save extra amounts of energy to the Municipality by making sure luminaires would be switched off during the hours, or days, buildings are not being used. Besides, these new devices should have integrated sensors for daylight (Copenhagen Municipality personal communication 2016), as it is already mandatory in workplaces in Denmark, since 2010 (Aggerholm 2013).

The wide adoption of these new LED luminaires would leave Copenhagen Municipality ready for another innovation – the Li-Fi. The City plans to implement this new technology in all its workplaces in the next 5 years due to its advantages of data security, communication speed and energy efficiency (Copenhagen Municipality personal communication 2016).

Copenhagen Municipality has no capacity nor knowhow to developed such luminaires, and for that it has to apply for funds and attract partners for its CELP. In order to make a good case study and prove the profitability of CELP, the Municipality made a cost-benefit analysis (CBA) of only 5% of its properties, by choosing 25 of its most energy demanding buildings (Copenhagen Municipality personal communication 2016). Copenhagen Municipality's calculations show how much money the Municipality would have to invest in this sample of buildings in order to replace their luminaires and light bulbs, and how long would be the payback time of the investment. From their calculations, the CBA of this small case results in an initial investment of 28 MDKK[6] with a payback time of 5 years. This is already a good case study and it shows that CELP could be successful since a project of its dimension should not exceed a payback time of 6 years in order to be accepted for funding (Copenhagen Municipality personal communication 2016).

1.7 Aim of the Study

Inspired by the cost-benefit analysis Copenhagen Municipality carried out for its efficient light project (CELP) applied to a small sample of its buildings; this report describes primarily, a CBA of CELP applied to four different scenarios, where different groups of municipal buildings are accounted for. The aim of this study is to prove the profitability of CELP on a large scale and find a scenario with a payback time inferior to 6 years where the Municipality could save considerable amounts of energy and avoid CO_2 emissions. This leads to the first two research questions:

1 - How a retrofit in the lighting system of municipal buildings could help Copenhagen Municipality achieve its energy and carbon goals?

2 - What could be the best scenario to implement Copenhagen Efficient Light Project?

By looking at the potential energy savings Copenhagen Municipality could generate by replacing their luminaires by more energy efficient devices, it is interesting to think on how much energy could be saved in the entire city if the same shift would occur in all buildings. Therefore, the second part of the analysis consist on estimating how much energy could be saved if every building in the city would have their luminaires replaced by more energy efficient devices, with the same characteristics as the luminaires designed for CELP.

When imagining a total retrofitting of the indoor lighting system in a city, it is important to understand what would that mean to a private household user. In this way, the third part of the analysis in this report refers to two CBA performed for the retrofitting of the lighting system on a hypothetical private household in Copenhagen. The first CBA studies what would happen if one luminaire in each house division would be replaced by luminaires similar to the ones that will be designed for CELP, while the second CBA does a similar study but for the case where the light bulbs in use are substituted by LED bulbs, without the replacement of luminaires.

If CELP is proved to be profitable and the potential energy savings in the entire city are significant, a sustainable transition to energy efficient lighting systems could occur in the near future. By using concepts from the Multi-Level Perspective (MLP) theory and the results from the analysis, a theoretical discussion will be carried out with the aim of understanding how a socio-technical change in the lighting system of municipal buildings could give the bases for a further sustainable transition within the lighting system of Copenhagen's private building sector as well. This leads to the third research question in this report:

3 - *Could Copenhagen Efficient Light Project trigger a sustainable transition within the lighting systems in Copenhagen's buildings?*

[6] Million Danish Krones

1.8 Content of the Report

After the introduction to this project, the following chapter presents the concepts of the Multi-Level Perspective theory that will be used to discuss the results from the analysis in this report. On the third chapter, the methodology used in the analysis in this report is presented.

The fourth chapter comprehends the analysis, which is divided into three main studies presented in three distinguished sections. The first section consisted of a cost-benefit analysis of the implementation of CELP in four different groups of municipal buildings. In the second section it is estimated the total amount of electricity that could be saved, in the City of Copenhagen, if every building in the city would have its luminaires replaced by energy efficient luminaires similar to the ones that will be design for CELP. The third section consists of two cost-benefit analyses applied to the lighting system retrofit in a household, where in the first one it is study the advantage of replacing the existing luminaires by more energy efficient ones, while in the second one it is approached the benefits of substituting the light bulbs in use, without the replacement of luminaires. In the forth and final section of the Analysis chapter, the analysis limitations found through out the report are revealed.

In the fifth chapter, which represents the discussion in the report, results from the analysis are used to support a theoretical discussion based on concepts from MLP theory in order to understand if a sustainable transition within the indoor lighting system is in progress. Finally, chapter six presents the conclusions of the report and is followed by the references' list in chapter seven and the appendixes, in chapters eight and nine, where calculations and data used in the analysis can be consulted.

2 Theoretical Framework

There is a general notion that the electricity spent in lighting is not that significant when compared to the electricity used in other domestic appliances. Indeed, an incandescent lamp of 100 W does not seem it should be a key target when aiming for large-scale energy savings while other domestic appliances have a much higher power rating: electric ovens are rated up to 5,000 W; window-units air conditioner, 1,000 W; toasters up to 1,500 W and desktop computers with monitor, 200 W (Humphreys 2008). However if one considers that, in average, a household in the USA has 45 light bulbs (in Canada, 30; and in the UK, 25) and that lights are normally used during much longer periods of time, in average 4 hours, than most of the other appliances, their energy consumption might be more significant than most of the people think (Humphreys 2008). Taking the example of a 1000 W toaster, that might be used for 5 min a day, its overall energy consumption would be 0.08 kWh per day, compared with the daily consumption of 12 kWh from IL of 100 W, in a house with 30 light bulbs. This is the equivalent of using 144 toasters for 5 min each day. If the light bulbs are all energy inefficient, the overall consumption in lighting will be indeed significant and a big share of the overall household's electricity consumption (Humphreys 2008).

In order to encourage citizens to choose more energy efficient products, EU has created energy and eco-label schemes to guide consumers. This measure has been successful within the white goods market, where consumers prefer to pay more for a more energy efficient appliance, for they are aware that it is possible to get the extra money back in the reduced energy bills. However, with indoor lighting the same measure has not been so successful, mainly because citizens are still not aware of the short payback periods of energy efficient lamps (Bertoldi & Atanasiu 2006; Schleich et al. 2014). For this reason, and as Jensen (2014) pointed out, in order to make a sustainable transition happening within the indoor lighting systems, it is important to take into consideration not only regulations and lighting products but also "*the way lighting is used and perceived*" by the users (Jensen 2014, p. 71).

Until the date there is no known large-scale project to shift the lighting system in buildings as it is happening in Copenhagen. Although Copenhagen Efficient Light Project might look simple, it has potential to bring huge savings to the municipality and to uphold the market of energy efficient luminaires, LED bulbs and LED drivers. For the media and scientific attention it might get for being the first large scale project showing the energy saving benefits of using indoor LED luminaires, this project has the potential to change the perception of lighting and the way it is used and thus encourage a sustainable transition within the indoor lighting field.

A **sustainable transition** is a process of shifting to a system with more environmental modes of production and consumption (Geels 2011). These transitions are goal-oriented for they access "*persistent environmental problems, whereas many historical transitions were 'emergent'*" (Geels 2011, p. 25). Therefore, sustainable transitions have some particularities. Besides the fact that the very concept of sustainability has a relative nature and might change over time (Markard et al. 2012), sustainability represents a collective good and thus 'sustainable' solutions might not offer direct users benefits (Geels 2011). In addition, environmental innovations have often lower price/performance coefficients than established technologies (Geels 2011). For that reason sustainable transitions are unlikely to occur without guidance and governance towards changes in the socioeconomic dimension (e.g., taxes, subsidies, regulatory frameworks) (Geels 2011; Markard et al. 2012). Other particularity of sustainable transitions relates to the fact that sustainability is mostly needed in sectors like transport, energy and agri-food, which are characterized by large firms that possess a wide range of *complementary assets* such as "*specialized manufacturing capability, experience with large- scale test trials, access to distribution channels, service networks, and complementary technologies*" (Geels 2011, p. 25). These complementary assets give a strong position to the established (*incumbent*) firms in opposition to forerunners, who are frequently the first developers of sustainable innovations (Geels 2011).

This is the case of Copenhagen Efficient Light Project, which aims for a transition to a sustainable lighting system within the Municipal buildings, by shifting from compact fluorescent lamps and incandescent lamps (well established technologies) to LED bulbs (a not so well established technology). In addition, the new luminaire design could open doors to other technology innovations, such as Li-Fi, a technology that is not established at all. Therefore, Copenhagen Municipality could be seen as a pioneer, triggering a sustainable transition not only on the technology of lighting in buildings but also on the way lighting is use and perceived.

The **multilevel perspective (MLP)** is the most used theory to study sustainable transitions and it aims at describing how socio-technical changes (transitions) occur (Pineda & Vogel 2014). A **socio-technical transition** implies a multi-dimension change in the system during a long-term process and with the involvement of a broad range of actors (Geels 2011; Markard et al. 2012). The difference between technological and socio-technical transitions lies in the fact that the later, besides the changes in the technological dimension, include changes in the user practices and in the socio-cultural dimension (Markard et al. 2012). This concept can be applied to the present case where a sustainable socio-technical transition within the indoor lighting system, besides a change in policy and technology, is depended on a change in the users practices and perception of lighting (Jensen 2014).

MLP distinguishes three analytical levels involved in a sustainable transition: the regime, the niche and the landscape (Pineda & Vogel 2014; Geels & Schot 2007).

The **socio-technical regime** represents the current well established rules and routines in a large community (Pineda & Vogel 2014; Geels & Schot 2007). In fact, transitions can be "*defined as shifts from one regime to another*" (Jensen 2014, p. 43). In the Copenhagen case study, the regime is the current state of lighting systems in the city's buildings, where there is still a high potential for optimization in terms of energy efficiency. It includes as well the way users perceive and use lighting systems and the way they seem to underestimate the potential energy savings.

The **niche** is where actors operate in order to present new socio-technical systems for the regime and normally is characterized by small but dedicated networks (Pineda & Vogel 2014; Geels & Schot 2007). Here the rules are in the making and for that there is space for creativity and innovation (Pineda & Vogel 2014). In the present case, the LED firms represent the main niche, where a new technology is already well developed however it is not yet widely used. This niche defends that it is possible to save huge amounts of money by improving the energy efficiency of lighting systems and in that way tries to persuade the regime to adopt its innovation.

The **socio-technical landscape** is the exogenous environment where well-established entities, macro-economic developments, ideologies, climate change, geopolitical aspects or cultural patters can influence the niche and regime's dynamics (Geels 2011). The landscape level is considered beyond of the direct influence of the regime and the niche and can either support the proposed socio-technical change or make the niche look obsolete for the regime (Pineda & Vogel 2014).

In the Copenhagen case, it is possible to see that in the recent years the landscape already suffered some changes that forced the regime to adapt and, in a way, gave momentum to the niche to get attention from the regime actors. These changes include the EU policies for encouraging the energy efficiency market (such as energy and eco-labelling), the ban of inefficient lamps within EU Member States, the scientific evidences of LED advantages, or even the fluctuation of oil prices, etc.. All these landscape changes created pressure on the regime leading to its destabilisation and forcing it, if not to change, at least to be more open to environmental innovations. These regime destabilizations created what Geels & Schot (2007) call *windows of opportunity* for niche-innovations that presented energy efficient solutions, such as LED firms.

However, at the same time that such landscape changes seem to be favouring and enabling the LED niche to build up internal momentum, there are still some barriers that might resist against a wide transition to LED lighting within buildings. Some regime actors profit from the current regime status and for that might resist to keep the regime's stability in order to avoid a transition by, for instance, "*influencing the public debate and lobbying policy makers*" (Smink et al. 2015, p. 95). According to Smink et al. (2015), one reason why the LED market has not yet reached the domestic lighting market in a large way can be due to negative influence some incumbent actors in the regime, such as compact fluorescent lamps firms, have had (Smink et al. 2015). Nevertheless, "*the transition to LED lighting seems inevitable*" (Smink et al. 2015, p. 98), and although incumbent firms might first represent resistance to LED niche-innovations, after some strategic reorganization, they might acquire the necessary capacities to deal with a regime change (Smink et al. 2015; Geels 2011). In fact, a positive support from incumbents and their complementary assets "*might accelerate the breakthrough of environmental innovations*" (Geels 2011, p. 25).

Geels & Schot (2007) developed the MLP theory further by distinguishing **four types of transition pathways**:

- **Transformation**: A Transformation pathway occurs when there is a moderate landscape pressure on the regime while the niches are not yet mature enough to be adopted (Geels 2011). In this case, incumbent actors change the direction of developments and initiate some innovations themselves in order to adjust the regime to the landscape pressures (Geels & Schot 2007).
- **De-alignment and re-alignment**: In this pathway there is a large and sudden change in the landscape for which the regime has neither knowledge nor resources to adapt and leads to its de-alignment. If there are no niches sufficiently mature, it creates space for multiple niche-innovations to emerge and compete for attention until one becomes dominant and helps to re-align a new regime (Geels & Schot 2007).

- **Technological substitution**: In this pathway, niche-innovations are mature enough when a change in the landscape occurs. The landscape pressures cause a window of opportunity for the innovations to open between regime actors that end up letting the niche dominate the regime and replace the existing technology (Geels & Schot 2007). Another way a technology substitution path can occur is when niche-innovations gained already "*internal momentum (because of resource investments, consumer demand, cultural enthusiasm, political support, etc.)"* (Geels 2011, p. 32), leading to the replacement of the regime without the influence from the changes in the landscape (Geels 2011).
- **Reconfiguration**: in this pathway, when the innovations developed in niches are symbiotic with the regime, the regime actors adopt them in order to adapt to the landscape changes. This incorporation can lead to subsequent adjustments without major changes in the regime, however it can also lead to changes in the users practices and perceptions and might create space for further adoption of other innovations (Geels & Schot 2007; Geels 2011).

In the present case study of Copenhagen Municipality's indoor lightning, the regime already started to respond to the landscape changes by taking several action like, for instance, launching the Copenhagen Climate Plan 2025 with its goals to reduce carbon emissions. This shows that some regime actors are engaged in making a transition to a new regime with reduced energy consumptions and CO_2 emissions.

That fact that nowadays LED is a familiar name and that it is available in the market, although it is not widely used yet, is a sign that the niche of LED firms was successful in bringing their innovation to the attention of regime actors. The increasing adoption of LED bulbs for lighting in buildings can be correlated to a sustainable transition with a *reconfiguration pathway* since the niche of LED innovations can be seen as symbiotic with the regime: LED lamps can be used in the same way as other lamps are used nowadays and, besides some luminaires replacement, do not require a major change in the regime.

The adoption of symbiotic niche-innovations might open windows of opportunities to further symbiotic niche-innovations that would not have the change to become a part of the regime if the first niche-innovation would not have been adopted already. Hence, in a transition with a reconfiguration pathway, a "*new regime grows out of the old regime*" (Geels & Schot 2007, p. 411) as a consequence of the adoption of multiple component-innovations in a row, which leads to a considerable change in the regime's basic architecture. While regime actors survive, incumbent firms might first resist against niche-accumulations, however, if they do not adapt to the new technologies they might lose the fight in the markets (Geels & Schot 2007).

It can be said that a transition was already occurring when regime actors, from Copenhagen Municipality, decided to launch Copenhagen Efficient Light Project and adopt the technology from the LED niche-innovation. In fact, if this pioneer project is successful and proves the benefits of adopting LED bulbs in large scale, it might inspire other regime actors to shift their lightning to LED as well. Further, if a wide adoption of LED occurs and it becomes an important part of the regime, it might open space for other niche innovations such as the ones represented by Li-Fi firms. This change could help the users to become more aware of the potential energy savings on lighting and to its potential to be used for other purposes than to light. In such a degree, this could change the users practices and perception of lighting.

It is important to note that this report only focus on MLP theory to explain a sustainable transition that could happen within the indoor lighting field in Copenhagen. However, as already stressed, in order for a sustainable transition to happen, not only regulations and technologies should change, but also the way users use and perceived lights should change. Users are in fact an important aspect in a transition and to approach them in a deeper way, future studies could use other theories that focus on the users practices, such as Practice Theory (Jensen 2014)

In the following analysis chapter, three studies will be carried out in order to understand the potential benefits of installing LED luminaires in municipal buildings; what would be the energy savings if LED luminaires would be used in every building in Copenhagen; and what would be the benefits for private household users to replace their luminaires, or only their light bulbs, by LED solutions. The results from these studies will be then discussed in the discussion chapter on the light of the MLP theory.

3 Methodology

In order to understand the benefits of replacing the existing indoor lighting systems by LED technology, three studies were conducted as presented in the analysis chapter in this report. This chapter was divided into three distinguished sections:

The **first section** of the analysis consists of a CBA of Copenhagen Efficient Light Project. This CBA is based on the methodology Copenhagen Municipality used in its own calculations for the CBA of its small case study (using only 5% of their buildings), with the difference that in this report the data for the whole municipal building area was used to create the four different scenarios analysed.

The **second section** estimates how much energy could be saved if a retrofit in the lighting system would happen in every building the City of Copenhagen. For environmental and financial considerations, the potential energy savings are converted into CO_2 emissions and monetary savings.

Finally, the **third section** consists of two CBA conducted for the lighting system retrofit in one hypothetical private household in Copenhagen. The first one, part A, considers the replacement of household luminaires by luminaires similar with the ones used for CELP, while in part B the CBA focus on the replacement of the light bulbs currently in use at the household by LED bulbs, without replacing the luminaires.

The results from the three sections of the analysis are then discussed and viewed in terms of how could they possibly trigger a sustainable transition by using concepts from MLP theory. The following figure summarizes the methodology used in this report.

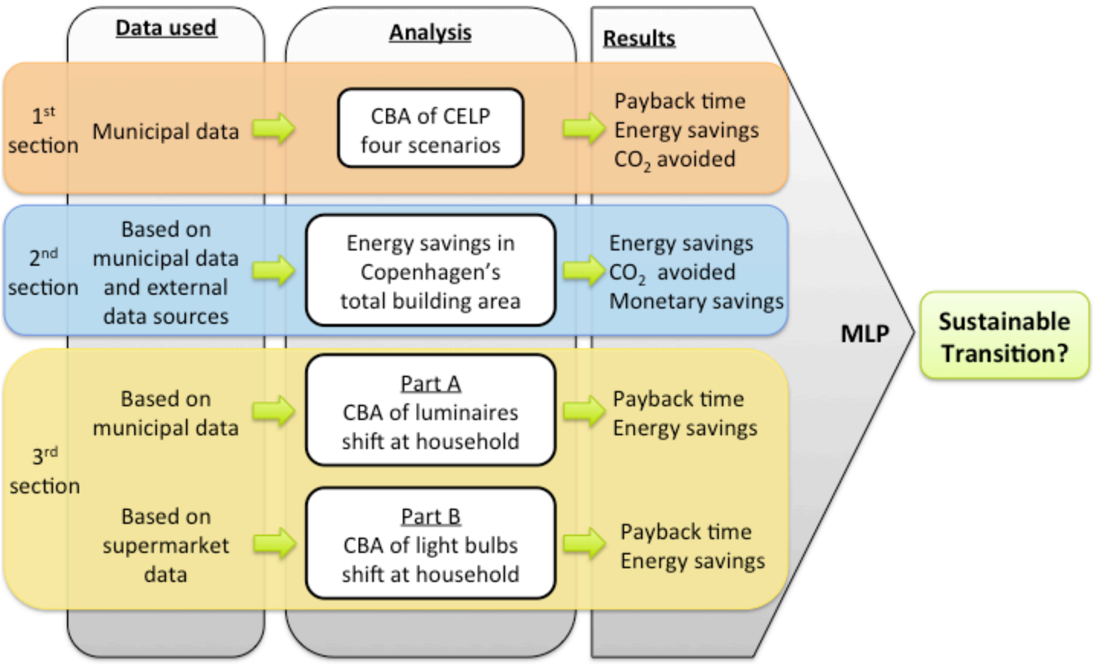


Figure 3: Schematization of the data input and results from the three analyses conducted in this report

3.1 Cost-Benefit Analysis Concepts

Cost-Benefit Analysis (CBA) is a scientific approach very used nowadays to evaluate new business or projects in a wide range of fields. In its theoretical roots, "*benefits are defined as increases in human wellbeing (utility) and costs are defined as reductions in human wellbeing*" (Pearce et al. 2006, p. 16).

In order to qualify a decision-making based on a CBA, the benefits for the society from a certain project or scenario must exceed its social costs and to compare them it is important to express these values in a common unit of measurement. Normally, they are expressed in monetary units by giving monetary values to every aspect to be considered, even the non-monetized aspects of the scenarios, such as environmental or health impacts (Pearce et al. 2006).

Usually, as money's value varies over time, it is important to account with this variations when conducting a CBA. These variations are not solely related to inflation but to the interest rates as well (Pearce et al. 2006). One Danish krone today can be invested and raise interest for five years, resulting that one Danish krone in the present would worth more than one Danish krone in five years. This temporal weight at which monetary costs and benefits vary is called ***discount factor***:

$$DF_t = (r+1)^{-t} \tag{1}$$

Where DF_t is the discount factor, with the ***discount rate*** r, that when multiplied by the money value of costs or benefits at the future year t will result in the discounted ***Present Value*** (PV) of those costs or benefits from the project. The sum of the differences between the benefits' present value and the costs' present value is called ***Net Present Value*** (NPV). It is according to their NPV that projects and alternatives should be evaluated, and only the ones with positive NPV should be taken into consideration, meaning the benefits overcome costs during the desired period (Pearce et al. 2006):

$$NPV = \sum_t (B_t - C_t) . (r+1)^{-t} > 0 \tag{2}$$

Where B represents the *Benefits* and C the *Costs*. Equation 2 means that the sum of all benefits must be higher than the sum of all costs during the period t in order to validate a certain alternative (Pearce et al. 2006).

One limitation of CBA is the fact that when discounting is practised, it is assumed that a constant positive **discount rate** is applied during the entire period of the analysis. In reality this discount rate might vary, especially when dealing with a long term project (Pearce et al. 2006), which is not the case of CELP. In the CBA of CELP a **discount rate of 4%** is used, which is the discount rate used for small environmental projects at Copenhagen Municipality (Copenhagen Municipality personal communication 2016). For the CBA of the lighting system retrofitting at a single household, it is used a **discount rate of 0%**, as it is the official discount rate adopted by the Danish National Bank (Danmarks Nationalbank 2016). The ***base year*** is "*the year to which future costs and benefits are discounted*" (Pearce et al. 2006, p. 44). In all CBAs carried out in this report, the base year is 2017 and the analysis goes until 2030, in order to include the year of 2025, when Copenhagen Municipality has to meet some important goals.

Due to ***inflation***, the costs and benefits values projected might vary in the future years. However, because future is uncertain and it is difficult to predict the evolution of inflation rates, applying this rate in a CBA might result in overestimated future costs and benefits. For that reason inflation rates are normally netted out from the analysis (Pearce et al. 2006), as they are in the CBAs in this report.

A **sensitivity analysis** can be used to test how the NPV is affected when some costs change (Pearce et al. 2006). This analysis should be carried out by varying one variable at a time, while increasing or decreasing it by some percentages (Sartori et al. 2014). Normally a critical variable, which has a heavy influence on the NPV, is chosen for this analysis. For all CBAs in this report, a sensitivity analysis is conducted in order to understand how a change in the new LED luminaires price, or in the LED bulbs price, could affect the payback time of the investments.

3.2 Cost-Benefit Analysis of Copenhagen Efficient Light Project

In the first section of the analysis, a CBA of CELP is carried out with a similar approach as used by the CBA of Copenhagen Municipality's small case study. Table 2 summarizes the costs and benefits accounted in this CBA.

Table 2: Costs and Benefits accounted in the CBA of CELP

Costs	***Benefits***
One-time costs:	**One-time benefit:**
– Lamps counting	– Sale of energy savings from the first year after investment[7]
– Dismantling of old Luminaires	**Annual benefits:**

[7] For projects saving over 50 MWh of electricity per year, it is possible to sell the electricity savings back to an energy supplier by 0.44 DKK per kWh in the first year after the investment (Copenhagen Municipality personal communication 2016; Dong Energy 2016) .

Costs	*Benefits*
– Disposal of PCB-containing capacitors – Purchase of new Luminaires – Installation of new Luminaires – Project management	– Energy savings – CO_2 emission savings – Maintenance costs savings

Definition of scenarios

A CBA was first conducted for a scenario where all luminaires currently installed in the buildings used by Copenhagen Municipality would be replaced by the new luminaire models. However, even though this might be the ultimate goal of CELP, such shifting might be complicated. For that reason, other three scenarios where only a specific number of municipal buildings have their luminaires replaced were defined in order to conduct three more CBAs and compare their results.

In order to simplify the implementation management of CELP, it was assumed that the best approach was to divide Copenhagen Municipality's buildings according to the departments running them. Therefore, by using the data for the number of municipal buildings, the time they are used per year and their annual electricity consumption, it was calculated which departments have higher electricity consumption in lighting. Table 3 shows the three building groups defined, where Group A (buildings from the education department) is the one with the highest electricity consumption in lighting and also the one that runs more buildings.

Table 3: Grouping buildings according with the departments running them

Groups	*Departments*	*Number of buildings*	*Scenarios*
Group A	Education	524	1, 2, 3, 4
Group B	Culture	183	1, 2, 3
	Social	73	
Group C	Buildings shared by several departments	32	1, 2
	Health	26	
	Technical / Environment & Administration Offices	71	
	Refugees	21	
	Economic	10	
Others	Other departments	195	1

In this way, four CBAs were conducted for each one of the following scenarios:

– **Scenario 1** - replacement of all luminaires in all buildings used by Copenhagen Municipality
– **Scenario 2** - replacement of all luminaires in buildings from Group A, Group B and Group C
– **Scenario 3** - replacement of all luminaires in buildings from Group A and Group B
– **Scenario 4** - replacement of all luminaires in buildings from Group A.

In order to calculate the annual benefits of energy savings and maintenance costs savings, the annual costs of the current situation at Copenhagen Municipality, mentioned as ***Current Scenario*** in this report, were compared with the annual costs from the scenarios defined above.

Data and Assumptions

Copenhagen Municipality provided most of the data used in the CBA of CELP. A detailed list of the total number of buildings owned and rented by the Municipality was used, which was extracted from Copenhagen Municipality database Agenda2100[8]. This database has, however, some flaws for the fact that all its inputs have been introduced manually by the responsible for the energy maintenance at each building (Copenhagen Municipality personal communication 2016). Nevertheless, this was the only detailed data source available with values for each building used by Copenhagen Municipality. Table 15, Appendix B, summarizes the data extracted from Agenda2100, where the information from the 1134 buildings in use is organized according with the municipal departments running

[8] *http://agenda2100.keepfocus.dk/*

them. The data extracted was very detailed, however only the total electricity consumption in 2015 and the building areas was used for the calculations.

The assumptions used by Copenhagen Municipality in their calculations are present in Table 15 as well. The same assumptions were adopted for the CBA of CELP to calculate the electricity used in indoor lights and can be explained as follow:

- **Percentage of electricity used in lighting:** The data extracted from Agenda2100 includes the total electricity consumption in the building, yet only a part of this amount of electricity is used in lighting. Different percentages of electricity spent in light were assumed to each building according with their use. For example, Schools and other educational institutions were assumed to use 50% of their electricity in lighting, while offices use 42% and sport facilities 36%.
- **Amount of time buildings are used per day:** According with each building use it was assumed different opening hours. For example, offices are assumed to be open for 12 hours per day while other institutions, such as handicap care or residential institutions, use their buildings 24h per day. Even thought there is daylight, it is assumed that lights are turned on during the whole time buildings are being used.
- **Information regarding the use of buildings during weekends:** Again, according with the type of building use, it was assumed that, for example, handicap care and residential institutions are opened during weekends, while offices and educational institutions are closed.
- **Percentage of outdoor lamps in buildings:** Because CELP only concerns the replacement of indoor luminaires; the number of outdoor lamps has to be excluded from the total number of lamps accounted for the calculations. Thereby, it was assumed that the percentage of outdoor lamps is related with the height of the building. In this way, one to two-story buildings were assumed to have 5% of their lamps outside, three to five-story buildings, 3% and higher than five-story buildings were assumed to have 1% of their lamps outdoors. For example, educational institutions were assumed to use three to five-story buildings, while health centres were assumed to be in one to two-story buildings.

Besides the data for the municipal buildings, Copenhagen Municipality provided the data related to the technical characteristics of light bulbs and ballasts, labour hours and prices, etc., which was used for the CBA of its small case study. These data was used for the CBAs performed in this report as well and is presented in Appendix B, from Table 16 to Table 20. Further, in Appendix A, some extra calculations used for the CBA in the first section of the analysis are explained.

At the end of the first section of the analysis, a **sensitivity analysis** was conducted in order to study how a variation of the new luminaires' prices would influence the payback period of CELP's investment costs in each scenario.

3.3 Energy Savings from Shifting the Indoor Lighting Systems in the Whole City

The second section of the analysis estimates the amount of electricity that could be saved if all luminaires from the entire building area in the City of Copenhagen would be replaced by more energy efficient luminaires. For this study, it was assumed that luminaires with the same characteristics as the ones described for CELP would replace the ones currently in use. Besides the total energy savings, the equivalent monetary savings and the consequent CO_2 emissions avoided are calculated as well.

Data and Assumptions

For the estimation of the amount of electricity that could be saved in the city, data from external literature sources was found to complement the data provided by Copenhagen Municipality. The following table shows the data sources used in the second section of the analysis.

Table 4: Data used in the calculations for the total energy savings in the City and their sources

Data	***Sources***
Total electricity consumption in the City of Copenhagen	Copenhagen Municipality personal communications (2016)
Percentage of electricity consumption used in lighting in each Danish sector	Energy Wiki (2013)
Number of governmental and municipal buildings in Copenhagen	*Københavns Kommune (2016)*

Several assumptions had to be made in order to adapt the data found to the values needed to complete this study. For instance, the data provided by the Municipality for the total electricity consumption is divided in sectors different from the sectors in which the data for the percentage of electricity used in lighting is divided (see Figure 1). This lead to the need of making some associations between the two data sources, as described in Table 5. For example, the data for the electricity consumption in *Trading & service enterprises* and *Building & infrastructure enterprises* was associated with the data for the percentage of electricity used in lighting in the *business and service* sector. The *Governmental buildings* and the *Municipal buildings* were divided into further sectors, according with the data available for the percentage of electricity used in lighting.

Table 5: Associations between the data for the total electricity consumption in Copenhagen City and the data for the percentage of electricity used in lighting in Danish sectors

Electricity consumption in Copenhagen	***Percentage of electricity used in lighting in Danish sectors***
Trading & service enterprises	Business and services
Private households	Households
Governmental buildings	*Was divided into:* Offices and administration Educational Institutes Hospitals Others
Industry	Industry
Municipal buildings	*Was divided into:* Offices and administration Educational Institutes Others
Building & infrastructure enterprises	Business and services

After the associations made in Table 5, the percentages of electricity the buildings in Copenhagen spend in lighting was assumed to be as presented in the following figure.

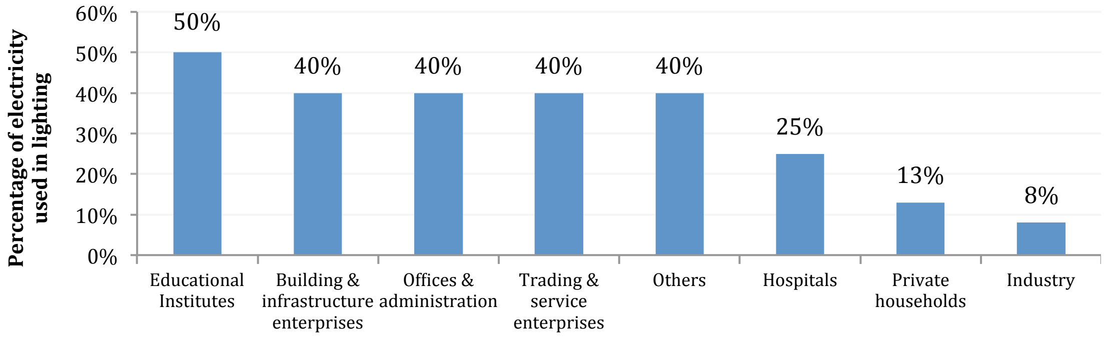


Figure 4: Assumptions on the percentage of electricity consumption used in lighting in Copenhagen City in each sector or group of buildings

In the figure, the buildings in category *Others* were assumed to spend 40% of their electricity consumption in lighting as this value corresponds to the average calculated from the data for the municipal buildings, in Table 15, Appendix B, after excluding *Offices* and *Educational institutes*.

In order to calculate the installed lighting capacity and the number of luminaires installed in each sector, it was assumed that the number of hours their buildings use lights per year could be based on the same assumptions used for the municipal buildings, as present in Table 15, Appendix B. For the private households, it was assumed that their lights are used 4 hours per day, every day of the week, as mentioned by Humphreys (2008). The following table shows the assumptions used in this report. The number of hours buildings in the *Others* category use their lights was calculated with the average of the values in Table 15.

Table 6: Assumptions regarding the number of hours lights are used per day in each building sector

Sectors	***Number of hours lights are used per day (h)***	***Used on weekends?***
Offices & administration	12	No
Hospitals	24	Yes

Sectors	Number of hours lights are used per day (h)	Used on weekends?
Educational institutes	12	No
Others	14	Yes
Trading & service enterprises	14	Yes
Building & infrastructure enterprises	12	No
Private households	4	Yes
Industry	14	Yes

Further, it was assumed that the lighting systems currently in use in the entire city follow the same pattern as the lighting systems currently in use in municipal buildings; i.e. the different lamp types and ballasts follow the same distribution as in municipal buildings and that they have the same capacity and lifetime (see Appendix B, Table 16). In the same way, it was assumed that the new luminaires to be installed in the entire city would have the same characteristics as the ones to be design for CELP; i.e. the same LED bulb and LED driver's capacities and lifetime and the ability to save 15% of electricity from the light bulb consumption by using daylight controls. Furthermore, some extra data and calculations used in this study can be found in Appendix A.

3.4 Cost-Benefit Analysis of Retrofitting the Lighting System at a Household

The third section of the analysis in this report is divided into two parts. In part A, a CBA of replacing the luminaires at a private household is conducted, while in part B a similar CBA is conducted but in this case it is consider the substitution of only the light bulbs in use at a household, without the replacement of luminaires.

3.4.1 Cost-Benefit Analysis part A

In the part A of the third section of the analysis, a CBA is carried out for the replacement of five luminaires in a private household in Copenhagen. The choice of using 5 luminaires in the calculations comes from the assumption that an average private household in Copenhagen has 2 bedrooms, one living room, one kitchen and a bathroom. For each house division there would be one luminaire replaced by a luminaire similar with the one Copenhagen Municipality will develop for CELP.

The major difference between the CBA of CELP and the CBA part A is the fact that in the private household, the user is assumed to take the initiative to substitute the luminaires and it is assumed that it is also the user who conducts most of the actions needed for the household lighting transition and maintenance. In this manner, there will be a reduced number of costs accounted than in the CBA of CELP, mostly for the suppression of labour and management costs. Table 7 shows the costs and benefits accounted in this CBA part A.

Table 7: Costs and Benefits accounted in CBA of replacing luminaires in a private household

Costs	Benefits
One-time cost: – Purchase of new Luminaires	**Annual benefits:** – Energy savings – Maintenance costs savings

Data and Assumptions

It was assumed that three different sets of lamps could possibly be in use in the household and therefore, replacing them could result in three different energy savings. The following table shows the three lamp sets used in both CBA in the third section of the analysis.

Table 8: Definition of three possible sets of lamps that could be currently in use in a private household

Sets	Type of lamps
Set 1	One halogen lamp Three compact fluorescent lamps One current LED bulb
Set 2	Five halogen lamps
Set 3	Five compact fluorescent lamps

As incandescent lamps are highly inefficient, it was assumed that at a private household in Copenhagen only halogen lamps could be found nowadays. It was also assumed that Copenhagen households use compact fluorescent lamps instead of fluorescent lamps and, for that reason, only electronic ballasts are accounted in the calculations. A set of five LED bulbs currently in use was not included in this study because this set would have already good energy efficiency levels and its replacement would not bring visible benefits.

It was assumed that the existing luminaires would be replaced by luminaires with the same characteristics as the ones design for CELP, including integrated daylight controls. In this way, the data provided by Copenhagen Municipality was used for the devices' prices, lifetime and capacity, as presented in Table 16, Appendix B. However, since no data for the capacity of the existing and new light bulbs was provided, it had to be calculated for this study. Based on Table 17 in Appendix B, the capacity of existing light bulbs was calculated together with the capacity of the new LED bulbs. The values used in the calculations for this CBA part A are present in the following table, which shows the capacity the new LED bulbs should have in order to substitute each lamp type currently in use, while maintaining the emission of the same amount of lumens.

Table 9: Values for the capacity of lamps used in the CBA of replacing luminaires in a private household

Lamp Types	***Capacity (W)***
Halogen Lamp	35
Compact Fluorescent Lamp	13
Current LED bulb	6
New LED bulb to substitute HL	3
New LED bulb to substitute CFL	7
New LED bulb to substitute current LED bulb	5

Finally, based on Humphreys (2008), it is assumed that in a private household, lights are used 4 hours per day, every day of the week.

3.4.2 Cost-Benefit Analysis part B

CBA part B is carried out for the replacement of five light bulbs currently in use in a private household in Copenhagen. The choice of using 5 light bulbs is based on the same assumptions for choosing the replacement of five luminaires in the CBA part A.

The CBA in part B is in almost all aspects conducted in the same way as the CBA in part A, with differences in the data used and the investment costs accounted. Nevertheless, CBA part B accounts the replacement of the same three different sets of lamps, set 1, set 2 and set 3, as defined for part A.

Because CBA part B concerns the replacement of only the light bulbs in use in a household, without the substitution of luminaires, the investment costs are now related with the prices of LED bulbs. The following table shows the costs and benefits accounted in the CBA in part B.

Table 10: Costs and Benefits accounted in CBA of replacing light bulbs in a private household

Costs	***Benefits***
One-time cost: – Purchase of LED bulbs	**Annual benefits:** – Energy savings – Maintenance costs savings

Data and Assumptions

In the case of replacing the light bulbs at a household without replacing its luminaires, some new considerations had to be made because in this case the LED bulbs should have integrated drivers in order to fit the luminaires currently in use, which do not possess daylight controls. Therefore, the only energy savings accounted in the CBA part B are the ones provided by the use of LED bulbs instead of halogen or compact fluorescent lamps.

In this manner, new data for the light bulbs capacities and prices had to be found since the data provided by the Municipality included only new LED bulbs and LED drivers as separate devices. Thereby, it was decided to use the data found at a well-known Danish supermarket's website, for the price and characteristic of LED bulbs. Besides, in order to make a more realistic comparison, it was assumed that the light bulbs currently in use at the household would have been bought at the same supermarket. It could be possible to find cheaper light bulbs in other online shops, however it was decided to use the data from a supermarket because it represents the products that are easily available for most of Copenhagen population. The following table shows the data used in CBA part B for the characteristics of the light bulbs, which are available at the Danish Supermarket Føtex®[9].

Table 11: Characteristics of light bulbs sold at the Danish supermarket Føtex®

Type of lamp	***Capacity (W)***	***Lumens (lm)***	***Lifetime (h)***	***Price (DKK/unit)***
HL	42	630	2,000	60
CFL	23	1,570	10,000	59
LED	6	470	15,000	100
LED	10	806	20,000	149

In an attempt to avoid a drastic reduction in the light quality (variation in lumens), when LED bulbs replace the light bulbs in use, it was assumed that LED bulbs of 6W would replace halogen lamps, and LED bulbs of 10W would replace compact fluorescent lamps. In the replacement of set 1 (one halogen lamp, three compact fluorescent lamps and one LED lamp), it was accounted the substitution of only 4 light bulbs for there would be no need of replacing the LED bulb already in use, assumed to have the capacity of 6W.

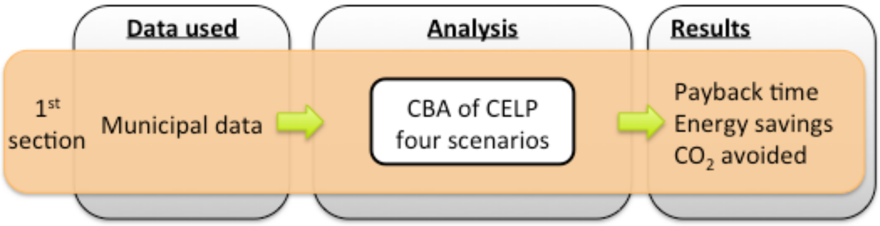
At the end of the CBA part B, a **sensitivity analysis** is carried out in order to understand how the LED bulbs prices variation would influence the payback time of the investment to replace the light bulbs in use at a private household.

[9] *https://www.foetex.dk*

4 Analysis

In order to answer the research questions, the analysis in this report was divided into three parts presented in the first three sections in this chapter. In the first section, a CBA of CELP is carried out for four different scenarios and with its results the first two research questions are answered. The second section of the analysis consists of an estimation of the potential energy savings that could be generated if every building in Copenhagen would have their luminaires replaced by more energy efficient devices. The third section, which is divided into two further parts, primarily presents the CBA of shifting the existing luminaires in a household by luminaires with the same characteristics as the ones used for CELP, and secondarily presents the CBA of shifting the existing light bulbs in a household, without replacing the luminaires. The results from the first three analysis sections are used in the next chapter in order to answer the third research question in this report. Finally, in the fourth and last section in this chapter all analysis limitations found in this report are presented.

4.1 Cost-Benefit Analysis of Copenhagen Efficient Light Project



In the first part of the analysis in this report, a CBA of Copenhagen Efficient Light Project is conducted in order to understand if an investment in replacing the existing luminaires by LED luminaires would bring more benefits than costs to the Danish society in general. The main benefit that the Municipality is seeking is a reduction in the electricity consumption from municipal buildings in order to comply with the Climate Plan 2025 goals. However, if the future energy savings will not pay back the investment in shifting the luminaires in a reduced period of time, this project might be disadvantageous in the sense that, even though it would help to achieve the energy consumption reduction goal of 40%, it would represent extra costs for the Danish society.

The CBA of CELP was carried out for four scenarios which group different number of buildings where, Scenario 1 accounts the luminaires replacement in the entire building area used by Copenhagen Municipality, whereas Scenario 4 accounts only the luminaires replacement in buildings used by the Education Department at the Municipality. The following figure presents the four scenarios used in this study and the respective number of buildings accounted and the departments running them.

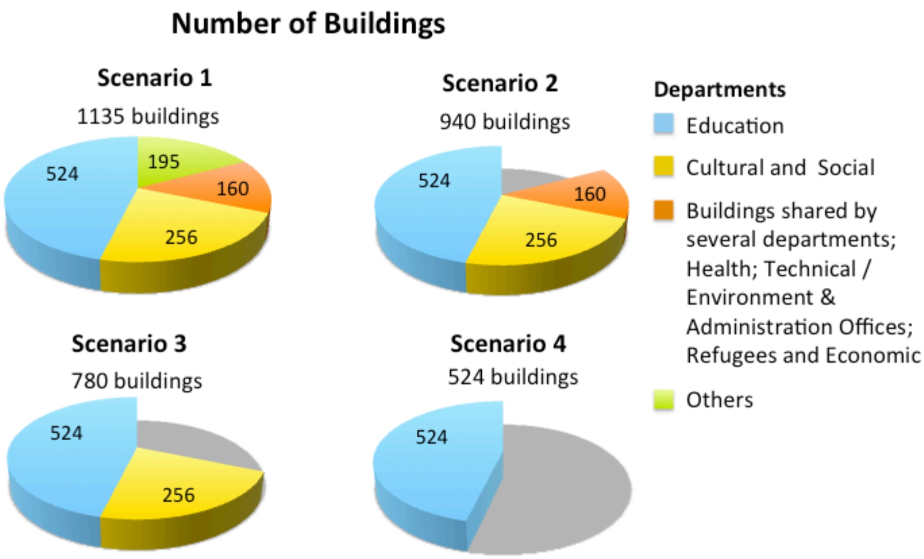


Figure 5: Number of buildings in each one of the four scenarios used in the CBA of CELP

From the previous figure it is possible to see that the Education department is the one that uses more buildings, corresponding to 46% of the total number of buildings used by the Municipality. For this reason and for the fact that schools use 50% of their electricity consumption in lighting (see Table 15, Appendix B), the Education Department should be a priority when implementing a retrofit in the lighting system at municipal buildings.

Figure 6 shows the annual electricity consumption used in the luminaires currently installed for each group of buildings correspondent to each scenario. These values were calculated by using the percentage of electricity used in lighting present in Table 15 in the Appendix B.

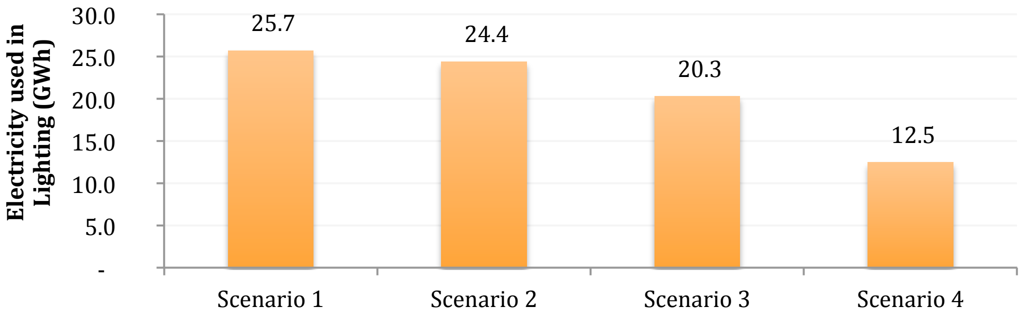


Figure 6: Annual electricity consumption in lightning with the luminaires currently installed in each group of buildings defined for each scenario

Again, it is interesting to notice that the buildings from the Education Department, that form scenario 4, represent a high share of the electricity used in lighting, corresponding to almost 50% of the total electricity consumed for lighting in all municipal buildings.

In the following two subsections, the costs and benefits regarding the implementation of CELP will be presented, in the third subsection the result of this CBA will be explained and in a the section a sensitivity analysis will be performed.

4.1.1 Costs

The costs related to CELP project correspond to the initial investments costs, and thus, they happen only once during the lifetime of the project. In this sub-section each cost related with this project will be presented for each scenario.

Luminaires counting

Before replacing the existing luminaires, it is necessary to know exactly how many luminaires have to be replaced. The estimations on the number of installed lamps are not enough when implementing CELP, therefore it would be important to know the exact number of luminaires to buy. For this reason, there are some costs related to the labour used for counting the luminaires in the buildings where CELP will be implemented.

The price of labour for a person hired by the Municipality to count the luminaires would be 400 DKK/h (Copenhagen Municipality personal communication 2016). It is estimated that to count the luminaires in a building with a total area of 1700 m^2, it would take 20.5 hours, which results in a price for counting luminaires of 0.5 DKK/m^2. In addiction, it was assumed that there would be an extra fixed cost of 800 DKK associated with the luminaires counting at each building (400 DKK for counting outdoors luminaires and 400 DKK for the first hour for making a recognition of the building together with the users) (Copenhagen Municipality personal communication 2016). The following figure shows the total costs in counting luminaires in each scenario.

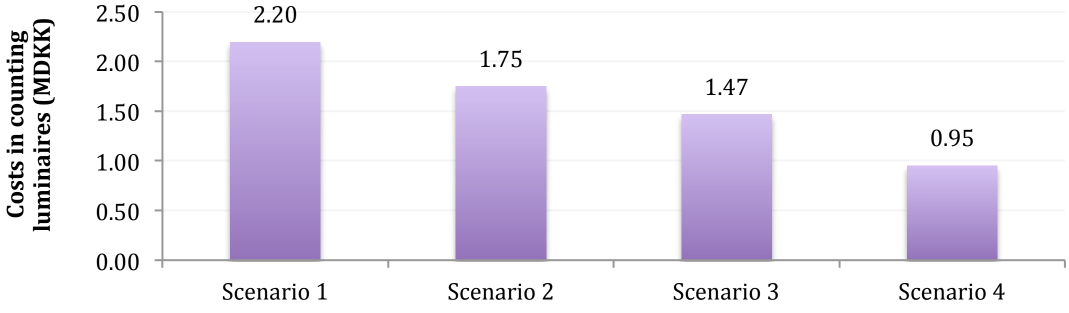


Figure 7: Initial costs associated with counting luminaires in each scenario

Purchase of new Luminaires

It was assumed that each new luminaire would cost 1,000 DKK, already including a new LED bulb and a new LED driver (Copenhagen Municipality personal communication 2016). The following figure shows how much would be spent in purchasing new luminaires in each scenario, based on the estimation of the number of luminaires replaced (see Appendix A).

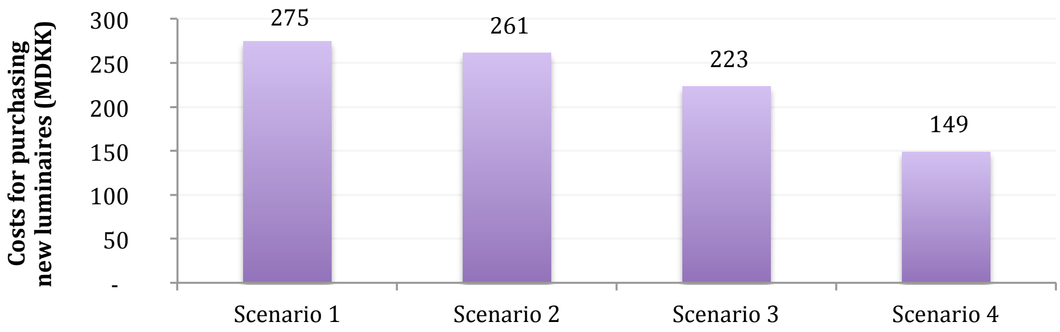


Figure 8: Initial costs for purchasing new luminaires in each scenario

Dismantling of old Luminaires, Installation of new Luminaires and Finishing works

The dismantling of old luminaires, the installation of new luminaires and respective finishing works (i.e. painting and closing holes, etc.) are calculated based on the labour time spent in each task (Table 18, Appendix B). With this value it is possible to calculate the total costs related to each one of this three tasks for each scenario, which are present in Figure 9.

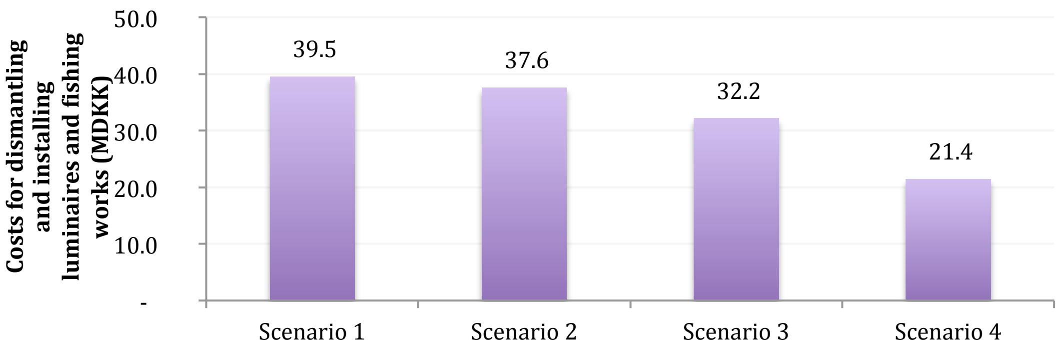


Figure 9: Total cost for dismantling and installation of luminaires and finishing works for each scenario

Disposal of PCB-containing capacitors

As mentioned in the introduction chapter, some old luminaires still contain capacitors made with PCBs. As this is a highly hazardous substance, some extra costs have to be spent on the disposal of these capacitors. It was assumed that 10% of the luminaires with electromagnetic ballasts (27% of the luminaires) contain capacitors made with PCBs. The values for the amount of PCB per capacitor, the price for its disposal and the labour time to dismantle a capacitor are present in Table 18, Appendix B. The following figure shows the costs related with disposal of capacitors with PCBs, based on the estimated number of luminaires to be replaced in each scenario.

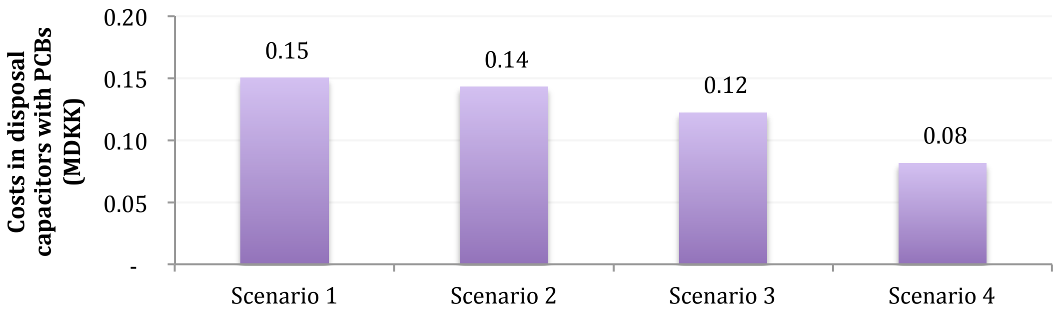


Figure 10: Costs in disposal capacitor containing PCBs in each scenario

Project manager

A new project manager would have to be hired in order to implement CELP. It was estimated that the implementation period would be 18 months and since the salary for a project manager in Copenhagen Municipality is 0.47 MDKK/year (Copenhagen Municipality personal communication 2016), the total cost on 1.5 years project manager would be **0.71 MDKK**. This cost is the same for all scenarios, for it is assumed that a project manager would be needed for the same period of time, independent on the number of buildings that would have their luminaires replaced.

Total investment costs

By summing up all costs presented above in this subsection, it is possible to calculate the total initial investment cost for each scenario, which are presented in the following figure.

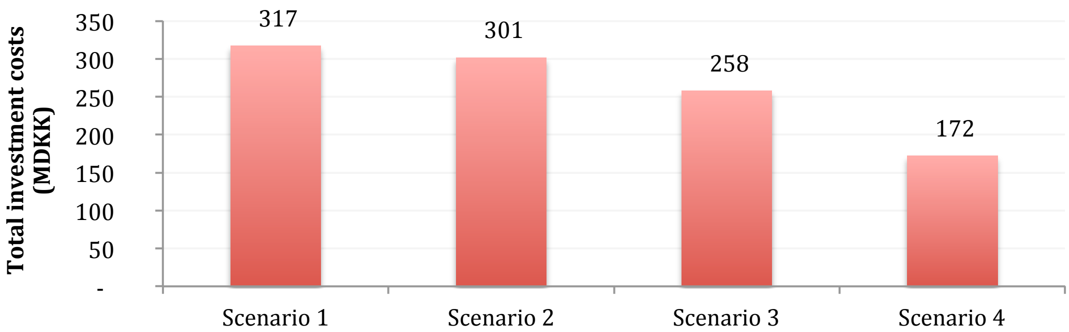


Figure 11: Total investment costs for each scenario

When looking back at each cost presented in the graphics from Figure 7 to Figure 10, it is interesting to note that the higher initial cost related with the implementation of CELP corresponds to the purchase of new luminaires, which accounts to 87% of the total investment on this project. This means that keeping the price of the new luminaires as low as possible is essential to make this project profitable. As new luminaires' price is a critical variable in this CBA, it will be the subject of a sensitivity analysis at the end of this section.

4.1.2 Benefits

The main benefits from CELP correspond to the annual energy savings this project could bring. However, besides the financial savings from the reduced energy consumption bills and consequent CO_2 emissions reductions, financial savings from the reduced maintenance costs the new luminaires require are also accounted. In addiction, one-time benefit is accounted, which corresponds to the first years' energy savings the Municipality can sell back to an energy supplier. In this subsection, all financial savings will be presented for each defined scenario.

Energy savings

In order to calculate the annual energy savings for each scenario, the energy consumed in the current scenario was firstly calculate for then subtracting it with the energy that would be consumed in the four defined scenarios, which happen to be significantly lower due to the higher energy efficiency of the new LED luminaires. Further, the total electricity consumed in lighting was divided into electricity consumed by the ballasts and electricity consumed by the light bulbs. In this way, the energy savings from shifting to the new LED drivers and from shifting to the new LED bulbs are calculated separately and their calculations can be found in Appendix A.

Besides the energy savings from shifting to more energy efficient devices, the new luminaires will have integrated daylight controls, which are assumed to save 15% of the energy spent in the new LED bulbs (Copenhagen Municipality personal communication 2016). Thus, the total energy savings from replacing the luminaires currently in use is calculated by summing the energy savings from shifting to the new LED driver with the energy savings from shifting to the new LED bulb in a luminaire with daylight control. The following figure shows the annual energy savings that could be achieved with the new luminaires, for each scenario.

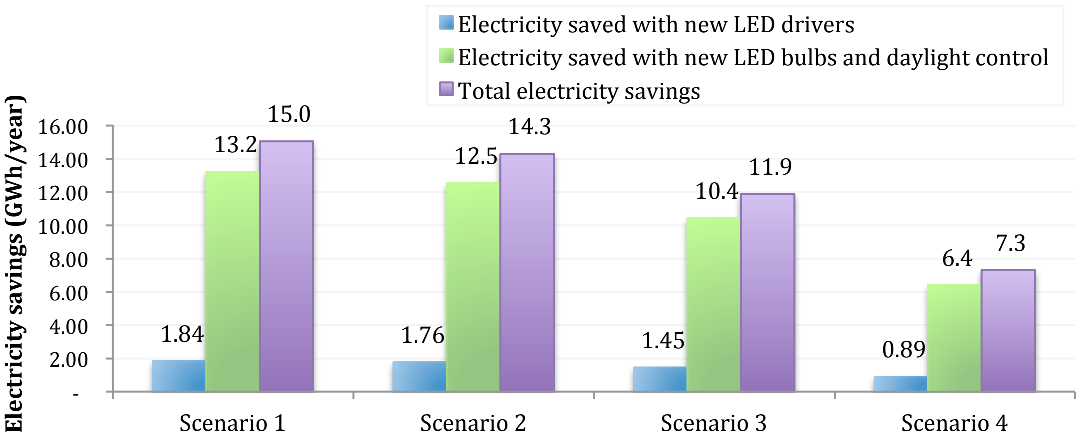


Figure 12: Annual electricity savings from shifting to the new LED drivers and the new LED bulbs in luminaires with daylight controls

The figure shows that, as expected, the highest amount of energy savings could be achieved by using more energy efficient LED bulbs in a luminaire with daylight control. However, although the energy savings from ballast replacement might not seem to be so much, compared with the savings from light bulbs replacement, it is interesting to stress that by using more energy efficient ballasts, around 1 GWh could be saved every year, meaning that the Municipality could save around 1.8 MDKK on energy per year only by replacing the ballasts.

The total annual electricity savings the new luminaires could enable are very significant, going from 15 GWh in scenario 1, to 7 GWh in scenario 4. This savings correspond to a reduction of **58%** of the electricity currently used in lighting in the buildings correspondent to each scenario. When comparing to the total electricity consumption at the Municipality, the replacement of luminaires in scenario 1 could enable a reduction in 52% of the total electricity consumption, while scenario 4 would allow a reduction of 25%, as it is shown Figure 13.

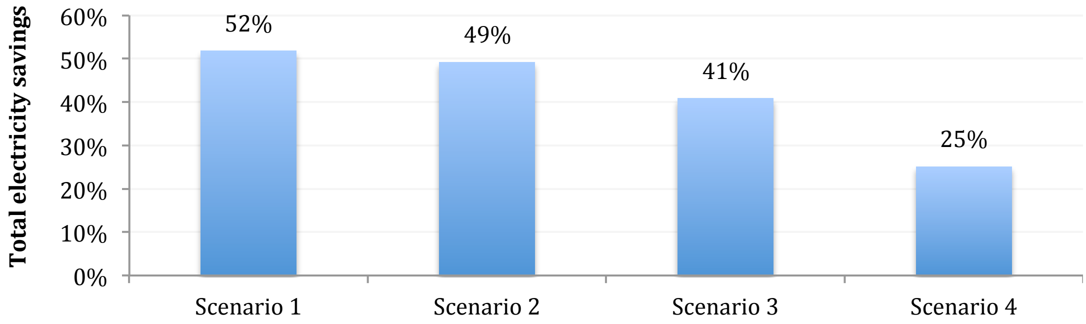


Figure 13: Annual electricity savings from the total electricity consumption at Copenhagen Municipality

With the previous two figures it is possible to understand the impact CELP could have in the total electricity consumption in the Municipality and in this way partially answer the first research question in this report - *How a retrofit in the lighting system of municipal buildings could help Copenhagen Municipality achieve its energy and carbon goals?*

One of the goals Copenhagen Municipality set in its Climate Plan 2025 was the reduction in 40% of the energy consumption in its buildings, in comparison with values from 2010, until 2025. The total energy consumption in municipal buildings in 2010 was 442 GWh of both heat and electricity (Københavns Kommune 2013). This implies that, until 2025, the Municipality wants to decrease in 177 GWh the total energy consumption in its buildings. However, if one considers solely the electricity consumption, which was 102 GWh in 2010 (Københavns Kommune 2013), a reduction in 40% would correspond to 41 GWh of electricity savings per year. In this manner, a reduction of 15 GWh (in scenario 1) in the electricity consumption of municipal buildings would correspond to achieve 37% of the electricity saving goals for 2025.

The monetary benefits corresponded to the annual electricity savings were calculated by using the electricity price for Copenhagen Municipality, which is 1.77 DKK/KWh (Copenhagen personal communication 2016), and are presented in the following figure.

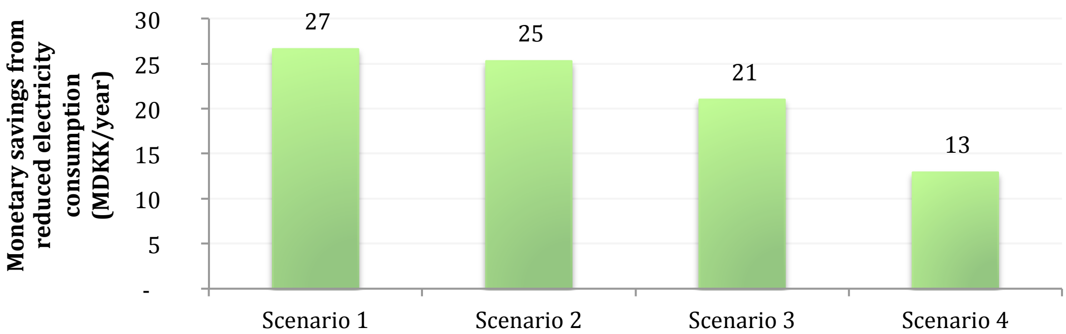


Figure 14: Annual monetary savings from reduced electricity consumption from the new luminaires

From the previous figure it is possible to see that all scenarios would allow considerable amounts of annual savings that could be allocated to further municipal projects.

As a consequence of reducing electricity consumption, CO_2 emissions are avoided. To calculate the CO_2 emissions equivalent to each kWh of electricity consumed in Copenhagen, it was used the rate 0.531 Kg eq./kWh (Aggerholm 2013).

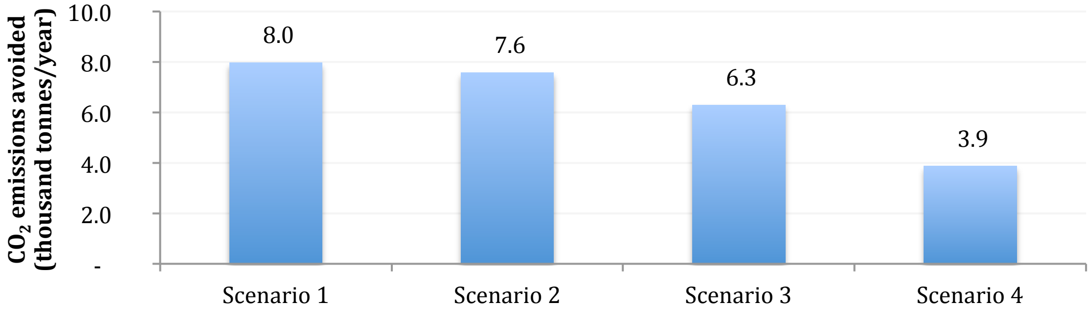


Figure 15: Annual CO_2 emissions reductions corresponded to the electricity savings in each scenario

The carbon footprint of Danish citizens was estimated in 7.2 tonnes of CO_2 emissions in 2011 (The World Bank 2016), meaning that in scenarios 1 and 2 it would be possible to avoid the carbon footprint of more than one thousand Danish citizens.

Because the costs of CO_2 emissions are foreseen to vary in the future years (see Appendix B, Figure 35), the monetary savings from avoiding CO_2 emissions are accounted in the net present value for this CBA, which is represented at the end of the next subsection, in Figure 20.

It is now possible to complete the answer to the first research question in this report - *How a retrofit in the lighting system of municipal buildings could help Copenhagen Municipality achieve its energy and carbon goals?*

By replacing the existing luminaires by more energy efficient devices it would be possible to save considerable amounts of electricity and consequently reduce the CO_2 emissions in the City. Copenhagen Municipality wants to become carbon neutral by 2025 meaning that it has to drastically reduce its emissions, which accounted to 110 thousand tonnes of CO_2 eq. in 2010. If CELP would be implemented in the entire municipal building area (scenario 1), the city's CO_2 emissions could be reduced by 7% already in 2017. If CELP would be implemented solely in buildings from the Education Department (scenario 4), the City's carbon footprint could still be reduced in 4%. These values, although small, are important to reach the ambitious goal of carbon neutrality.

A specific goal from the *administration initiatives* theme in the Climate Plan 2025 concerns the reduction of the City's carbon footprint in 10 thousand tonnes until 2025 with actions in the building sector. With scenario 1, 80% of this goal could be achieved already in 2017, however with scenario 4, only 40% of these reductions could be reached.

According to Copenhagen Municipality, the energy savings from the first year after an investment can be sold back to the electricity supplier by 0.44 DKK per kWh. In this way, it is possible to calculate one more benefit of CELP, which unlike the previous annual benefits mentioned, occurs only one time. For each scenario, the sale of energy savings results in the values present in the next figure.

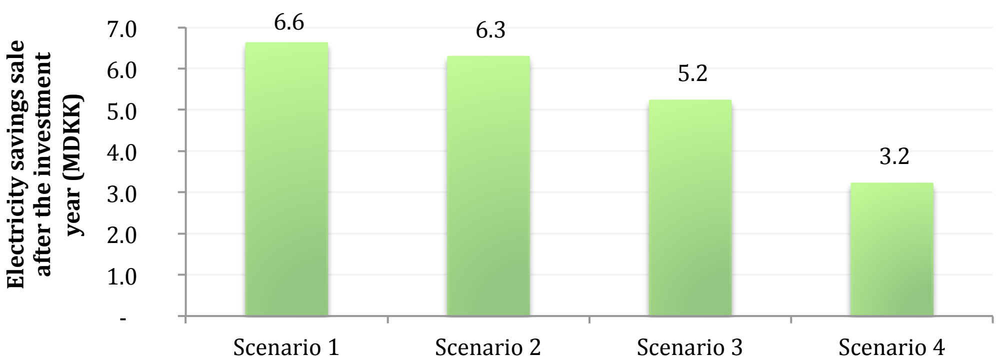


Figure 16: Monetary benefits from selling the electricity savings after the investment year

Maintenance costs savings

Because the new LED bulbs and the new LED drivers have longer lifetime than most of the devices used in the current scenario (see Appendix B, Table 16), they would have to be replaced fewer times per year, which would reduce the luminaires' maintenance costs.

The reduction in maintenance costs was calculated by subtracting the maintenance costs in the current scenario by the maintenance costs in the four new scenarios. Because it is not known how old the light bulbs and the ballasts in the current scenario are, it was assumed that each year a parcel of them would have to be replaced, resulting in an homogenous annual cost (see calculations in Appendix A).

If CELP would be implemented on the beginning of 2017, not only the luminaires would be new, as would be the LED bulbs and the LED drivers. Therefore, the new LED bulbs and the new LED drivers would have to be replaced only after their full lifetime is spent. Here lies the major difference between the calculations made by Copenhagen Municipality in the CBA of its small case study and the calculations made in this report. Copenhagen Municipality chose to calculate the maintenance costs of the new luminaires in the same way it calculated the current luminaires' maintenance costs. Instead, in this report the maintenance costs of the new luminaires vary during the years as represented in the following two figures showing the number of LED drivers and LED bulbs that would be replaced in each scenario, in the buildings where the luminaires currently in use would be substituted by the new ones.

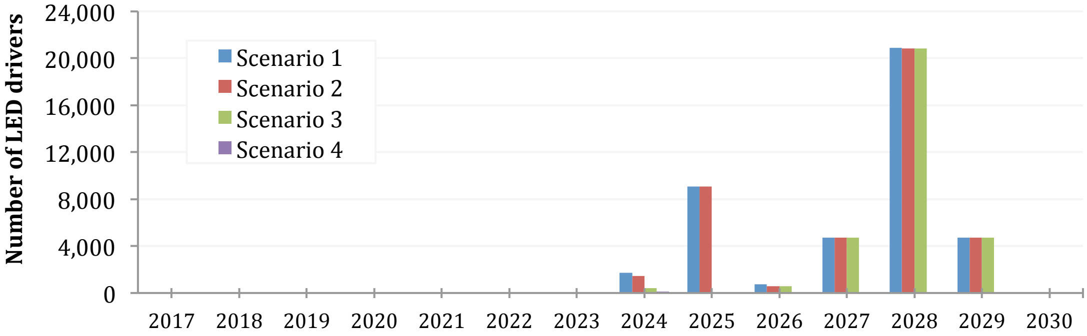


Figure 17: Number of new LED drivers' replacement each year in the new scenarios

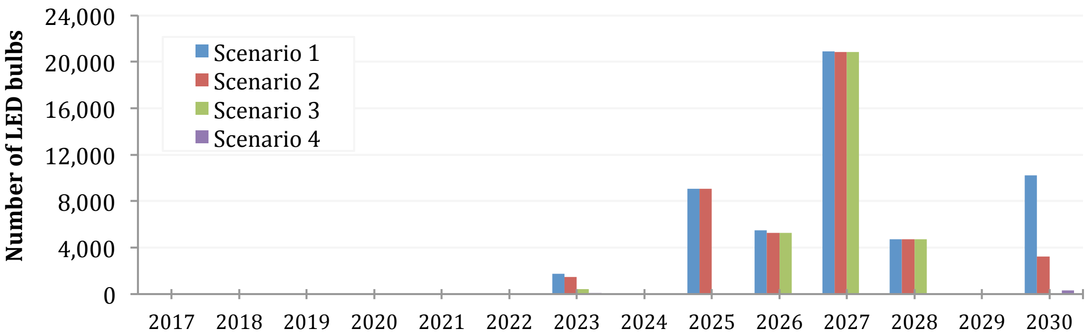


Figure 18: Number of new LED bulbs' replacement each year in the new scenarios

The graphics in Figure 17 and Figure 18 show that in the first years after installing the new luminaires, there would be no need for replacing LED drivers or LED bulbs due to their long lifetime (65,000 h and 60.000 h, respectively). It is interesting to point out that in scenarios 1, 2 and 3 considerable higher quantities of LED drivers and LED bulbs would have to be replaced because this scenarios include buildings that are open 24 h per day, every day of the year (such as residential institutions from the Social Department). On the other hand, buildings in scenario 4 (Education Department) are open between 12 h and 14 h per day and are closed during the weekends, meaning that their LED bulbs and LED drivers last longer because they are used during fewer hours and that their high-energy consumption is a consequence of a high number of luminaires installed.

The maintenance costs in the new scenarios are lower than in the current scenario not only for the fact that less devices would have to be replaced due to their longer lifetime, but also for the fact that there would be no labour costs for replacing the LED drivers – the new luminaires will be designed in a way that users can easily replace LED drivers as they replace the LED bulbs.

The total maintenance costs savings in the new scenarios result from subtracting the costs of replacing the new devices over the years from the annual maintenance costs in the current scenario. Figure 19 shows the potential maintenance costs savings for each new scenario, considering that CELP would be implemented in the beginning of 2017. It is important to note that the values presented in Figure 19 represent the value of the total maintenance costs savings over the years, without discounting with the discount rate.

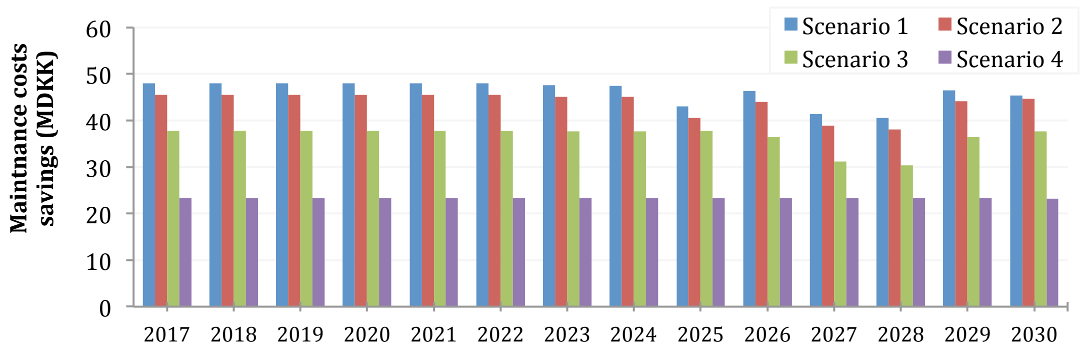


Figure 19: Present values of potential maintenance costs savings from replacing the luminaires in each scenario

Looking at the previous figure, it is possible to see that the maintenance costs savings only vary significantly between 2025 and 2028, which corresponds to the years where more LED drivers and new LED bulbs would have to be replaced. The values between 2017 and 2022 correspond to the savings of the total maintenance costs from the current scenario, since during those years there would be no maintenance costs in the new scenarios.

4.1.3 Results

As mentioned in the methodology chapter, the results from a CBA correspond to the study of the Net Present Value (NPV). After summing up all costs and benefits presented before, the resulted value (the net benefit) was discounted with the discount rate, which in this case is 4%, resulting in the net present value for each one of the four scenarios. The following figure shows the evolution of the NPV for each scenario during the years.

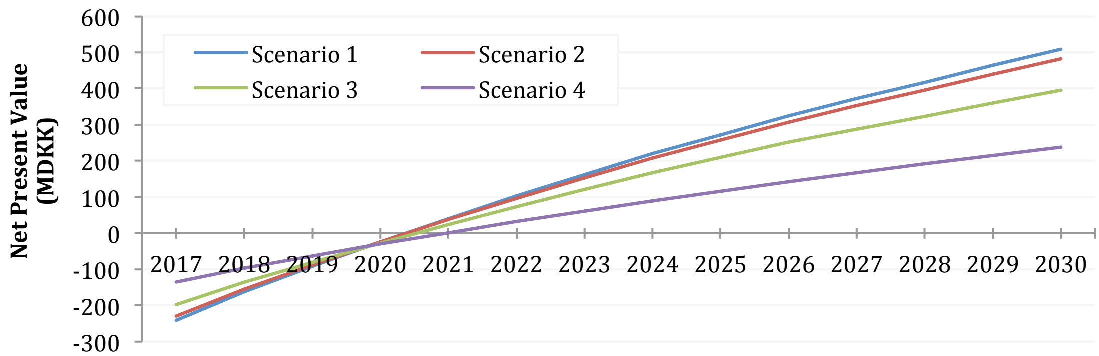


Figure 20: Net present value of Copenhagen Efficient Light Project for each scenario

From Figure 20 it is possible to see that due to high initial investment costs (Figure 11), the NPV for all scenarios in 2017 has a high negative value. However, since in the following years there are only benefits, the NPV grows quickly in all scenarios, becoming a positive value right before 2021 (even for scenario 4, its NPV is 2 MDKK in 2021). This means that for all scenarios the **payback time is 4 years**, which complies with Copenhagen Municipality's requirement of a payback time inferior to 6 years.

The scenarios with higher investment costs are the ones that allow more environmental benefits: higher electricity reductions and consequently more CO_2 emissions avoided. In addiction, these are the ones that allow higher monetary savings in future years as well. In this way the decision Copenhagen Municipality should make depends on how much it can invest in CELP in 2017. Nevertheless, the choice should always go for replacing the current luminaires in the highest number of buildings possible, giving priority to the buildings from the departments where more electricity is used in lighting.

In this sense, a direct answer to the second research question in this report - *What could be the best scenario to implement Copenhagen Efficient Light Project?* – is scenario 1, if there is enough money to make the investment to replace all luminaires in every municipal building. Otherwise, scenario 2 should be chosen, or even another version of scenario 2 with some fewer buildings accounted. The important point is that, due to their high electricity consumption in lighting, buildings accounted in scenarios 4 and 3 – buildings from Education, Social and Culture Departments – should be prioritised in this order, when implementing a shift in the indoor lighting systems.

4.1.4 Sensitivity Analysis

In order for Copenhagen Municipality being able to fund its Efficient Light Project, it is important that, even though some variables might change, the payback time continues inferior to 6 years. As the new luminaires' price is a critical variable in this CBA, a sensitivity analysis was conducted in order to test how the payback time would change if the price of the new luminaires would increase or decrease. In this way, four new CBA were carried out for each scenario, where only the value for the new luminaires' price was changed, by increasing and decreasing it in 25% and in 50%. The following figure shows the results of this sensitivity analysis by comparing the new payback periods with the ones obtained for the original CBA, where the new luminaires' price is 1,000 DKK.

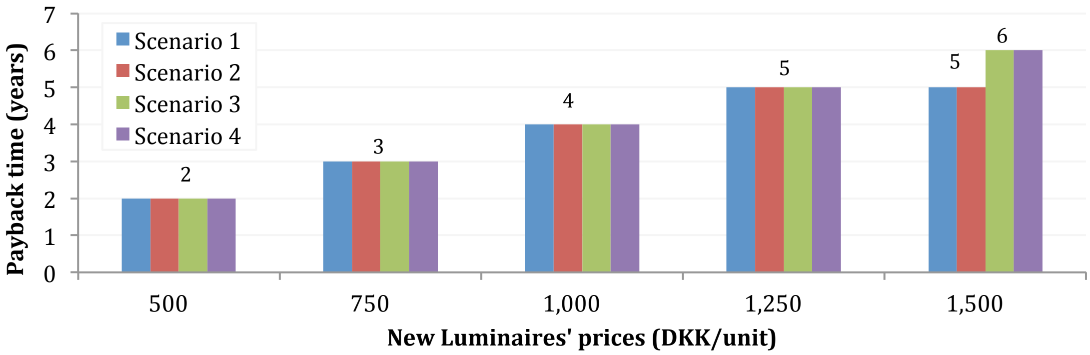
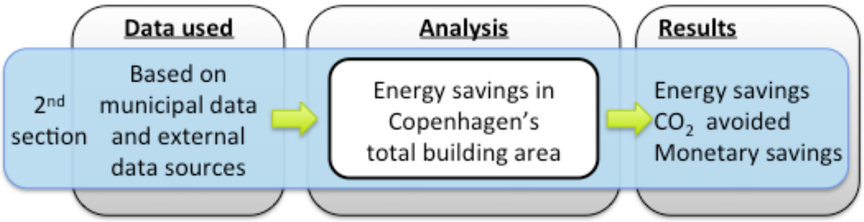


Figure 21:Variation of payback periods for each scenario by changing the prices of new luminaires

This sensitivity analysis shows that even if the price for the new luminaires increases in 50%, scenarios 1 and 2 would still have a payback period inferior to 6 years, meaning that they could still be accepted for funding. Contrariwise, if the luminaires would cost 1,500 DKK, it would not be advantageous for the Municipality to replace luminaires solely in the buildings included in scenarios 3 and 4, for the initial investment would be paid back in 6 years. Nevertheless, if the price for the new luminaires increases in 25%, all scenarios could still be considered for funding. On the other hand, if the price for the new luminaires would decrease in 50%, which would be very unlikely, the payback period would be only 2 years.

This analysis shows that independently of the price of the new luminaires, the scenario to be chosen in order to implement CELP continues to be scenario 1. In this way, the answer to the second research question in this report does not change.

4.2 Energy Savings from Shifting Every Indoor Luminaire in All Copenhagen's Buildings



This section consists of an estimation of the amount of electricity savings that could be achieved if the luminaires from every building in Copenhagen would be replaced by LED luminaires similar with the ones from CELP, i.e. with LED bulbs and LED drivers with the same characteristics and with integrated daylight controls. In this section, the results from several steps taken in order to calculate the electricity savings from substituting the existing luminaires by more energy efficient ones are explained.

Electricity spent in lighting in the City of Copenhagen

In order to calculate the total electricity spent in lighting in the City of Copenhagen, data regarding the annual electricity consumption in the City was needed. This data was provided by Copenhagen Municipality in form of the total electricity consumption in 2015 in the city, as presented in the following figure.

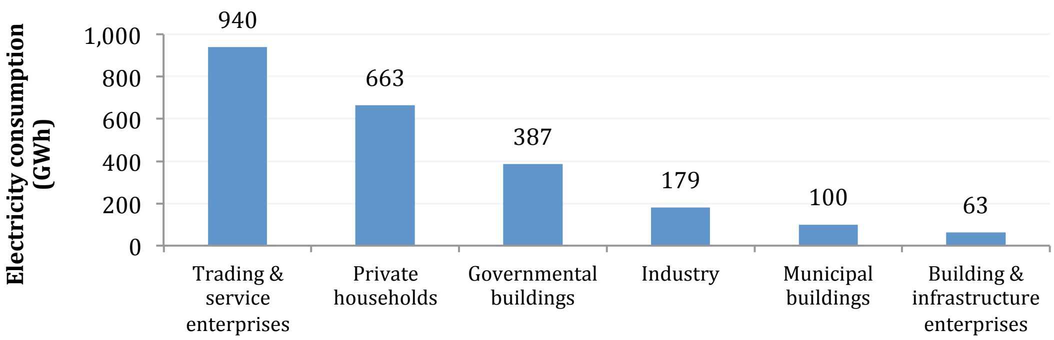


Figure 22: Total electricity consumption in the City of Copenhagen in 2015 (Copenhagen Municipality personal communications 2016)[10]

As it can be seen in Figure 22, *trading & service enterprises* is the sector with the highest electricity consumption in buildings in Copenhagen, which corresponds to 40% of the total electricity used in the city, followed by *private households* that use 28% of the total electricity consumed.

By multiplying the total electricity consumption in buildings (Figure 22) by the percentage of building area of different governmental and municipal departments (see Appendix A, Table 12 and Table 14) and the percentage of electricity spent in lighting (Figure 4) it was possible to calculate the estimated values for the electricity consumption in lighting in Copenhagen's buildings, as presented in Figure 23.

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[10] **Note:** The value for the total electricity consumption in Municipal buildings in this section (100 GWh in 2015) is very different from the value used in the CBA of CELP in the previous section, where the total electricity consumption in municipal buildings is 56 GWh in 2015 (Appendix B, Table 15). This is due to the fact that both values, although provided by Copenhagen Municipality, had different data sources (in the CBA of CELP the data was extracted from the database Agenda2100; whereas the data used in this section resulted from statistics conducted by the Municipality). For this reason, the results from these two sections, regarding the values for the total municipal building area, will be very different.

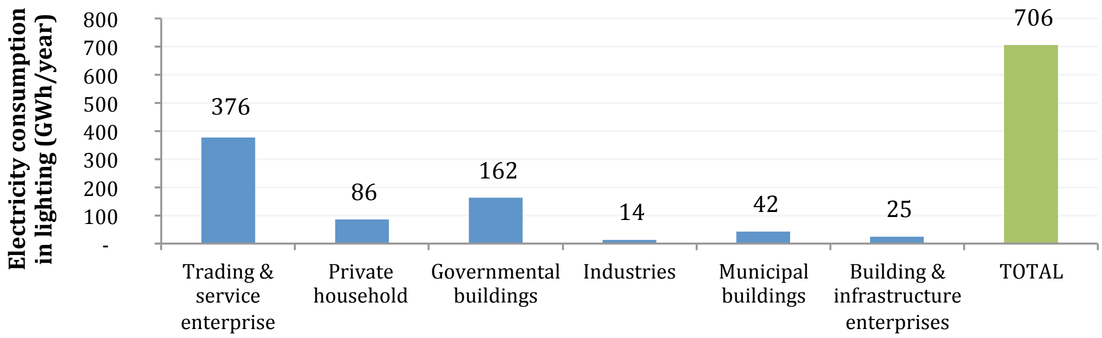


Figure 23: Annual electricity consumption in lighting in Copenhagen's buildings

From the figure, it is interesting to notice that *Trading & services enterprises* is by far the sector where more electricity is consumed in lighting, being responsible for 53% of the total electricity used in lighting in Copenhagen's buildings. This sector is followed by *Governmental buildings*, which consume 23% of the total electricity used in lighting, and *Private households*, which consume 12%. In this way, a retrofit in the lighting system of buildings from *Trading & services enterprises* could be a priority when trying to reduce the total electricity consumption in the City of Copenhagen.

Electricity savings from installing more energy efficient luminaires

An estimated number of luminaires installed in each sector in Copenhagen was calculated with the same approach as the one used in the first part of the analysis (see Appendix A). This total number of luminaires was used to calculate the energy savings from replacing the existing luminaires in the City of Copenhagen by luminaires with the same characteristics as the ones described for CELP. In this way, the total energy savings result from summing up the energy savings from using the new LED bulbs with the energy savings from using the new LED drivers and the energy savings from using luminaires with daylight controls (15% reduction on the light bulb electric consumption). The same capacities and percentage for the existing and new devices were used (see Appendix B, Table 16 and Table 17), however, due to lack of data for the percentage of outdoor lamps in the buildings this number was not removed from the calculations (see section 4.4, Analysis Limitations). The following figure presents the potential annual electricity savings from replacing the existing luminaires in the City of Copenhagen's buildings by more energy efficient devices.

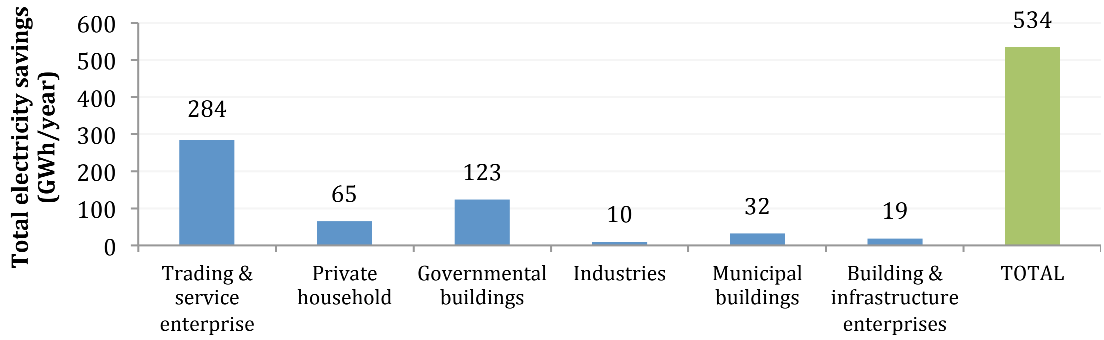


Figure 24: Annual electricity savings from replacing the existing luminaires in the City of Copenhagen by more energy efficient devices

The results present in Figure 24 show that the potential electricity savings from using more energy efficient luminaires are proportional to the electricity used in lighting in each sector and represent a reduction of **76%** of the total electricity consumed in lighting in the city. By comparing with the total electricity consumption in Copenhagen (Figure 22), it is possible to see how much electricity could be saved in each sector:

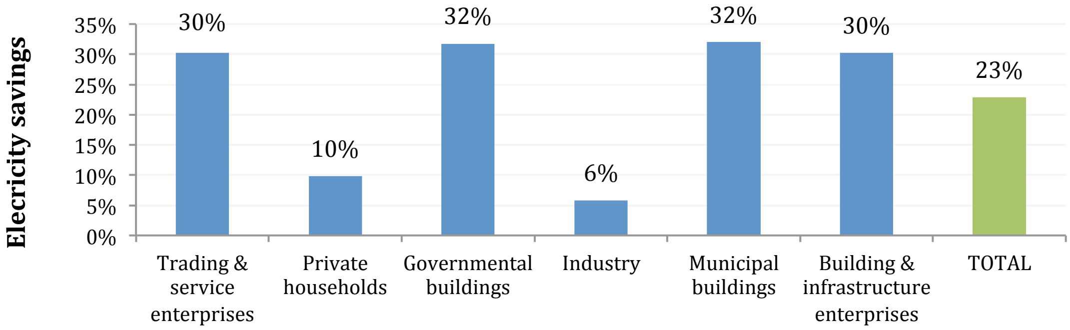


Figure 25: Potential electricity savings, in comparison with the total electricity consumption in each sector, from replacing the existing luminaires in the City of Copenhagen by more energy efficient devices

The highest percentage of electricity savings could be achieved in *governmental* and *municipal* buildings, where the replacement of existing luminaires by some more energy efficient ones could save up to 32% of the total electricity consumption. In fact, the governmental administration should act as an example, just as Copenhagen is starting to do, in order to retrofit the luminaires in their buildings and encourage other sectors to do the same. In the *Trading & services enterprises* sector up to 30% of electricity could be saved, however, since this is the sector where more electricity is consumed per year, it should be a priority when trying to find legislation to force an indoor lightning system retrofitting in the City of Copenhagen. Looking at the full picture, a retrofit in the lighting system of every building in the city could allow a reduction of 23% of the total electricity consumption in Copenhagen, which would correspond to saving up to 534 GWh per year.

The amount of CO_2 emissions avoided due to the reduction in electricity consumption was calculated with the 0.531 Kg eq./kWh rate. The following figure shows the amount of CO_2 emissions that could be avoided in each sector.

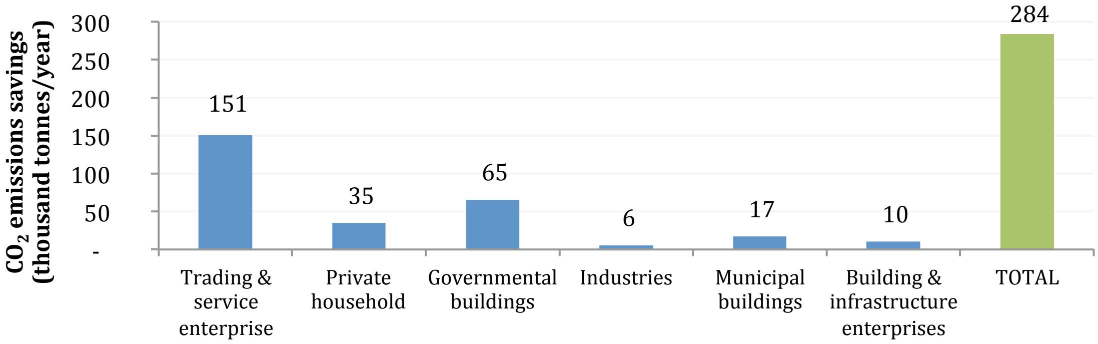


Figure 26: Total amount of CO_2 emissions avoided from reducing electricity consumption in lighting

If the entire building area in Copenhagen would have its luminaires replaced by more energy efficient ones, it would be possible to avoid the emission of up to 284 thousand tonnes of CO_2, which is more than the double of the carbon footprint of Copenhagen Municipality in 2010. However, in 2012 the whole city emitted 1,900 thousand tonnes of CO_2 eq. (CPH 2012), meaning that a total shift in the lighting system would reduce in 15% the City's carbon footprint, which would be already an important achievement.

By comparing the values from Figure 26 with the carbon footprint of Danish citizens (7.2 tonnes of CO_2 eq. per year), it is possible to assert that replacing the existing luminaires in every building in the City of Copenhagen, by more energy efficient ones, could avoid the carbon footprint of 39 thousand Danish citizens. A retrofit in the lighting system in *Trading & service enterprise* buildings alone could avoid the carbon footprint of 21 thousand Danish citizens; while in the *Governmental* sector could avoid the carbon footprint of 9 thousand Danish citizens.

The monetary savings corresponded to the annual energy savings were calculated by using the electricity price for Copenhagen Municipality (1.77 DKK/KWh) while the price for CO_2 emissions in 2016 (Figure 35) was used to calculate the monetary savings from CO_2 emissions avoided. The following figure shows the total monetary savings that could be achieved in each sector from reducing electricity consumption in lighting and consequently avoid CO_2 emissions costs.

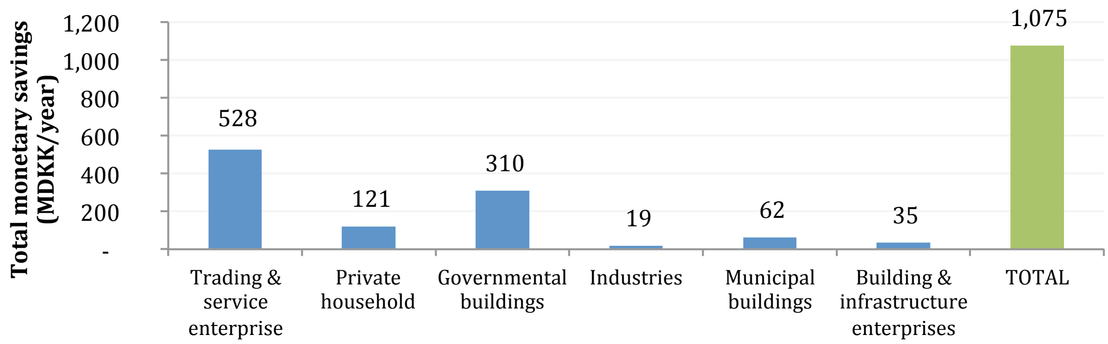


Figure 27: Total monetary savings in each sector from reducing electricity consumption in lighting and consequently avoid CO_2 emissions costs

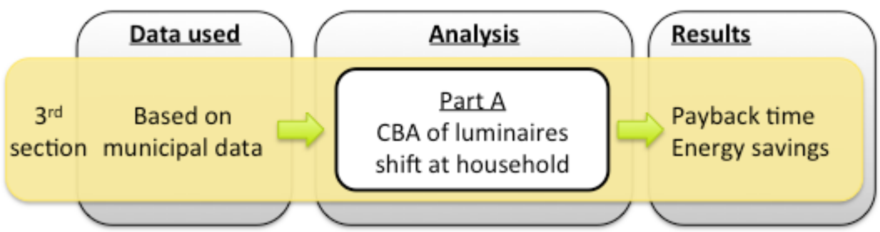
Unlike CO_2 emissions savings, monetary savings in private sectors represent benefits solely for the enterprises, and not for the society in general. For that reason, although the highest monetary savings would come from the *Trading & service enterprises* sector, it would be difficult to know how much this would benefit each enterprise. Nevertheless, Figure 27 shows that *Governmental* and *Municipal* administrations could save considerable amounts of money (310 MDKK and 62 MDKK per year, respectively) if they would retrofit the lighting systems of their buildings in Copenhagen. These savings already represent benefits for the Danish society in general since the public administrations could invest this money in further projects – for instances, creating incentives for private business retrofit the lightning systems in their buildings.

4.3 Cost-Benefit Analysis of Shifting Luminaires in a Private Household

In order to have a total shift in the lighting system in Copenhagen's buildings, it would be needed to replace the luminaires not only in public buildings, but in private ones as well. The shifting in public buildings could be the easiest one to implement by regulations, followed by the buildings owned by enterprises. However, in private households, the implementation could be more difficult to enforce. Therefore, if it is possible to prove the direct benefits for the household users of retrofitting their lighting systems, this shifting could happen without the need of enforcing it.

In this sense, in this third section of the analysis, two cost-benefit analyses are conducted: the first one will focus on the shifting to more energy efficient luminaires in private households (part A), while the second one will study the benefits of shifting the light bulbs, without replacing the luminaires (part B).

4.3.1 Cost-Benefit Analysis Part A



For this study, it was assumed that in a private household with two rooms, one living room, one kitchen and one bathroom, there would be one luminaire replaced at each house division, implying that five new luminaires with the same characteristics as the luminaires described for CELP would replace the existing ones. It was also assumed that three potential sets of lamps could be currently in use, and for that three CBA were made for the following sets:

– **Set 1** - 1 halogen lamp, 3 compact fluorescent lamps and 1 current LED bulb;
– **Set 2** - 5 halogen lamps;
– **Set 3** - 5 compact fluorescent lamps.

Although the prices and some characteristics of domestic luminaires, light bulbs and ballasts might be different from the ones purchased for the Municipality's buildings, for this study it was assumed that in a hypothetical private household in Copenhagen the devices' prices and characteristics would be the same as for the case at Copenhagen Municipality.

In the following two sub-subsections, the costs and benefits for replacing five luminaires in a private household are present followed by a third subsection where the results of this CBA are explained.

4.3.1.1 Costs

It is assumed that the household users would be able to dismantle the old luminaires and install the new ones without the need of hiring external services. In this way, the only investment cost associated with the shifting of lighting devices at a private household is the purchase of new luminaires, which already include a new LED bulb and a new LED driver.

Assuming that the new luminaires for a household would cost the same as they cost for Copenhagen Municipality (1,000 DKK), the investment cost for replacing 5 luminaires would be 5,000 DKK.

4.3.1.2 Benefits

Electricity savings

One of the benefits accounted in this CBA include the energy savings from shifting to more energy efficient LED bulbs and LED drivers. The Electricity savings from replacing five existing luminaire in a private household by more energy efficient ones was calculated with the same approach as used in the first section of the analysis and as it is descried in Appendix A. First, the electricity currently in use by the ballasts and the light bulbs was calculated for then subtracting it by the electricity that would be used by the new luminaires.

As it is assumed that the new LED luminaires will have integrated daylight controls, there will be 15% of savings in the electricity spent in the new LED bulbs. The following figure shows the annual electricity savings from shifting five luminaires to the new LED luminaires in a private household and their correspondent monetary savings, which differs for the three different sets of lamps.

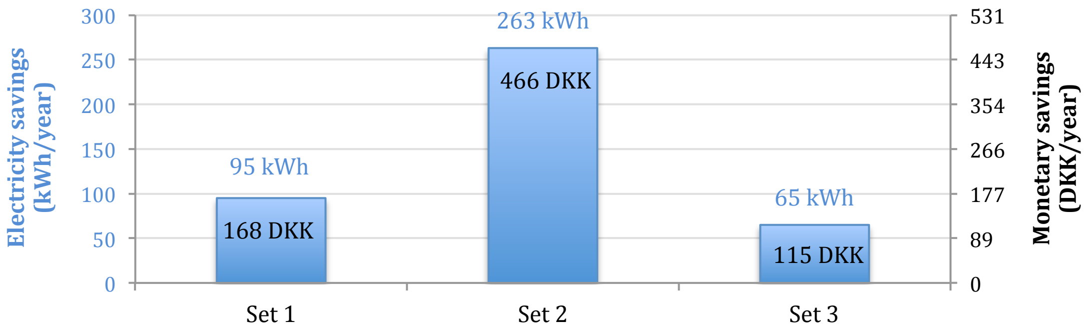


Figure 28: Annual electricity savings and correspondent monetary savings from replacing three different sets of lamps by new luminaires

The savings are considerable higher for replacing Set 2, for it corresponds to the replacement of 5 halogen lamps, the most inefficient among the lamps considered for the three sets.

Maintenance costs savings

The only cost accounted for the maintenance of luminaires is the purchase of light bulbs or ballasts, since it is assumed that it is the household user who replaces them. In order to do a more fair comparison, it was assumed that both light bulbs and ballasts in use in a hypothetical private household would be new in 2017 and therefore they would have to be replaced only by the end of their lifetime.

For the fact that lights are used for few hours per day at households and that the lifetime of ballasts, new LED drivers and new LED bulbs are assumed to be very long (see Appendix B, Table 16), there would be no need for replacing any of them in the next 30 years. Therefore, the costs of purchasing new LED bulbs, new LED drivers or ballasts currently in use were not accounted in this CBA, which covers only the period from 2017 to 2030.

In this way, the maintenance costs savings for replacing luminaires in a private household correspond to the savings costs of purchasing light bulbs for the luminaires currently in use. The following figure shows the maintenance costs savings over the years, considering each set of lamps.

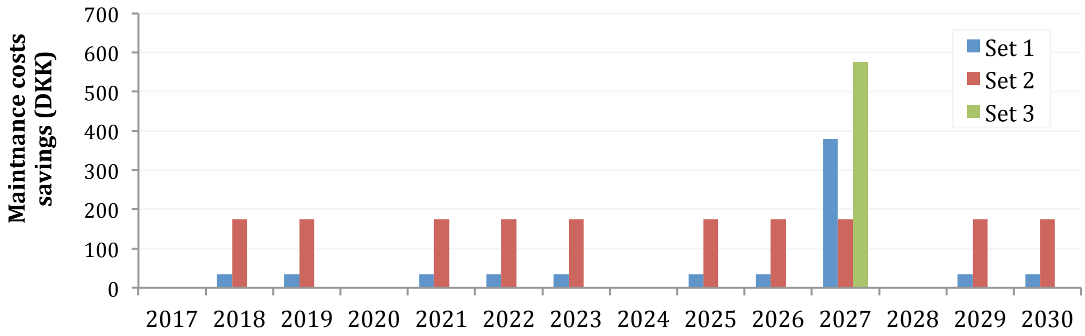


Figure 29: Maintenance costs savings for each set of lamps

The figure shows that replacing Set 3 by LED bulbs would bring great benefits but only in few years, since compact fluorescent lamps, which are relatively expensive, would have to be replaced only every 10 years due to their relatively long lifetime.

On the other hand, halogen lamps are cheaper than compact fluorescent lamps, however they have a short lifetime meaning that they would have to be replaced almost every year. This makes the maintenance of Set 2 more expensive in a long term; meaning that replacing 5 halogen lamps by the new LED bulbs would allow the highest maintenance costs savings.

4.3.1.3 Results

After summing up all costs and benefits presented before, it is possible to analyse the net present value of replacing the luminaires in a private household, which in this case is not discounted, since it was considered a discount rate of 0%. Figure 30 shows the evolution of the NPV during the years, for replacing each set of lamps.

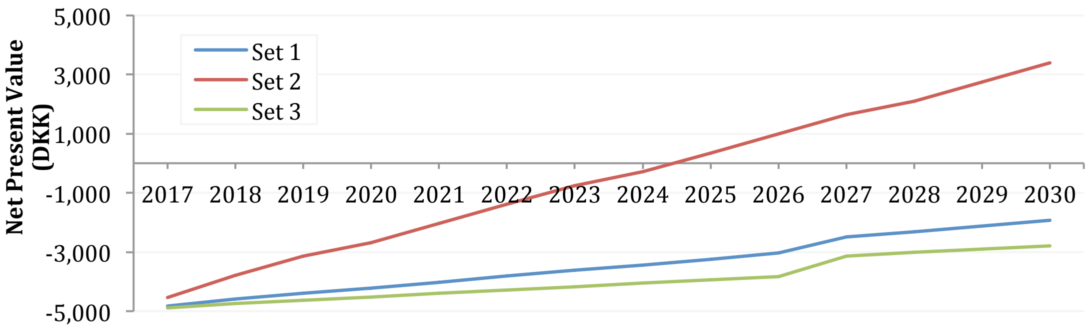


Figure 30: Net present value of replacing the luminaires in a private household, if the new luminaires cost 1,000 DKK per unit

In Figure 30 is possible to see that only the replacement of five luminaires with halogen lamps (Set 2) would have a payback time during the period of this analysis, meaning that replacing set 1 or set 3 would not bring overall benefits to the household users. However, the payback period for replacing set 2 is 8 years, which might be already too long for the household users. In this way, the replacement of the existing luminaires with the new ones designed for CELP would not be very attractive to the economy of a private household if they would cost 1,000 DKK.

For the electricity savings a more energy efficient luminaire would bring, which would correspond to saving up to 466 DKK per year for replacing set 2, the household users should not have to wait more than 2 years to see their investments paid back[11].

Nevertheless, even if the price for the new luminaires would decrease in 50%, which is not very likely, the payback time for replacing set 2 would decrease only to 4 years, as it is shown in the following figure.

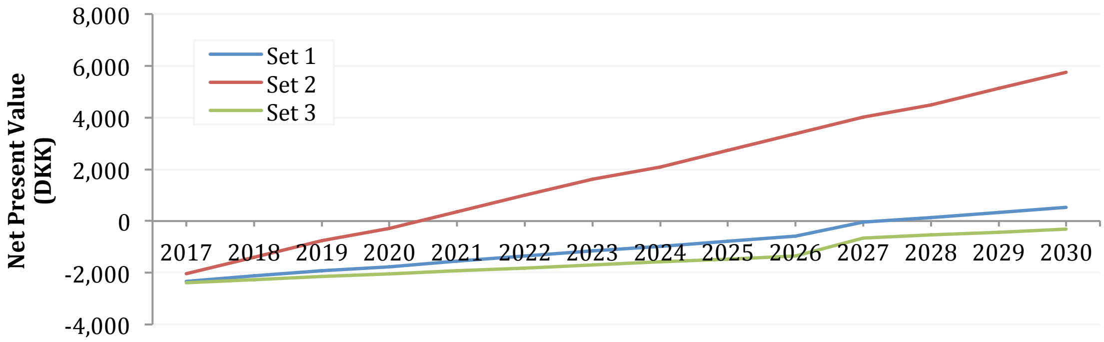
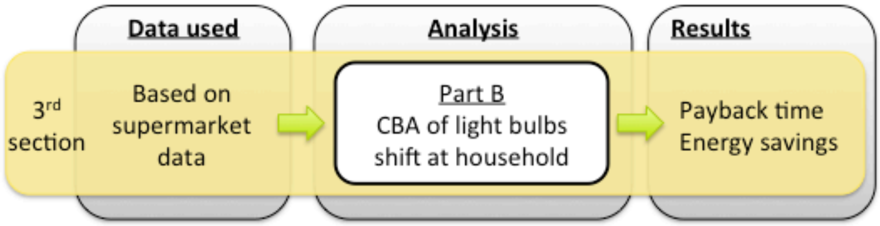


Figure 31: Net present value of replacing the luminaires in a private household, if the new luminaires cost 500 DKK per unit

The figure shows that replacing set 1 and set 3 would still be very disadvantageous even if the new luminaires would cost 500 DKK.

In this way, substituting solely the existing light bulbs by more energy efficient LED bulbs, without replacing the luminaires, could be a more simple and attractive solution to improve the energy savings in a household's lighting system. This is the subject of the following CBA part B.

4.3.2 Cost-Benefit Analysis Part B



For this study, it was assumed that in a private household with five room divisions, there would be one light bulb substituted by LED bulbs in each room division, without replacing the luminaires. It was also assumed that the same three sets of lamps defined for CBA part A could be currently in use.

The CBA part B is conducted with the same steps as CBA part A, however the data used is different. In this case, data collected from the Danish supermarket, Føtex®, was used for the prices and characteristics of all light bulbs.

Another difference between CBA part B and CBA part A is the fact that when the luminaires are not replaced, the energy savings concern solely the savings from using LED bulbs in comparison with using halogen or compact fluorescent lamps (there are no energy savings from using daylight controls in a new luminaire neither from using more energy efficient LED drivers).

In this way, the new electricity savings from replacing the light bulbs currently in use by LED bulbs would be as represented in the following figure.

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[11] For the analysis in this report, it was assumed that, in order to be accepted by household users, the payback time of investments for retrofitting the lighting system at their household should not be more than 2 years. This assumption was not based in any scientific study, however in order to conclude over the CBA results it is important to define a threshold that should not be crossed.

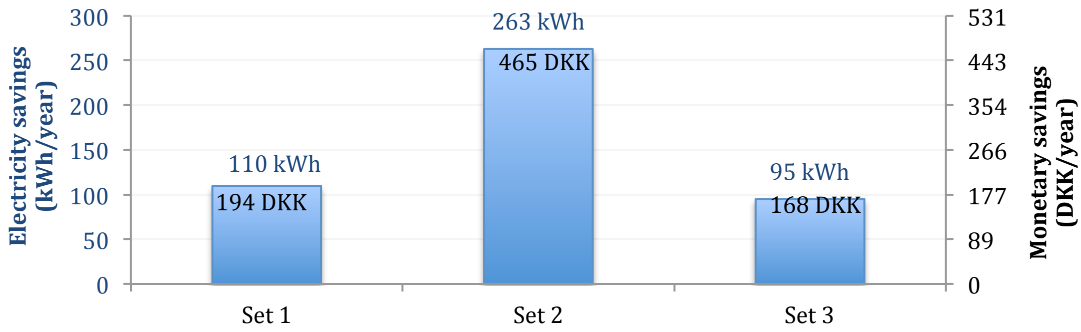

Figure 32: Annual electricity savings and correspondent monetary savings from replacing three different sets of lamps by LED bulbs, without replacing the luminaires

As it was expected, because the LED bulbs have now higher capacity, the savings for replacing sets 1 and 3 by LED bulbs are lower than the savings from replacing all luminaires in CBA part A (see Figure 28). Only for replacing set 2, the electricity savings are the same as in CBA part A, because in this case (part B) the capacities, used in the calculations, for both LED bulbs and halogen lamps currently in use are higher.

Nevertheless, with LED bulbs available at a supermarket, not only their capacities and prices differ from the ones that would be used with the new luminaires designed for CELP, but also their lifetime is different (Table 11). Meaning that, if used for 4 hours per day, these LED bulbs would have to be replaced every 10 and 13 years, respectively, which also affects the NPV.

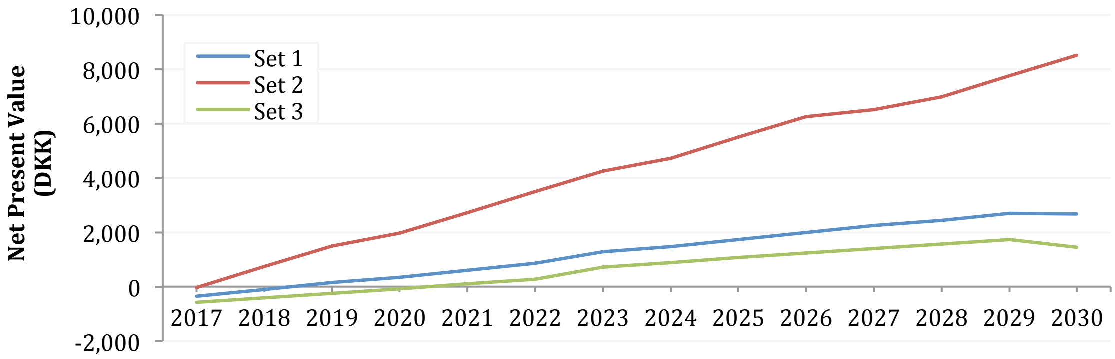

Figure 33: Net present value of replacing the light bulbs in a private household by LED bulbs available at a Danish supermarket

The figure shows that the replacement of set 1 and set 2 by LED bulbs could bring overall benefits to the household user, since their payback period would be 2 years and 1 year, respectively. The replacement of five halogen lamps by LED bulbs appears to be very advantageous since, not only the payback period is very short as it allows the savings of up to 8,000 DKK in 13 years, with an investment of 500 DKK.

Figure 33 also shows that if five LED bulbs would replace five compact fluorescent lamps (set 3), it would take 4 years to have a full return of the investment (NPV of set 3 in 2020 is -73 DKK). Meaning that LED bulbs available nowadays at the supermarket still not offer considerable greater advantages over compact fluorescent lamps, both in terms of price and in terms of energy savings.

4.3.2.1 Sensitivity Analysis

A sensitivity analysis was carried out by varying the price of LED bulbs for it represents the only costs on replacing the light bulbs currently in use in a household. In this way, the prices for the LED bulbs of 6W and 10W, available at the Danish supermarket, were increased and decreased in 25% and 50%. The following figure shows the results of this sensitivity analysis by comparing the new payback periods with the ones obtained for the original CBA.

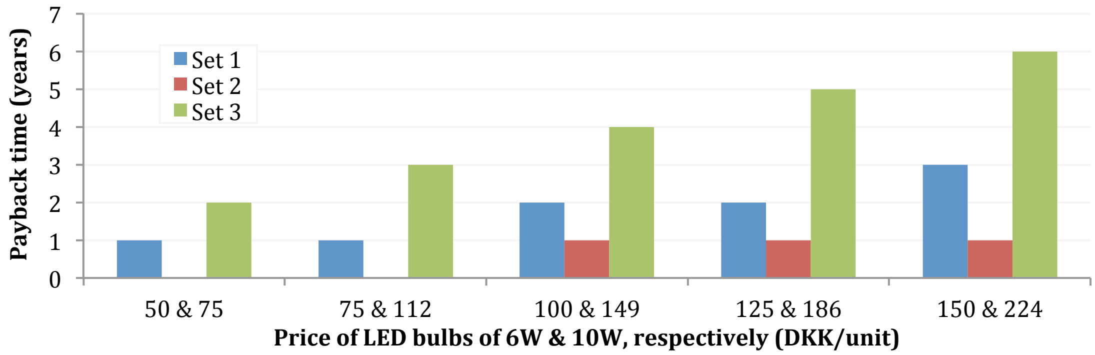

Figure 34: Variation of payback periods for replacing each set of light bulbs by LED bulbs, by changing the price of LED bulbs

This sensitivity analysis shows that even if the price for the LED bulbs would increase in 50%, it would still be advantageous for the household users to replace five halogen lamps (set 2), for its payback period would not increase. This strengthens the idea that LED bulbs should be always chosen over halogen lamps, for they are much more efficient.

On the other hand, the replacement of five compact fluorescent lamps (set 3) would be advantageous (with a payback period inferior to 3 years) only if the LED bulb prices would be reduced in 50%, when they would be at the price level of halogen and compact fluorescent lamps. Finally, the replacement of set 1 would still bring overall benefits to the household users if the LED bulbs prices would increase in 25%.

4.4 Analysis Limitations and Future Studies

The data used in this report is mostly based on **Copenhagen Municipality's own data and assumptions**, which are subject to uncertainty. For instance, since CELP is still in a design phase, it is only possible to estimate the new luminaires' price and their respective LED bulbs and drivers' prices. When an agreement is made with a producer, it will be possible for the Municipality to have a more accurate value for the prices and a more accurate CBA can be performed.

As it was mentioned in the introduction chapter, the **data referred to the municipal buildings** and extracted from a database has some flaws, since all its inputs have been introduced manually. To improve the reliability of its data, Copenhagen Municipality is developing a new and automatic software system to collect values from energy consumption and other parameters in each building (Copenhagen Municipality personal communication 2016). Future projects regarding energy savings in lighting would benefit if the data provided by this new software would provide exact values for the buildings' area, number of floors (or maybe the amount of electricity used in outdoor luminaires) and number of hours the buildings are used per day.

When calculating the energy savings of shifting the luminaires from the entire building area in Copenhagen City to more energy efficient ones, the percentage of **outdoor luminaires** in each building was not excluded, for these values were not available. Assumptions for this value could have been made based on assumptions for the number buildings' floors. However, it would be difficult to estimate the number of floors for the buildings in each sector, since they might vary a lot. It can also happen that more than one sector coexists in the same building, which is the case of residential buildings with trading and service business on the ground floor. Further, some small buildings might not have outdoor luminaires, like some private households. For this reason it was decided to not exclude, what would be, an almost arbitrary percentage from the total number of luminaires calculated.

The **data used for the CBA part A** of replacing the luminaires in a **private household** was based on the data from the Municipality, even though in reality the values might be very different. The type of luminaires used in public buildings are, in most cases, very different from the ones used at households, and since most of the times they have to light a much larger space, their lamps capacities might be higher as well. However, in order to study the advantages of implementing luminaires with the same characteristics as the ones designed for CELP, the data provided by the Municipality was used at a household scale.

The acceptable **payback period** for the private household users to have their investments returned was assumed to be, in maximum, 2 years. As mentioned in a previous footnote, this number is not based in any scientific evidence, however it was important to define some threshold. In reality, some household users might be able to wait a longer period to have their investments returned, while others might prefer an even lower payback period. In this sense, new studies could be made in order to consider different preferences for payback periods when retrofitting the lighting system at private household.

In conducting a CBA it is important to limit the analysis since it is impossible to include exactly every cost and every benefit related to a certain project. For that, although it is normal to leave some parameters outside of this CBA, some parameters should in future studies be included in order to increment the quality of a CBA of CELP. This is the case of the **disposal of discharge lamps**. As mentioned in the Introduction chapter, discharge lamps contain small amounts of mercury and for that they require special care in their disposal. This would bring extra costs for the Municipality that could be added to the CBA. However, the financial costs for their disposal were not available and for that reason were left outside of this study.

Other considerations for a future CBA of CELP concern the **conversion of several indirect benefits into monetary values** in order to include them in the calculations. Some of the indirect benefits that could be accounted, if it is possible to give them a monetary value, are the improvement of work productivity and health benefits (for example from reduced recovering time) due to better light quality from LED lamps. The environmental benefits form removing PCB containing luminaires and mercury containing lamps from municipal buildings could also be accounted.

If the new LED luminaires are implemented in municipal buildings, they might accelerate the adoption of other technologies, such as **Li-Fi** and **lighting management software**. In this way, future studies could consider the energy savings a transition to Li-Fi could bring (for using less routers for Wi-Fi) and the energy savings a LED lighting system connected to a software management could generate.

5 Discussion

In this chapter, it will be discussed how a sustainable transition within the indoor lighting system in the City of Copenhagen might be in the making. Results from the analysis in this report will be used to support the discussion based on the definitions of transition pathways, from Geels & Schot (2007), and other concepts from the Multi-Level Perspective theory. Nevertheless, since the transition in focus is hypothetical, one can only guess the path it will take in the future.

Landscape pressures already destabilized the regime

As it was mentioned back at the Theoretical Framework chapter, nowadays it is already possible to see the attempt of regime actors in adapting to the landscape changes. When pressures from the climate change, the fluctuation of oil prices, etc., got stronger, in the direction of forcing the regime to reduce its energy consumption, regime actors had no choice than to change some rules and habits in order to respond to the changes. In this sense, the Danish Government, a regime actor, decided to implement some energy saving measures and is pressing further regime actors to follow the same path. One of its measures was the establishment of the national goal for Denmark becoming fossil fuel free by 2035, which makes it essential for the country, not only to invest in renewal energy sources but also to reduce the national energy demands.

This ambitious goal pressed other regime actor to follow the lead and in that way Copenhagen Municipality, as part of its Climate Plan 2025, created the Copenhagen Efficient Light Project. This project aims at reducing the electricity consumption at municipal buildings by replacing the existing luminaires by new highly energy efficient ones. This project is opening a window of opportunity for the development of the LED niche-innovation, which represents a technology that, although already familiar, is not yet available at its full energy efficient potential in the market.

A sustainable transition with a reconfiguration pathway started already

Thanks to the initiative of Copenhagen Municipality with its CELP, a sustainable transition to indoor LED lighting seems to be inevitable at the municipal buildings. LED technology can be seen as symbiotic with the regime, for it does not require a completely different way of using lamps, this transition can be described with a reconfiguration pathway.

The first section of the analysis in this report indicates that this promising project would allow the Municipality to save up to 15 GWh of electricity, every year, if every municipal building would have its luminaires substituted by the new energy efficient ones. This would correspond to a reduction of 8 thousand tonnes of CO_2 emissions and monetary savings of 28 MDKK per year (in 2016 prices). This project is almost certain to become successful since even if the price of the new LED luminaires would increase in 50%, it would still be advantageous for the Municipality to implement the project.

In this sense, CELP can become an important turning point for the LED niche-innovation for, if successful, it can prove the enormous benefits of using LED lighting in buildings and it will also support the development of a new line of LED luminaires, LED bulbs and LED drivers. These developments of the LED technology and the proof of its energy saving benefits could then help to boost the LED market.

The aim of Copenhagen Municipality in retrofitting the lighting systems in its buildings is to reduce their electricity consumption in order to comply with the goals set by the Climate Plan 2025. There is no known precedent project about shifting to LED indoor lightning in the same scale as CELP, and for that Copenhagen Municipality, as a pioneer, has the important role of being an example to other regime actors and to spread the knowledge it will get out of this project. For the media and scientific attention CELP might get, it has the potential to change the overall misunderstanding that lighting in buildings is not an important aspect to focus on when aiming for significant electricity savings in buildings.

Copenhagen Municipality could inspire other regime actors to change the lighting systems in their buildings

The success of CELP could lead other regime actors to consider a change in the lighting systems of their buildings as well. For instance, if the Danish Government would follow the initiative of Copenhagen Municipality and would retrofit the lighting system at its own buildings in Copenhagen, it could save up to 123 GWh per year in electricity.

This corresponds to avoid the emission of 65 thousand tonnes of CO_2 and monetary savings of 310 MDKK per year (in 2016 prices), as the second section of the analysis suggests.

One way this monetary savings could be used is by creating incentives; either in a national or in a municipal scale, for other regime actors to implement energy savings, such as retrofitting the lightning systems in their buildings. Nevertheless, as already mentioned, incentives and regulations do not work by themselves, mainly because sustainable solutions might not offer direct benefits to the users. Thereby it is important that users understand the benefits they would get in a near future, when there are initial investment costs for shifting to energy efficient lighting. Hence, examples of projects like CELP could not only benefit both municipal and governmental sectors, but could also bring the LED niche-innovation to the attention of other regime actors and make a shift to LED lighting in buildings much more attractive to buildings' users.

Some regime actors might gain interest on a transition to LED indoor lighting

Some regime actors might gain interest on the adoption of LED niche-innovation and for that they might lobby other regime actors into doing the same. If the LED technology would become part of the regime and every Copenhagen's building would have its indoor luminaires replaced by energy efficient ones, it would be possible to save up to 534 GWh of electricity per year, which corresponds to avoid the annual emissions of 284 thousand tonnes of CO_2. This would support, albeit in a small scale, the Danish Government in reducing the national energy demand until 2035.

Besides, the fact that LED do not contain mercury, as discharge lamps, and that the replacement of old luminaires with capacitors containing PCBs would bring environmental value to the city, could represent extra stimulus for the municipal or national governments to encourage a wider transition to new LED luminaires.

If incentives for private owners to retrofit the lighting systems of their buildings would be created, it would be important to focus on the Trading & services enterprises sector, since it is the one with higher electricity demand and, as a consequence, higher potential for electricity savings in lighting in buildings, as suggested in the second section of the analysis. An incentive large companies could already take advantage of is the fact that each time they implement energy saving measures and save more than 50 MWh per year, they can sell the first year's savings to the energy supplier.

Another consideration the municipal or national governments should keep in mind is the fact that it would be easier to encourage building owners to implement LED lighting in buildings when they are still in the design phase, where new LED luminaires could be implemented right away. This could be important for the fact that, until 2025, Copenhagen's building area is expected to increase in 6.8 million m^2.

Sustainable transition in the lighting system at private households

The results from the third section of the analysis indicate that the replacement of luminaires at a household by luminaires similar to the ones used for CELP would not bring overall benefits to the private household economy, even if the new luminaires would cost only 500 DKK. Nevertheless, the same analysis suggests that the substitution of solely the light bulbs in use by LED bulbs currently found on the market could represent advantages to the household users.

The analysis proposes that LED bulbs found on the market nowadays might not represent considerable advantages, in terms of cost-benefits analysis, over compact fluorescent lamps. But on the other hand, the results from the same analysis indicate that there would be great overall benefits for the household users in replacing halogen lamps by LED bulbs, even though they cannot be found in the market at their full energy saving potential yet. Even if the prices for the LED bulbs would increase in 50%, it would still be highly lucrative to replace the halogen lamps by LED ones, and the payback period could be as short as 1 year.

Examples from large projects like CELP might get the attention of private household users to the benefits LED technology could offer. However, the difference in scale and the fact that lights are used for much fewer hours at households, could make the users feel that there is no correlations between the benefits LED technology could bring in a large-scale implementation and the benefits it could bring to a household economy. In this way, in order to make a shifting happening in the lighting systems of private households, without the need of enforcing it with regulations, it is important that household users become aware not only to the potential energy savings but, specially, to the fact that the payback time for having their investments returned in lower electricity bills can be very short.

To such a degree, the acknowledgment of the benefits of LED bulbs over incandescent or halogen lamps could speed the transition to a LED lighting adoption in households. Thereby, as a vicious cycle, the wider adoption of LED niche-innovation by the regime actors could also encourage the further development of this technology. In this manner, it is important to stress again that LED technology has the potential of becoming much more efficient in the next years and in the near future it could become a serious competition to compact fluorescent lamps as well.

The adoption of LED technology by regime actors could open windows of opportunities to further niche-innovations

If LED technology would be widely incorporated in the lighting systems of buildings by regime actors, a window of opportunity could be opened to other niche-innovations that depend on the use of LED, such as Li-Fi.

Copenhagen Municipality has already plans to implement Li-Fi in its workplaces in the near future, in an attempt to improve the inter-communication speed and data security. Although it is not already proven, this technology might have potential to contribute to electricity savings as well. Nevertheless, if the advantages of using Li-Fi over Wi-Fi are proven in the future, it could make LED technology look like something imperative in every work space, making compact fluorescent lamps and halogen lamps, on the other hand, look obsolete in offices. This could make Li-Fi radical niche-innovation stronger and more organized in order to become a symbiotic niche-innovation together with other regime actors that already adopted LED technology.

This niche-accumulation would strengthen even more the place of LED technology in the market, which would easily resist against incumbent firms, such as compact fluorescent lamps that at the time seem to be the biggest barrier left to the wide adoption of LED niche-innovation by the regime.

Sustainable transition within the lighting system of private buildings in Copenhagen

With all said before, it is possible now to summarize the main ideas in order to answer the third research question in this report in a more concise way - *Could Copenhagen Efficient Light Project trigger a sustainable transition within the lighting systems in Copenhagen's buildings?*

A direct answer is 'yes'. The landscape pressures already made regime actors change some habits and rules and to look for ways to reduce energy consumption. Copenhagen Municipality, with the aim of comply with the national goals, created CELP which has the potential for saving huge amounts of electricity at municipal buildings. This project will help the LED niche-innovation develop its technology further by creating a new concept of highly energy efficient LED luminaires for the municipal buildings.

The success of CELP and the fact that some regime actors might even see other benefits in adopting LED than only energy savings, could create pressure on other regime actors from within the regime itself. This could be the case of municipal or national governments that could see the environmental and public health advantages of adopting LED technology for it could enable a reduction of hazardous substances in the city (such as mercury from discharge lamps and PCBs from old luminaires). Then, the increasing adoption of LED could stimulate the further development of the technology, making it a serious rival to compact fluorescent lamps and an attractive investment for most of regime actors, including household users.

The use of luminaires with daylight controls (as they are already mandatory in workplaces in Denmark) and their connection to lighting management software could bring building's lighting to a new level of energy efficiency. The incorporation of LED in these intelligent systems could optimize the electricity savings in workspaces and open space for the implementation of other symbiotic technologies, like Li-Fi. In this way, if proven successful, the adoption of Li-Fi by pilot projects could make LED bulbs a requirement in workspaces in the future, which would change the users practices and perception of lighting as a technology that could be used not only to light but also to communicate.

What is starting as the adoption of LED technology with the aim of saving electricity, could in fact end in a sustainable transition within the indoor lighting system, especially in workplaces, where luminaires could be used for other purposes than just to light and could become part of interconnected light management software in a smart building.

6 Conclusion

If Copenhagen Efficient Light Project would be implemented in every building used by Copenhagen Municipality, it would allow saving 15 GWh of electricity per year, which represents a reduction of 52% of the total electricity consumption in municipal buildings. This could help Copenhagen Municipality reach its electricity savings goal in 37%. The amount of CO_2 emissions that could be avoided in this way could help the Municipality to reach 80% of its carbon reductions target already in 2017.

When implementing CELP, scenario 1 should be chosen, where the luminaires in every municipal building are substituted by the new energy efficient LED luminaires. Scenario 1 would bring more benefits in the near future and even if it has the highest initial investment costs, estimated in 317 MDKK, it would have a payback period of only 4 years. Even if the price for the luminaires increases in 50%, scenario 1 would still be the one that should be chosen, since the payback period would continue to be less then 6 years. If there is not enough money for the initial investments, scenario 2 should be chosen, or even a reduced version of this scenario. Nevertheless, it is important to prioritise the substitution of luminaires in buildings used by the Education, Social and Culture Departments, in this order, as they are the ones with the highest electricity consumptions.

If the entire City of Copenhagen would follow the Municipality example in replacing the luminaires in every building by the ones designed for CELP, it would be possible to save up to 534 GWh of electricity, which represents a reduction of 23% of the total electricity consumed in the city in 2015. At a household scale, the same shift of luminaires, although would bring electricity savings, would not be very profitable for the household economy. On the other hand, if LED bulbs would replace the halogen bulbs in a household, it would bring great overall benefits to the household users. However, the same would not happen for the replacement of compact fluorescent lamps, since the results from this report suggest that LED bulbs available nowadays in the market do not represent a real competition against compact fluorescent lamps.

Although LED technology is not at its full energy efficiency potential yet, technology developments might allow LED bulbs becoming more profitable over compact fluorescent lamps in the near future. The fast deployment of this technology and the increasing implementation of LED in indoor lighting solutions may induce a wide incorporation of the LED niche-innovation by the regime. Besides, lightning in buildings is an important field where the potential for electricity optimization is high and should no longer be underestimate, meaning that a sustainable transition to LED lighting in buildings, especially in workplaces, might be inevitable and could in fact be accelerated with the success of projects like CELP.

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8 Appendix A

The following sections present calculations and assumptions used in this report for each section of the analysis.

Cost-benefit analysis of replacing luminaires in municipal buildings

Calculation of the total number of luminaires installed in each building

In order to calculate the number of lamps installed in each building it is necessary to know the installed lighting capacity in each buildings, i.e. the total power, measured in Watts, from all installed lamps, which was calculated with the following equation:

$$\begin{matrix} Installed\ Lighting \\ Capacity\ (W) \end{matrix} = \frac{\begin{matrix} total\ electricity \\ consumption\ (Wh/year) \end{matrix} \times \begin{matrix} percentage\ of\ electricity \\ used\ in\ lighting \end{matrix}}{hours\ used\ per\ year\ (h/year)} \quad (3)$$

Where, the data for the total electricity consumption and the assumptions for the percentage of electricity used in lighting were provided by the Municipality (see Table 15, Appendix B). The total number of hours lights are used per year was calculated with the assumptions present in Table 15 as well.

Copenhagen Municipality provided a procurement list of light bulbs, where it is possible to calculate the percentage of lamps purchased for each power rate. Table 20, Appendix B, shows this list with the respective percentage for each lamp capacity. Assuming that this same distribution of lamps' capacity can be replicated in all municipal buildings, it is possible to calculate the total number of light bulbs installed in each building with the following equation:

$$\begin{matrix} Total\ Number\ of \\ Lamps\ Installed \end{matrix} = \begin{matrix} installed\ lighting \\ capacity\ (W) \end{matrix} \times \sum_{capacity} \frac{\begin{matrix} percentage\ of\ lamp \\ per\ capacity \end{matrix}}{lamp\ capacity\ (W)} \quad (4)$$

Then, it was necessary to exclude the percentage of outdoor lamps (see Table 15, Appendix B) from the total number of lamps installed in each building. With this data it was possible to estimate the total number of indoor lamps in each municipal building and it was assumed that the number of lamps would be equal to the number of luminaires, implying that each luminaire would have only one lamp.

Electricity used in ballasts

The total electricity used in lighting represents the electricity consumed by the lamps and by the ballasts, in order to create the optimal conditions to turn the lights on. The following equation was used to calculate the electricity consumed by the ballasts in each building:

$$\begin{matrix} Electricity \\ used\ by \\ Ballasts\ (Wh) \end{matrix} = \begin{matrix} total\ num. \\ of\ lamps \end{matrix} \times \begin{matrix} hours\ used \\ per\ year\ (h) \end{matrix} \times \sum_{ballast\ type} \left(\begin{matrix} ballast \\ capacity\ (W) \end{matrix} \times \begin{matrix} percentage \\ of\ ballasts \end{matrix} \right) \quad (5)$$

The energy savings from shifting to the new LED drivers were calculated by subtracting the electricity consumption of the ballasts currently in use by the electricity consumption of the new LED drivers, considering that they have a capacity of 0.5 W, as mentioned in Table 16, Appendix B. To calculate the electricity spent by the new LED drivers, the previous equation is used again, however the percentage of new LED drivers is 100% for the buildings where the luminaires would be replaced.

Electricity used in lamps

The electricity consumed by the lamps in the current scenario, is the difference between the total electricity used in lighting and the total electricity consumed by the ballasts. To calculate the energy savings from shifting to the new lamps, the electricity consumed by the new LED bulbs was subtracted from the electricity used in lamps in the current scenario.

For the new scenarios, not only the energy savings are important, as it is to maintain the quality of light in the buildings. In this way, it is important that the new LED bulbs emit the same lumens as the lamps in the current scenario while consuming less energy. Based on the average luminous efficacy of each lamp type (see Table 17, Appendix B) it was calculated how many Watts would be needed for the new LED bulb emit the same lumens as the lamps in the current scenario. It was assumed that the luminous efficacy of the new LED bulbs would be 30% higher than the luminous efficacy of the LED bulbs currently in use due to the fact that in the new design the driver is not integrated inside the light bulb (Copenhagen Municipality personal communication 2016).

With the referred data, the energy savings from shifting the lamps were calculated with the following equation:

$$\begin{matrix} Electricity \\ used\ by\ New \\ LED\ (kWh) \end{matrix} = \sum_{lamp\ type} \left(\begin{matrix} electricity\ used \\ in\ lamps\ (kWh) \end{matrix} \times \begin{matrix} percentage \\ of\ lamps \end{matrix} \times \begin{matrix} new\ LED \\ capacity\ percentage \end{matrix} \right) \quad (6)$$

Maintenance costs of luminaires in the current scenario

To calculate the maintenance costs for replacing ballast in the current scenario, it was used the following equation:

$$\begin{matrix} Ballasts \\ Maintnance \\ Costs\ (DKK) \end{matrix} = \begin{matrix} total \\ number \\ of\ lamps \end{matrix} \times \sum_{ballast\ type} \left(\frac{\begin{matrix} hours\ used \\ per\ year\ (h) \end{matrix}}{\begin{matrix} ballast \\ lifetime\ (h) \end{matrix}} \times \left(\begin{matrix} price\ of \\ ballasts \\ (DKK) \end{matrix} + \begin{matrix} labour\ for \\ shifting \\ ballasts\ (DKK) \end{matrix} \right) \times \begin{matrix} percentage \\ of\ ballasts \end{matrix} \right) \quad (7)$$

For calculating the maintenance costs of replacing light bulbs in the current scenario, a similar equation was used, equation (8), however it was assumed that there would not be labour costs for shifting the light bulbs, since this is an easy task that can be carried out by the users, without the need to hire external electrician services.

$$\begin{matrix} Lamps \\ Maintnance \\ Costs\ (DKK) \end{matrix} = \begin{matrix} total \\ number \\ of\ lamps \end{matrix} \times \sum_{lamp\ type} \left(\frac{\begin{matrix} hours\ used \\ per\ year\ (h) \end{matrix}}{\begin{matrix} lamp \\ lifetime\ (h) \end{matrix}} \times \begin{matrix} price\ of \\ lamps\ (DKK) \end{matrix} \times \begin{matrix} percentage \\ of\ lamps \end{matrix} \right) \quad (8)$$

Energy savings from retrofitting the lighting system in Copenhagen's buildings

Governmental and municipal building area data and calculations

In order to divide the total electricity consumption for the governmental and municipal buildings into their departments, some extra data was needed.

By using the data provided by Copenhagen Municipality (see Appendix B, Table 15), it was possible to estimate the percentage of building area of some departments at the Municipality, as it is shown in the following table.

Table 12: Total number of municipal buildings and building area per department

Departments	***Number of buildings***	***Building area (km²)***	***Percentage of building area in Copenhagen Municipality***
All municipal buildings	1134	2,765	100%
Offices & administration	71	287	10%
Educational institutions	104	639	23%
Others	959	1,839	67%

The percentages in the previous table were used to estimate the electricity consumption in the mentioned departments, by multiplying with the total electricity consumption in municipal buildings (Figure 22). From the statistics bank at Copenhagen Municipality website it was possible to find the data about the total number of governmental and municipal buildings in Copenhagen City.

Table 13: Total number of governmental and municipal buildings in Copenhagen City (Københavns Kommune 2016)

Departments	***Number of buildings***
Total number of governmental and municipal buildings	4,462
Offices & administration	382
Hospitals	112
Educational institutions	946

By subtracting the number of buildings in Table 12 from the values in Table 13, it was possible to calculate the number of governmental buildings in Copenhagen City and their percentage.

Table 14: Total number of governmental buildings in Copenhagen City and their percentage

Sectors	***Number of buildings***	***Percentage in the governmental buildings***
Total number of governmental buildings	3,328	100%
Offices & administration	311	9%
Hospitals	112	3%
Educational institutions	842	25%
Others	2,063	62%

Because there was not data found for the area of governmental buildings, the percentage for the number of governmental buildings from each sector was used instead to calculate its buildings electricity consumption.

9 Appendix B

Table 15: Summary of building's data and assumptions provided and used by Copenhagen Municipality

Type of building/use (translation)	Type of building/use (Original in Danish)	Number of Buildings	Total Electricity Consumption in 2015 (GWh)	Total building Area (km^2)	Percentage of Electricity used in Lighting	Hours opened per day (h)	Closed on weekends?	Percentage of outdoor lamps in buildings
Department of Culture								
Offices	Administration	25	0.18	74.98	42%	12	No	3%
Citizens/culture houses	Medborger-/kulturhuse	39	0.34	60.57	36%	16	No	3%
District Heating Distribution	Varmecentral Energifordeling	1	0.37	0.00	42%	5	Yes	5%
Libraries	Biblioteker	11	4.04	11.21	36%	14	No	3%
Museums	Museum	8	2.91	16.79	36%	14	No	3%
N.d.	Erhverv	5	1.23	0.21	42%	12	Yes	3%
Property with several tenants	Ejendom med flere lejere	2	1.23	6.17	36%	12	Yes	5%
Sports / swimming pools	Idræts-/svømmehaller	32	13.30	69.65	36%	16	No	3%
Stadiums and Sports Facilities	Stadion og idrætsanlæg	88	1.04	248.59	36%	8	No	5%
Unknown	Ukendt	2	0.14	2.28	36%	11	Yes	3%
Department of Economy								
Offices	Administration	12	0.35	22.71	42%	12	Yes	3%
Rescue Institutions	Redningsberedskab	10	0.06	31.33	42%	24	No	5%
Department of Education								
Counselling Institution	Rådgivningsinstitution	1	0.18	2.42	50%	12	No	3%
Educational Clubs	Klubber mv.	14	0.03	14.92	50%	12	Yes	3%
Extensive special Education Institution	Vidtgående specialUv.	16	0.02	50.76	50%	14	Yes	3%
Institutions for Leisure Time	Fritidshjem	73	0.01	58.08	50%	12	Yes	3%
Integrated Educational Institutions	Integrerede institutioner	149	0.07	167.70	50%	12	Yes	3%
Kindergartens	Børnehave	82	0.05	91.58	50%	10	Yes	3%
Low Energy Building	Lav-energibygning	1	0.12	2.19	36%	12	Yes	5%
N.d.	Andre faste ejendomme	5	1.23	3.59	36%	12	Yes	3%
N.d.	Kolonier	1	0.66	0.48	50%	14	Yes	3%
N.d.	Ungdomsskolevirks	2	0.31	3.74	50%	14	Yes	3%
N.d.	Udflytter Børnehave	2	1.60	0.87	50%	10	Yes	5%
Nurseries	Vuggestue	57	4.22	48.32	50%	14	Yes	3%
Schools	Folkeskoler	104	7.66	644.65	50%	14	Yes	3%
Special Day Care / Club	Særlige dagtilbud/klub	6	0.01	6.55	50%	12	Yes	3%
Student Residence	Elevhjem	1	0.08	0.38	31%	24	No	3%
Unknown	Ukendt	3	0.03	2.42	36%	11	Yes	3%
Youth Clubs	KKFO	9	0.02	9.28	50%	14	Yes	3%
Department of Health								

Type of building/use (translation)	Type of building/use (Original in Danish)	Number of Buildings	Total Electricity Consumption in 2015 (GWh)	Total building Area (km^2)	Percentage of Electricity used in Lighting	Hours opened per day (h)	Closed on weekends?	Percentage of outdoor lamps in buildings
Offices	Administration	2	0.36	0.69	42%	12	Yes	3%
Adult Day-care Centre	Dagcenter til ældre	1	0.15	0.72	50%	12	Yes	3%
Health Centres	Sundhedshus / Lægehus	4	0.02	18.51	31%	12	Yes	5%
Nursing Institutions	Plejehjem og bsk. boliger	21	0.00	107.24	50%	20	No	3%
Department for Refugees								
Offices	Administration	3	2.57	8.80	42%	12	Yes	3%
Counselling Institution	Rådgivningsinstituti on	21	0.21	135.60	50%	12	No	3%
Social Department								
Offices	Administration	21	0.02	17.21	42%	12	Yes	3%
Children and Family Counselling Institution	Børn og Familier	16	0.34	27.53	50%	16	Yes	3%
Drug addiction Institutions	Stofmisbrugsinstituti oner	4	3.35	3.89	50%	18	No	3%
Handicap care	Handicap	15	0.05	78.59	50%	24	No	3%
N.d.	Kolonier	1	0.13	0.26	50%	10	Yes	3%
Residential institutions	Døgninstitution for B&U	11	0.30	8.94	50%	24	No	3%
Special day care/clubs	Særlige dagtilbud/klub	2	0.08	0.28	50%	10	Yes	3%
Unknown	Ukendt	2	0.10	2.19	36%	11	Yes	3%
Vulnerable and Psychiatry institutions	Udsatte og Psykiatri	22	0.92	104.22	50%	16	No	3%
Technical and Environmental Department								
Offices	Administration	16	0.00	208.13	42%	12	Yes	1%
Cemeteries	Kirkegårde	10	0.21	4.40	36%	12	No	5%
Crew buildings	Mandskabsbygning	26	0.02	2.79	36%	12	Yes	3%
Crew buildings 24 h	Mandskabsbygninge r 24 timer	2	0.11	0.11	36%	24	Yes	3%
Drinking Fountain	Drikkepost	1	0.00	-	2%	12	No	5%
fountains	Springvand	17	0.00	0.00	2%	12	No	3%
Garages	Garage	3	0.01	2.24	42%	24	No	5%
N.d.	Iltningsanlæg	3	0.00	-	2%	12	No	5%
Other Buildings	Øvrige bygninger	2	0.05	0.01	36%	11	Yes	3%
Parks	Parker	1	0.00	-	36%	11	No	3%
playgrounds	Legeplads - bemandet	24	0.42	2.49	36%	12	No	3%
Rental Buildings	Udlejningsbygninger	1	0.02	-	42%	24	Yes	3%
Storage	Opbevaringsrum	4	0.15	8.88	50%	12	Yes	3%
Toilets	Toiletter	8	0.55	0.00	36%	12	No	3%
Toilets 24h	Toiletter 24 timer	47	0.05	0.24	36%	24	No	3%
Warehouses	Oplagsplads	1	0.07	0.06	36%	11	No	3%
Workshops	Værksted	3	0.02	2.97	36%	12	Yes	3%
Buildings shared by Several Tenants								
Shared Energy Consumption	Forbrug fordeles via et fordelings regnskab	34	2.92	257.85	36%	12	Yes	3%

Type of building/use (translation)	Type of building/use (Original in Danish)	Number of Buildings	Total Electricity Consumption in 2015 (GWh)	Total building Area (km^2)	Percentage of Electricity used in Lighting	Hours opened per day (h)	Closed on weekends?	Percentage of outdoor lamps in buildings
Buildings from Private Tenants								
N.d.	Erhverv	1	0.03	2.98	42%	12	Yes	5%
Private Tenant	Privat lejer	13	0.57	12.63	36%	12	Yes	3%
Unknown								
Drug Addiction Institutions	Stofmisbrugsinstitutioner	7	0.23	10.44	50%	18	No	3%
N.d.	Erhverv	1	0.07	0.00	42%	12	Yes	5%
Unknown	Ukendt	2	0.49	3.02	36%	11	Yes	3%
Total		**1134**	**56**	**2,686**				

Table 16: Data provided by Copenhagen Municipality – Characteristics of lamps and ballasts

Parameter	***Value***	***Unit***
Lamps and Ballasts Price		
HL / IL	35	DKK/unit
FL / CFL	115	DKK/unit
Current LED bulb	650	DKK/unit
New LED bulb	250	DKK/unit
Electromagnetic ballast	160	DKK/unit
Electronic ballast	350	DKK/unit
Current LED driver	900	DKK/unit
New LED driver	300	DKK/unit
Lamps and Ballasts Lifetime		
HL / IL	2000	h
FL / CFL	16000	h
Current LED bulb	45000	h
New LED bulb	60000	h
Electromagnetic ballast	90000	h
Electronic ballast	50000	h
Current LED driver	30000	h
New LED driver	65000	h
Ballast's Capacity		
Electromagnetic ballast	5	W
Electronic ballast	2	W
Current LED driver	1	W
New LED driver	0.5	W
Percentage of lamps and ballasts at Copenhagen Municipality's buildings		
HL / IL	16%	
FL / CFL	64%	
Current LED bulb	20%	
Electromagnetic ballast	27%	
Electronic ballast	37%	
Current LED driver	20%	

Table 17: Copenhagen Municipality's calculations for the average luminous efficacy of each lamp types

Lamp Type	***Capacity (W)***	***Lumens (lm)***	***Luminous Efficacy (lm/W)***
Incandescent Lamps and Halogen Lamps			
IL	40	410	10.25
HL	30	410	13.67
Average IL / HL			11.96
Discharge Lamps			
CFL (butterfly)	16	1050	65.63
CFL (2p)	13	900	69.23
CFL (4p)	10	600	60.00
Average CFL			64.95
T8 Tubes	10	650	65.00
T5 Tubes	14	1100	78.57
Average FL			71.79
Average DL			68.37
LED			
LED lighting1 E27	9	1055	117.22
LED lighting3 E28	15	1522	101.47
LED lighting4 E29	6	470	78.33
Average LED			99.01
New LED			
30% more efficacy than average LED (because it has not embedded ballast, which increases efficacy)			128.71
Watts needed for emitting the same amount of lumens			
New LED compared to Incandescent / Halogen Lamps			9%
New LED compared to Discharge Lamps			53%
New LED compared to current LED			77%

Table 18: Data provided from Copenhagen Municipality – Extra costs

Parameter	***Value***	***Unit***
Labour price for maintenance of the current luminaires		
IL and CFL replacement	0	DKK/unit
Current LED bulbs replacement (requires electrician service)	400	DKK/unit
New LED bulbs replacement	0	DKK/unit
Ballast replacement (requires electrician service)	1500	DKK/unit
Current LED driver replacement (requires electrician service)	1500	DKK/unit
New LED driver replacement	0	DKK/unit
Counting lamps		
Price for counting lamps	0.5	DKK/m²
Price for counting outdoor luminaires	400	DKK/building
Price for the first hour (meeting the users, making a recognition of the buildings, etc.)	400	DKK/building
Costs for purchasing and installing new luminaires		
Price for new luminaire (already including LED and driver)	1000	DKK/unit
Time for dismantling old luminaires	15	min
Time for installation new luminaires	7	min
Time for finishing works	5	min
Price for labour	320	DKK/h

Parameter	*Value*	*Unit*
Disposal of PCB capacitors from old luminaires		
Price for disposal of PCB	5.4	DKK/kg
Weight of PCB per capacitor	50	g/unit
Time required to disassemble a PCB capacitor	3	min
Percentage of luminaires with electromagnetic ballasts that contain PCB capacitors	10%	

Table 19: General data provided by Copenhagen Municipality

Parameter	*Value*	*Unit*
Price of Electricity at Copenhagen Municipality	1.77	DKK/kWh
Labour price of external electrician company	400	DKK/h
Salary for project managing	466,000	DKK/year
One-time energy savings sale after the investment year	0.44	DKK/kWh
Energy savings associated with implementation of daylight control in new luminaires	15%	
Interest rate for small environmental projects at Copenhagen Municipality	4%	

Table 20: Copenhagen Municipality's procurement list for light bulbs

Power (W)	*Number of light bulbs purchased*	*Percentage of light bulbs for each power rate*
14	2261	3.34%
15	1335	1.97%
16	3434	5.07%
18	20437	30.18%
19	63	0.09%
20	272	0.40%
21	270	0.40%
22	423	0.62%
23	16	0.02%
24	2084	3.08%
25	498	0.74%
26	5653	8.35%
28	4668	6.89%
30	528	0.78%
32	2016	2.98%
35	1018	1.50%
36	9559	14.12%
38	888	1.31%
39	244	0.36%
40	1422	2.10%
41	90	0.13%
42	3464	5.12%
45	146	0.22%
49	378	0.56%
50	430	0.64%
51	120	0.18%
54	616	0.91%
55	1682	2.48%
57	210	0.31%
58	3099	4.58%
60	77	0.11%
73	40	0.06%
80	260	0.38%
100	10	0.01%

The CO_2 emission costs in Denmark are presented in the following figure.

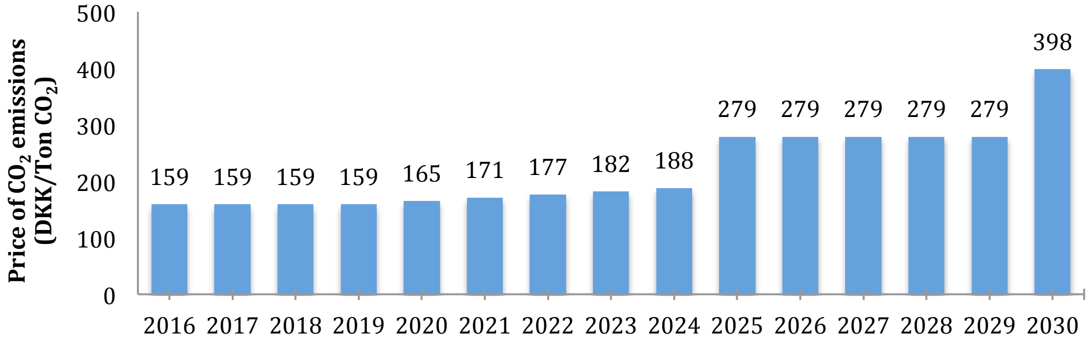

Figure 35: Evolution of CO_2 eq. emissions' costs in Denmark (Aggerholm 2013)