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Smart street lighting

The advantages of LED street lighting and
a smart control system in Uppsala municipality

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Abstract

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The purpose of this bachelor thesis is to examine how LED street lights and a smart street light control system can reduce the energy consumption, costs and in extension the CO_2 equivalents in a geographically delimited area. In 2015 the municipality of Sala installed LED armatures connected to a smart control system in the whole municipality. The smart control system enables for instance adjustment

of the light intensity at specific times during the day and a supervision of the street

light network. The LED lights high efficiency and the possibility to lower the intensity of the light reduced the energy consumption of the street lights in Sala with 77.8 %. LED lights have a longer life time compared to traditional street lights, which reduces the maintenance cost and the cost for purchasing new armatures. In this report the project in Sala is evaluated and the concept is used to investigate the advantages for a similar project in Uppsala municipality. The research goal is to develop a general model that examines the energy-, economic- and environmental savings when installing LED lights and a smart control system. One third of the armatures in Uppsala municipality have already been replaced with LED, therefore the simulations and calculations only includes the two thirds left. The results show that Uppsala municipality annually saves 79.2 % in energy and CO_2 equivalents with a system like this and the economic savings during the life time of the armature is 182 MSEK, and the pay-off time is 6.9 years. A sensitivity analysis is carried out to verify the economic results by altering the electricity price. The analysis shows that the system used in Uppsala today is more sensitive to a varied electricity price than when a smart control system is installed.

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Occurring Terms and Abbreviations

Street light
Street lights are the lights in streets, public areas and walk- and bicycle paths.

Armature
Armature is the attachment between the lamp post and the bulb (or diode).

HPS
High Pressure Sodium lamps are one of the most common lamps for street lighting. It is a gas-discharge lamp that uses sodium in an excited state to produce light.

LED
Light Emitting Diodes are semiconductor diodes that emit light when they are exposed to a current flow.

Dimming
LED light gives the potential to dim and that means that the light intensity is possible to vary.

Dimming curve
A dimming curve is a schedule for a street light's intensity for different times of the day. For example, 80 % intensity from dusk until 22 o'clock and after that 60 % until dawn.

Stand-alone system
A system with LED armatures that uses a fixed dimming curve which is set before installation. The dimming curve cannot be changed once the armature is installed.

Control system
Control system is a software program that can regulate a system, in this case a street light system. Regulation means for example to switch on and off the lights and obtain the power output in a certain situation. The features of the system depend on the manufacturer.

Smart control system
A smart control system is an extension of a control system. In this report, it is referred to as web-based and flexible in terms of individual regulation for each armature, while a basic control system only can regulate a group of armatures or the whole system. The difference between a stand-alone system and a LED armature connected to a smart control system is that it is possible to regulate a single armature and its dimming curve after installation, while the dimming curve installed in the stand-alone system is fixed.

1. Introduction

Two wide-ranging trends in society today are urbanization and consciousness of sustainable development. The urban areas grow larger which requires new technical solutions for the urban infrastructures to be energy efficient. One such important system is street lighting. More street lighting is needed to satisfy the extended networks of roads and walkways, and many street lights are outdated and need to be replaced. According to Ożadowicz and Grela (2015) and other previous studies, street lighting is one of the largest electrical energy consumers and accounts for almost 40% of the total electrical energy consumption in cities. This part of the city infrastructure is therefore a part which is possible for the municipalities to improve and thereby save both energy and money.

Street lighting installations are also, except energy consuming, crucial in terms of comfort and safety because they provide lighting for roads, streets, public areas, pavements etcetera (Ożadowicz and Grela 2015). Lighting has a large importance as an urban environment creator and one of its most significant function is to give people guidance, help to orientate and provide safety. Out on the streets is where people meet and an inviting lighting inspire people to stay outdoors, which in turn makes the city safe. (Uppsala municipality 2014a)

The technical shaping of the armatures, for example the efficiency of the light, has a large impact on both the operational cost and sustainability of street lights (Uppsala municipality 2014a). The lighting sector has gone through a substantial transformation in recent years because of the need for low-cost and durable armatures, and one large innovation that enabled this revolution is the Light Emitting Diode (LED). LED lights have a higher efficiency and longer lifetime than the traditional high pressure sodium lamps (HPS) (International Institute for Industrial Environmental Economics 2015). Therefore, the LED armatures reduce the costs of maintenance and operation. The white light from a LED light is also an advantage from a safety and comfort perspective because it makes it easier to see colours and details. Another beneficial technique to reduce the energy consumption is the usage of a smart street light control system. The smart control system enables regulation and supervision in the street light network, since it is possible to adjust the light intensity and see when an armature needs maintenance in the system software. (Philips 2015)

One of Europe's largest street light installations with smart control system is located in the municipality of Sala, 60 km to the west of Uppsala, Sweden. The municipality of Sala together with the technology company Philips projected a new system of LED lights and a smart control system that was installed in 2015. Approximately 4700 armatures were replaced and the municipality reduced their energy consumption with 77.8% (Olsson interview).

Uppsala municipality is currently replacing their street lights with LED lights, today ⅓ of their street lights have been replaced with LED and there is no smart control system installed (Johansson interview). The aim of this report is to investigate the energy- and economic advantages of replacing the street lights in the municipality of Uppsala to LED and installing a smart control system. To be able to fulfil the purpose a model is developed in two parts that examines the energy and economic savings when replacing the current armatures with LED armatures and a smart control system. The model is

general but in this report applied on Uppsala municipality. A sensitivity analysis is carried out to see how the electricity price affects the energy cost.

1.1 Aim

The aim of this report is to investigate the advantages of replacing the street lights in the municipality of Uppsala to LED and installing a smart control system. The focus is energy- and economic savings but the environmental savings are considered as well. The street light system is based on the project in the municipality of Sala. The research goal is to create a general model which can be used anywhere in the world and for armatures from different manufactures, but the proposal to Uppsala municipality is based on the lighting system in Sala. One part of the model simulates the hourly energy consumption during a year and calculates the energy- and environmental savings based on the reduction of energy consumption. The other part of the model calculates the economic savings over a 25-year period. The research questions are the following:

- If Uppsala municipality would switch to LED lighting and install a smart control system, how large would the energy savings be? As a consequence of the energy savings, how large would the decrease in CO_2 equivalents be?

- What are the economic benefits of LED lighting and a smart control system?

1.2 Limitations and delimitations

The investigation is limited as it is based on the new system in Sala where Philips LED armatures and a certain type of smart control system were installed. This report only investigates how Uppsala can utilize their street light system by using the same system (LED armatures and smart control system) as in Sala, compared to the system the municipality is installing today. No other methods for saving energy are considered. Since Uppsala already has replaced one third of their street lights, only the two thirds left are investigated. It is not reasonable that the municipality would replace the recently installed LED-armatures. Considering that Uppsala is constantly growing, more armatures are needed the coming years but that is not taken into account.

The model is general and can be used wherever in the world, as long as the users have the data needed for the particular parameters. The simulations are delimited to the geographical area of Uppsala municipality.

The usage of LED armatures accounts for the majority of the CO_2 equivalents and the energy consumption, when compared to the manufacturing process. Therefore, only the operation time is considered when calculating the energy consumption and CO_2 equivalents of the armatures. The Nordic electricity mix is used when calculating the CO_2 equivalents. The costs for the new system consist of investment- and installation costs of the new armatures, electricity costs and maintenance. The focus categories and what they include are illustrated in figure 1.
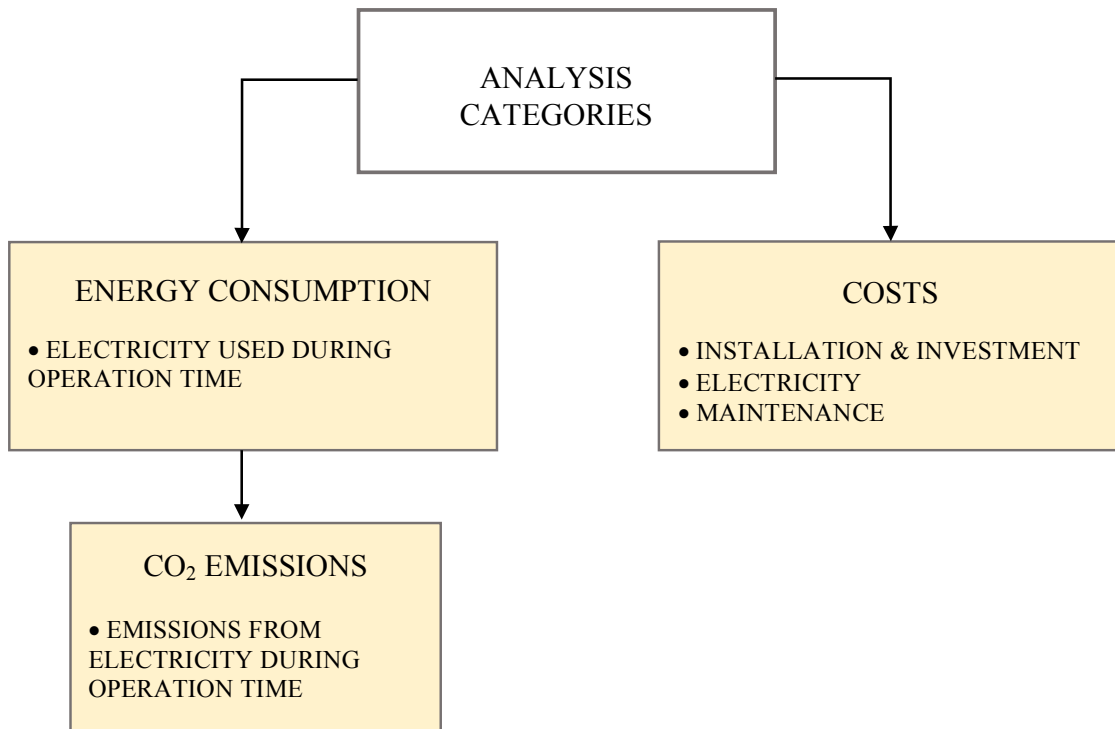
Figure 1. An overview of the analysis categories and what they include.

1.3 Disposition

This report begins with section 2 presenting background information relevant for the study. In section 3 the model used to calculate the energy consumption and the costs are presented followed by data in section 3.2. In the same section assumptions and parameters are motivated. In the end of section 3 a validation of the model is presented. The results of the simulations and calculations and the sensitivity analysis are presented in section 4. Lastly, the results are discussed in section 5 and the report ends with a conclusion section where the research questions are answered.

2. Background

This section provides background information and begins with information about street light systems in Sweden. This is followed by facts about the environmental effects of street lights and a section about carbon dioxide equivalents in section 2.2 and 2.3. Section 2.4 describes the LED project in Sala and finally information about the street light system in Uppsala municipality is presented in section 2.5.

2.1 Street lights, LED and other luminaries

The most common luminaries for street lighting in Sweden are HPS armatures with a characteristic yellow light. The armature has satisfying light yield but the reflection of different colours is unsatisfactory because of the yellow light. Reflection of colours is important to register details in traffic and to avoid accidents due to poor sight. White light gives the best ratio for sight because of the thorough reflection of colours which makes the LED light a good alternative. Figure 2 shows the difference between the lights. LED are small diodes with high efficiency, long lifetime and a wide range of colour temperatures. For reasons such as energy, environmental and economic savings, it can be an advantage to regulate the intensity of the light from the armature. The Swedish Transport Administration's (Trafikverket) recommended times for dimming the street lights are between 22.00 o'clock and 05.00 o'clock. By using a smart control system or a stand-alone system the intensity can be regulated and adjusted to the local needs. Roads are suitable for a lower light intensity during night when the traffic flow is low while places like crosswalks and bike- and bicycle paths require a higher intensity (Trafikverket 2014, pp 33-37).

Figure 2. Four LED lights in the foreground and old HPS lamps with the characteristic yellow light in the background. (Photo: Jon Forsmark 2014)

Trafikverket sets requirements and guidelines for street lighting in Sweden. The regulations are defined according to directives from the European Union (EU). In 2015 mercury lamps were forbidden at the market, and the most inefficient HPS lamps and metal halide lamps are being phased out. There are also restrictions for how much light the armatures are allowed to spread out (light pollution), and the requirements for product information are tightened (such as the amount of mercury in one lamp) (Trafikverket 2014). Today only four types of armatures are allowed in new constructions and reinvestment: LED, HPS, metal halide and fluorescent sources (Trafikverket 2015).

2.2 Life cycle assessment of road lighting luminaries

A life cycle assessment (LCA) makes it possible to compare LED lights with the common HPS lamps. The life cycle assessment describes the environmental impacts of a lamp from the manufacturing to the bin. Tähkämö and Halonen (2015) analyze the LCA of a LED luminaire and a HPS luminaire calculated with European electricity mix. The results show that the manufacturing process accounts for 4 % for HPS and 13 % for LED of the environmental impact, and 96 % for HPS and 87 % for LED for the usage calculated over 30 years. The impact of the discarding of the lamps is less than one percent for both types.

Thus, the majority of the environmental impact occurs when the lamp is being used and the LED lamp is better from an environmental view compared to HPS lamps because it consumes less electricity. Still, there are uncertainties about the possibility to recycle the LED lamp. The rare metals that are used in HPS lamps are used in LED lamps as well and that is also an important environmental issue (IIIEE 2015). The Tähkämö and Halonen study stresses that the LED technology is constantly and fast developing, and predict that the advantages with LED will increase compared to HPS.

2.3 Carbon dioxide equivalents and Nordic electricity mix

The established measuring unit for emissions of greenhouse gases is called carbon dioxide equivalent (CO_2-e). Translating all types of greenhouse gases into one scale makes it easier to compare and evaluate emissions from different sources of energy. The CO_2-e includes the greenhouse gases carbon dioxide, methane and dinitrogen oxide.

The carbon dioxide equivalent for a certain amount of electricity is connected to what energy source the electricity comes from. Electricity from coal power plants has a high value of CO_2-e, while hydropower is low in comparison. (NE 2017) The power grid in Sweden is connected to the Nordic electricity system, so the electricity in Sweden consists of the Nordic electricity mix which is a composition and average production of energy in the Nordic countries. The emission factor for the Nordic countries electricity gives the grams of CO_2-e per kWh. (Svensk Energi 2017)

2.4 Sala municipality project

Sala Heby Energi Elnät AB (SHE-e) is an energy company that owns all street lights in the municipality of Sala. In an interview with operation manager Mats Olsson, he explained that the company started to discuss new solutions for the street lights in 2014. At that time the present lights were different power types of HPS lamps with a life time

of 16 000 hours. The light bulbs had to be exchanged every fourth year and between that they had to make regular rounds three times per year to look for broken lamps. In 2014 the LED technology had developed in quality and became a competitive alternative to the HPS lamps. SHE-e let four lighting companies suggest solutions and in the end they chose to work with the technology company Philips. The initial goal was to change to LED armatures and thereby save energy, but when Philips presented their smart control system SHE-e chose to install that too. During the autumn in 2014 twelve test armatures were installed in Sala, four on walk- and cycle paths, four on residential area streets and four on a transit route. SHE-e were satisfied with the test period concerning energy savings and light yield, and decided to implement the system full-scale in the municipality. In February 2015, they started to install the new armatures and the smart control system. It took a year to finish and they installed about 20-40 armatures per day. The project was the largest LED project for street lighting in Sweden at that time, now there are more examples of similar solutions in a few cities in Sweden (Olsson interview).

2.4.1 Installation of LumiStreet armatures

One of Philips LED products that SHE-e chose to install is LumiStreet which is a product with a high efficiency and long life time of approximately 25 years, compared to the traditional HPS light bulb with a life time of approximately four years (Ljung interview). It is possible to adjust the light intensity of the LumiStreet. When replacing a burnt out HPS light bulb every fourth year only the light bulb is changed, however when a LED light is used after 25 years the whole armature is replaced, not only the diodes. Approximately 4700 Philips LED armatures were purchased by Sala, divided into several different types. SHE-e installed the armatures themselves (Olsson interview). Table 1 presents the four most common armatures and their replacement. The other 193 armatures were more unusual kinds, and some of them not connected to the smart control system.

Table 1. The amount of the four most common armatures in Sala and their replacement.

Location	Armature type before	Replacement	Amount
Walk- and cycle paths	HPS 50W	LumiStreet 21W	750
Roads in residential areas	HPS 70W	LumiStreet 32W	2185
Collecting streets	HPS 150W	LumiStreet 56W	1083
Major roads	HPS 250W	LumiStreet 80W	489
Sum			4507

(Olsson interview)

2.4.2 Installation of CityTouch smart control system

CityTouch is Philips smart control system for street lights which enables SHE-e regulation and supervision over all armatures in the municipality of Sala. Every armature is supplied with a puck on top with a GPS sender/receiver that provides the system with each armatures position. The individual armatures then communicate through the GSM and 3G net to the CityTouch software, which sends information when SHE-e change the light intensity installation in a certain way (Philips 2017). With CityTouch SHE-e can see when an armature needs maintenance and manually adjust the light intensity on roads where the sight is reduced and in that way, improve the traffic safety. (Philips 2015)

The armatures turn on and off following the dusk and dawn through a relay that switches on and off when the light outside reaches a certain limit. The smart control system enables SHE-e to apply different dimming curves to the armatures. A dimming curve is the schedule for an armature's intensity during different times of the day. For example, 80 % intensity from dusk until 22.00 o'clock and after that 60 % until dawn. CityTouch can handle many different dimming curves for different parts of the city. This feature saves energy since the power of the dimming is linear, so if a 80W light is dimmed 50 % it consumes 40W. In short, the on and off switching is controlled by the relay and the intensity depends on the dimming curve. A consequence of that is during summer a possible scenario is that the light turns on after 22 pm, so only the lowest intensity is used that day. (Olsson interview)

The design of the dimming curves depends on the location of the armature, and the dimming curves can be changed whenever in the CityTouch software. The locations can differ in how crowded it is, the type of street and if there is incoming light from other sources such as shops or restaurants. The dimming curves stay the same over the year, but CityTouch gives SHE-e the possibility to for example lower the intensity during a period with snow covering the ground. In addition to the most usual dimming curves SHE-e have a few different curves that are used in various parts of the city. For cycle paths through dark places like forests the armatures are always on full effect for comfort and safety reasons. For SHE-e it is important that the inhabitants in Sala feel safe and the light is an important aspect of that. According to performance tests made by Philips before the installation, the energy savings gained by the dimming curves are between 11 %-20 % depending on the intensities. The project is still in its early stages so it is not yet completely optimized. It is possible to further adjust the dimming curves to optimize the system. (Olsson interview)

2.4.3 Economic benefits

Since Sala Heby Energi AB owns the street lights, they are responsible for the payment to Philips for the investment and they pay-off during a ten-year period. SHE-e has already seen the economic benefits of the new LED armatures and CityTouch. Considering that CityTouch can alarm when an armature is broken, less regular maintenance rounds are needed for SHE-e today. This feature makes the work for SHE-e easier and less time consuming. The longer life time of the LED lights reduces the cost for purchasing new light bulbs and the maintenance cost for replacing them. (Olsson interview)

2.4.4 Result of the new street light system

The aim of the Sala project was to reduce the CO_2 emissions and save energy. Another incentive to replace the HPS lamps was its content of mercury. Olsson describes that according to Philips they would save 50 % if they only switched to LED armatures and 80 % with the smart control system installed as well. After the installation SHE-e has saved 78 % in energy consumption during operation time. The longer life time of the LED armature was an important aspect in the decision to change the street lights. Olsson says that it is evident that they do not have to spend as much time on maintenance as before. The energy consumption before the installation was 1.8 GWh per year and the consumption today is 0.4 GWh per year. (Olsson interview)

SHE-e is overall very satisfied with the system today, the armatures are working as they should but a few armatures have problems with water leaking which result in problems with the puck. This brings on problems with the communication to the software. They have received a few complaints from the community in Sala, people mostly complain when the lights are dark and that is the same now as before they changed to LED. Some people find that their gardens are not as lit up as before since the old armatures spread light backwards while the LED have a more directed light. The directed light compared to the more spread out light the HPS armatures generated caused SHE-e to raise a few more lamp posts along a cycling trail (Deleryd interview). A combination of the directed light and an avenue of trees between the cycling trail and a bigger street caused SHE-e to raise 10 new lamp posts along the trail (Olsson interview).

2.5 Uppsala municipality

The Street and societal environment committee at Uppsala municipality are responsible for the street lighting in Uppsala and the energy company Vattenfall manages the street light system. The municipality has public guideline- and strategy documents describing the various focus areas when projecting street lighting. The documents describe how the street lighting in different parts of Uppsala should be projected (Uppsala municipality 2014b). The municipality have approximately 37 000 armatures, one third is LED and the rest is based on older techniques such as HPS lamps, metal halide lamps and a small part is mercury lamps. The reason why Uppsala only have changed one third so far is mainly economic limitations but also because the equipment today is relatively new, according to project manager Per-Erik Johansson at the Street and societal environment committee. Uppsala municipality owns almost all the street lights on public roads and areas except around e.g. schools and along highways where The Swedish Transport Administration maintain the armatures (Johansson interview).

2.5.1 Armatures

When the municipality buy armatures, they have to do a procurement to ensure that they buy the product with best price. At the moment, the municipality are replacing old armatures with LED and the ambition is to change all the street lights. In some areas, the armatures were changed to non-LED technique 5-6 years ago and the municipality therefore consider it as capital destruction to change them to LED too soon. The municipality install LED in all new-built areas, and if an armature is broken they always replace it with LED (Johansson interview). Right now, Philips Lumistreet and Prisma Elliot are the most common armature types that are being installed. The armatures are

installed with a fixed dimming curve (DC) which is set before the installation of the armature, and cannot be changed during its life time. That kind of system is called stand-alone system. The curve has three intensities; 100 %, 70 % and 50 % as shown in figure 3 (Hersan and Dansk interview).

Dusk

Dawn

100%   100%

70%   70%

50%

21.00   04.00
   00.00   06.00
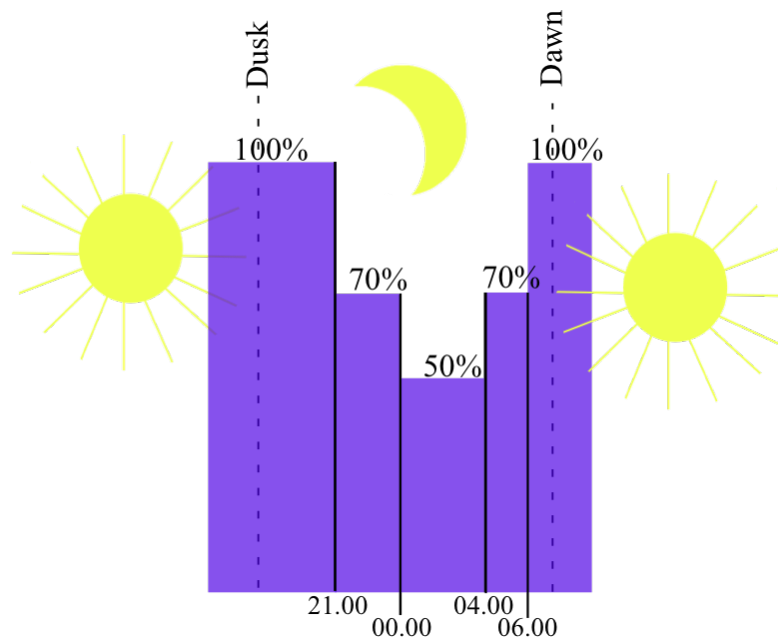
Figure 3. The differing intensities during one day for Philips stand-alone system. The position of the crosshatched lines marked with "dusk" and "dawn" will vary from day to day depending on when the sun goes up and down.

2.5.2 Control system

The control system used in Uppsala today is a software from the technology company TelliQ. The system consists of 420 control boxes, each one running a trail of armatures. Centrally located in Uppsala, there is a dusk relay that measures the daylight to regulate when the control box should turn the power on and off. The box can deliver information about the energy consumption for the whole trail but no information for each individual armature. The energy consumption for one box should be approximately the same over time. A difference in the power output indicates that something is wrong and needs to be investigated, but the system is not able to point out what is wrong and where. (Johansson interview)

2.5.3 Maintenance

All the maintenance of the street lights is done by the energy company Vattenfall after an agreement with the municipality. Vattenfall runs the street lights and takes care of repairs, installations and purchase of armatures and lightbulbs. The non-LED light bulbs are changed to new ones of the same type every fourth year (Johansson interview). Apart from this they do inspections when only broken light bulbs are replaced two times per year for all areas except the most central parts of Uppsala where they check the lights four times per year. The inspections are done in the same way for the parts of the city with non-LED and the parts with LED. (Hersan and Dansk interview)

In areas with LED armatures installed the need for maintenance is significantly lower because of the longer life time of LED. Even though Uppsala municipality have changed one third to LED they still run the maintenance as if there were no LED at all. Today the routine is to drive around with a sky lift when checking the lights. If all lights were LED, they could check the lights with a car - which is cheaper - and after that bring the sky lift only when needed. (Hersan and Dansk interview)

2.5.4 Improvement possibilities

Uppsala municipality want to reduce their energy consumption, and a first step for them is to install LED. According to Johansson (2017) a smart control system is interesting and could be a suitable solution for the municipality in their endeavor to reduce their consumption even more, but economic restrictions hold them back. Hersan and Dansk (2017) describe the control system as well-functioning today, despite some technical errors when the weather outside is very cold. They see many advantages with a smart control system that enables communication with individual armatures, e.g. individual dimming and reduced maintenance.

3. Methodology

This section explains the method used for answering the research questions and contains data and calculations used in the model. Data and information are obtained by contact with actors participating in the project in Sala, Uppsala municipality, Vattenfall and from articles. Four interviews are made; with Mats Olsson on SHE-e, Joel Hersan and Johan Dansk on Vattenfall, Per-Erik Johansson on Uppsala Municipality and Daniel Ljung at Philips. The former CEO of SHE-e who also is supervisor of this bachelor thesis, Kenneth Mårtensson, contributes with both technical and economic knowledge. In addition to the interviews email correspondence is used to answer complementary questions.

To be able to fulfill our purpose a simulation is made for the street light system in the municipality of Uppsala. The simulations and calculations are achieved from the model for two different scenarios. These two are:

1) Install LED armatures connected to a stand-alone system (LED stand-alone system)
2) Install LED armatures connected to a smart control system (LED smart control system)

These two scenarios are thereafter compared with the annual energy consumption and costs today, which results in the energy- and economic savings.

3.1 Model

The model is based on the project in Sala and implemented partly in MATLAB and partly in Microsoft Excel. MATLAB is a software from MathWorks used for mathematical and technical calculations, and built-in functions enable calculations for many different purposes. Excel is a software from Microsoft that summarise and organise data in spreadsheets and enable mathematical calculations. Excel has several data analysis features to visualize results in diagrams etcetera.

The input parameters to the model are data from user and data from supplier such as the current annual energy consumption, electricity costs, budget for maintenance, installation cost and purchase of armatures. The energy consumption part of the model is a MATLAB script that simulates the energy consumption for the new system. Economic calculations are made in Excel and use the input parameters: data from user, data from supplier and the new energy consumption simulated in MATLAB, see figure 4. The output parameters from the model are energy-, carbon dioxide equivalent- and economic savings. The model is general but the data and parameters used are for Sala and Uppsala. The validity of the model is confirmed by the Sala case.
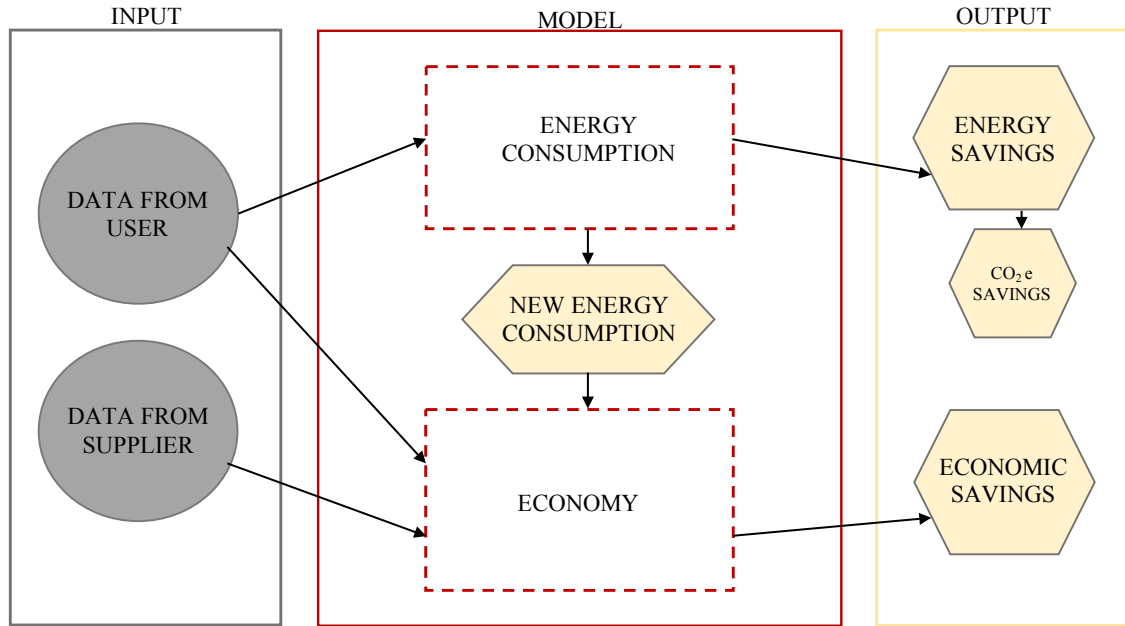
Figure 4. Overview of the model and its input and output parameters.

3.1.1 Energy savings

Energy savings are calculated as the difference between energy consumption today and energy consumption with LED armatures connected to a smart control system or a stand-alone system. The model simulates energy consumption for every hour during a year (equation 1), depending on how light it is outside and what time it is. The light outside determines when to turn the street lights on and off. The time sets the intensity of the light depending on the power of the armature and the current dimming curve. During one day the model calculates the used energy for each armature using each dimming curve, and thereafter sums up for how many there are of each. The annual CO_2 equivalents are calculated by multiplying the annual energy consumption with the emission factor for electricity in the Nordic countries (equation 2).

E - energy [kWh]
P - power [kW]
t - time [hours]
CO_2e - carbon dioxide equivalents [g]
ef - emission factor [gkWh]

$$E = P \cdot t \tag{1}$$

$$CO_2e = E \cdot ef \tag{2}$$

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3.1.2 Economic savings

The economic savings during an armatures life time are calculated as the difference between the costs today and the costs with LED armatures connected to a smart control system or a stand-alone system. The annual cost for the street lights is calculated based on maintenance and energy costs. The total cost during the system's life time consists of the annual cost for the system times the life time of the armature plus the investment cost. The model calculates e.g. net income, annual saving, pay-off time and total saving during 25 years. This is made in Excel, using data and results partly from the municipality and partly from the energy simulations in MATLAB.

3.2 Data

The different parameters used in the model are explained below. The values of the parameters come from interviews, email communication and online articles.

3.2.1 Light conditions

To be able to use the model in different locations, times of when the street lights switch on/off is one of the input parameters in the model. The street lights switch on/off depending on a dusk relay that measures the light outside. Due to limited amount of data from Vattenfall about these times, it is gathered from an astronomical calculator. Streets lights are needed when the civil twilight occurs. That is the time after sunset and before sunrise when the sun is about 6 degrees below the horizon. At that time there is generally enough natural light to carry out most outdoor activities. The data used in the model comes from the calculator with location as input and times for civil twilight for sunrise and sunset respectively as output. The calculator gives the time in hours, minutes and seconds but the time is rounded off to hours since the model simulates over hours. (Palmqvist 2010)
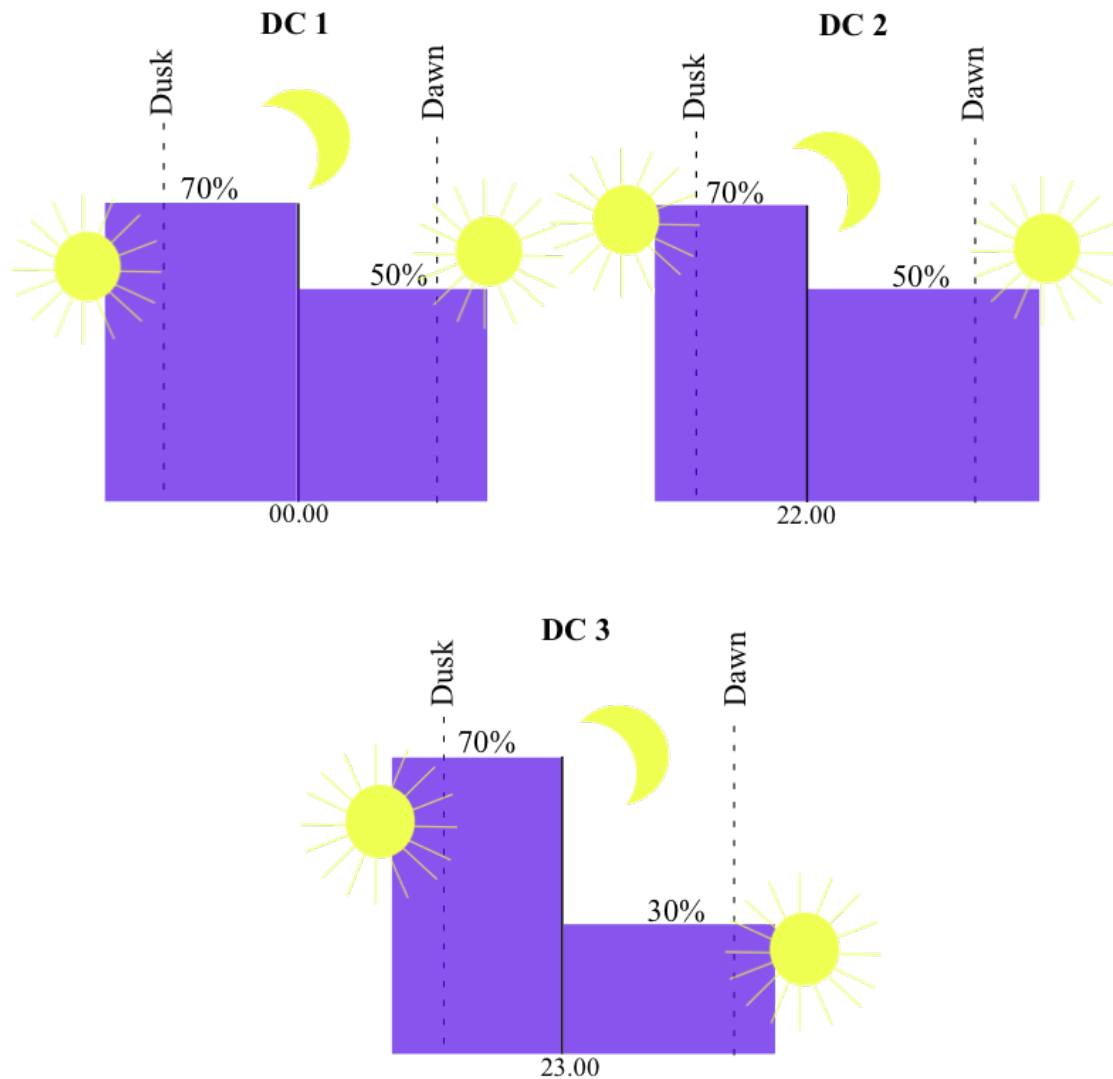
3.2.2 Dimming curves

This section presents the dimming curves used if a smart control system or a stand-alone system is connected to the armatures. The used dimming curves in the smart control system are a combination of three usual ones from Philips and the ones used in Sala. The control system makes it possible to make far-reaching adjustments to optimize the dimming curves. Sala hasn't fully optimized their curves so the curves used in the model are adjusted to optimize the smart control system even more.

The three most common curves that are applied on the system in Sala have the intensities 80 %/60 %, 60 %/40 % and one that is on 100 % during the whole day. To make the model more general Philips dimming curves are used in the model, but with some adjustments. Two of Philips curves go down to 70 % or 50 % intensity but for different time intervals of the day. The third one has intensities 30 %/70 %. Figure 5 presents the curves.
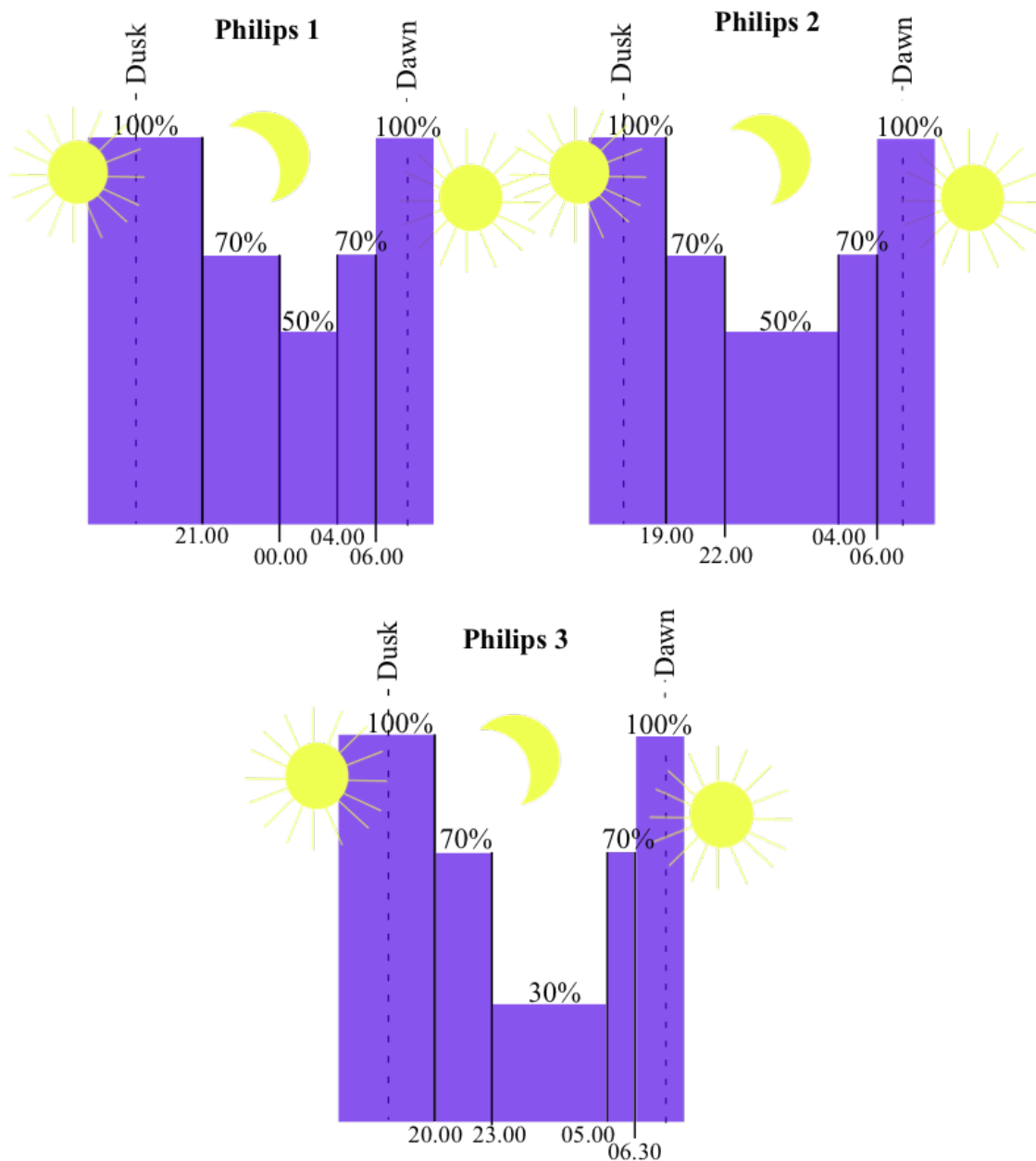
Figure 5. Philips dimming curves showing the differing intensities during one day. The position of the crosshatched lines marked with "dusk" and "dawn" will vary from day to day depending on when the sun goes up and down. Note that "Philips 2" is the same as Philips stand-alone system curve in figure 3.

The curves above are used as a base for the ones used in the model, but two changes are made to optimize the curves. Just like the Sala curves, they never go up to 100 % during the day, plus they always start on 70 %. Also, the curves stay on the lowest intensity until the lights turn off in the morning. So instead of 100 %-70 %-50 %-70 %-100 % curve 1 is adjusted to 70 %-50 %, but it switches between the intensities at the same time as for the original curve. Figure 6 presents the adjusted curves.

Figure 6. The dimming curves used in the model. The position of the crosshatched lines marked with "dusk" and "dawn" will vary from day to day depending on when the sun goes up and down.

If the LED armatures are connected to a stand-alone system, Philips stand-alone curve in figure 3 is used in the model since that is the dimming curve Uppsala municipality are using in their stand-alone system today (as described in section 2.5.1). This curve is the same as Philips 1 in figure 5.

3.2.3 Number of armatures

The four most common armatures in Sala are used for the simulation in Uppsala as well, and they are Philips LumiStreet 21W, 32W, 56W and 80W. Considering limited data of what kind of armatures that are used in Uppsala today, it is difficult to estimate how many new LED armatures of each type that would be needed. The method that is used to estimate these numbers is to start with the mix of armatures that were installed in Sala and apply that to Uppsala. The composition of streets, city centre, countryside, bike- and walking paths etcetera of Sala municipality is comparable to Uppsala municipality (except that Uppsala is larger), which strengthens the choice of Sala as a comparison city. A distribution of Sala is created for the different armatures and

dimming curves they are using. The distribution, which table 2 below declares, is based on data given by SHE-e and is applied on Uppsala municipality. If there were many cities in Sweden with this type of system a combination of the distributions in the cities could have been made. But since that is not the situation today the distribution table for Sala is used.

Table 2. Distribution table of armatures and dimming curves. All sum up to 100%.

Power/Dim curves	DC1	DC2	DC3
21 W	9.98%	6.66%	0
32 W	0	48.48%	0
56 W	0	24.03%	0
80 W	0	6.41%	4.44%

(Olsson interview)

The total number of armatures used in the simulation are 24 667 (Johansson interview). The number of armatures used on each dimming curve is calculated with the distribution table 2 above and is presented in table 3 below.

Table 3. The number of armatures for each armature and dimming curve. All sum up to 24 667.

Power/Dim curves	DC1	DC2	DC3
21 W	2462	1643	0
32 W	0	11958	0
56 W	0	5927	0
80 W	0	1581	1095

3.2.4 Energy consumption today and emission factor

To be able to calculate the savings, the annual energy consumption today (without LED) is needed. This number is estimated, since there is no specific data for how much the non-LED lights consume. In Sala, the annual energy consumption before the replacement of LED armatures was 1.8 GWh, and the number of armatures were 5 100 (not 4700, since all of them was not replaced with LED). An average energy consumption per armature is calculated as 1.8 GWh divided by 5 100, which results in 353 kWh per armature. The number of armatures is 24 667, so the annual energy consumption is estimated as 24 667 times 353 kWh which results in 8.71 GWh.

Considering that the transmission of electricity between the Nordic countries is interconnected, a mean value for the emission factor from the Nordic countries in 2010 is calculated, see table 4.

Table 4. Emission factor for the Nordic countries in 2010 and their mean value.

Country	Emission factor (g /kWh)
Norway	10
Denmark	360
Sweden	30
Finland	229
Nordic countries	157

(Driving sustainable economies 2013)

3.2.5 Economy

Data given by Uppsala municipality and Vattenfall regarding the economy is presented in table 5 below. All the economic calculations are excluding VAT.

The cost for electricity in Sweden consists of three parts; electricity price, grid fee and taxes. Electricity price is the cost per kWh the consumer is using and the grid fee is the cost for the transmission of electricity. Grid fee consists of a fixed subscription fee and a varied transmission fee that depends on how much electricity the consumer uses and at what time of the day (Vattenfall 2017a). Uppsala municipality's facilities have the 25-ampere subscription at Vattenfall (Hersan interview) with fixed subscription fee of 7 160 SEK/year/box, VAT included (Vattenfall 2017b). The total fixed subscription grid fee is then calculated based on numbers of TelliQ control boxes. The varied transmission fee is approximated by an average of the fixed transmission fee for a several control boxes during a year. Even though the electricity price for street lighting in Uppsala varies monthly during the year, the price is delimited to a fixed approximation according to the electricity cost for March 2017. March is a representative month since it is not during a period with the highest or the lowest electricity price. A mean value for the electricity price during a year would have been more suitable, but due to limited amount of data the price in March 2017 is used. The three costs electricity price, varied transmission fee and taxes are summed and multiplied with the energy consumption and thereafter added with the fixed grid fee to generate the total energy cost.

The data of investment cost and life time of 25 years for the armatures is given by Philips. The budget for maintenance today is gathered from Vattenfall. The reduction of the budget for maintenance for a system with LED connected to a smart control system is estimated to be 70 % by Philips and 87 % by Sala Heby Energi. The average of these numbers, 78.5 %, is used in the model. The difference in workload for the two different systems is that the smart control system alarms when there is a broken armature, while when the stand-alone system is used the operators must do several inspections without knowing what is broken (Hersan and Dansk interview). The reduction of the budget for

maintenance for a system with LED connected to a stand-alone system compared to the system today is therefore assumed to be 60 %.

Due to the limited data given, installation of new armatures and maintenance is approximated to a fixed price per armature. The average price for a smart armature and a stand-alone armature is given from Ljung at Philips. The price is thereafter reduced thus it is assumed that the price for the armatures would be lower if Uppsala municipality decided to buy 24 667 armatures. The reduction is based on the prices in Sala and the prices is shown in table 5. Some armatures are damaged before the life time has passed because of external reasons. Uppsala municipality replace all their broken armatures to LED today and the reinvestment cost is included in the maintenance cost.

A subscription is needed for the armatures connected to the smart control system and that is included in the price for the first ten years. The price for the subscription after ten years is difficult to estimate so that cost is not included. The budgets for maintenance and the energy cost today in table 5 is estimated.

Table 5. Electricity price, electricity tax, grid fee, energy cost, annual budget for maintenance and cost for installation of one armature etc. All numbers are excluding VAT.

Object	Price
Electricity price	0.368 SEK/kWh[1]
Electricity tax	0.292 SEK/kWh[1]
Varied transmission fee	0.192 SEK/kWh
Fixed grid fee	2 404 000 SEK/year
Energy cost	9 822 000 SEK[2]/year
Budget for maintenance today	5 333 000 SEK[2]/year
Cost for installation of one new armature	500 SEK[2]
Average cost for armature smart control system	███████
Average cost for armature stand-alone system	███████

[1](Dahlberg interview)
[2](Hersan and Dansk interview)

The economic results have been calculated as the following:

Annual cost: annual maintenance- and energy cost.

Annual saving: difference in annual costs for the system today and the smart control system or the stand-alone system

Depreciation: total investment cost divided by the life time of the armature (25 years)

Net income: according to annual income statement. Annual saving subtracted by the depreciation

Pay-off time: calculated as the investment cost divided by the annual saving

Total investment cost: ██

Total cost during 25 years: annual cost multiplied with 25, added with the investment cost

Total saving during 25 years: difference in total costs during 25 years for the system today and the smart control system or the stand-alone system

3.3 Validation of the energy part of the model

In this section a validation of the simulations of the energy savings is presented. The model is validated by the Sala case, since the outcome of energy consumption of their new system is known. The parameters for Sala municipality are used and the results from the model are thereafter compared with the results presented by SHE-e. The total number of armatures simulated is 4507, since these armatures represent the four most common ones. The rest of the armatures installed (approximately 200) are not included. The simulation is based on the three most common dimming curves used in the municipality, and the number of armatures for each power and dimming curve is gathered from Olsson at SHE-e, see table 1 in section 2.4.1. The dimming curves used in Sala are implemented in the MATLAB script and thereafter the energy consumption is simulated. Table 6 presents the results of the simulation compared to the known data from SHE-e.

Table 6. Comparison of the known data and the results simulated in the model. The energy consumption today is with a smart control system installed with the three most common dimming curves in Sala.

|	Data	Results	Difference
Energy consumption before	1.8 GWh[1]	-	-
Energy consumption today	0.4 GWh[1]	0.39 GWh	0.01 GWh
Energy savings	77.8%[1]	78.3%	0.5%

[1](Olsson interview)

4. Results

This section consists of results from the simulations and calculations divided into energy savings and economic savings for the two scenarios presented in section 3 above:

1) Install LED armatures connected to a stand-alone system (LED stand-alone system)
2) Install LED armatures connected to a smart control system (LED smart control system)

The section ends with a sensitivity analysis where the electricity price is varied.
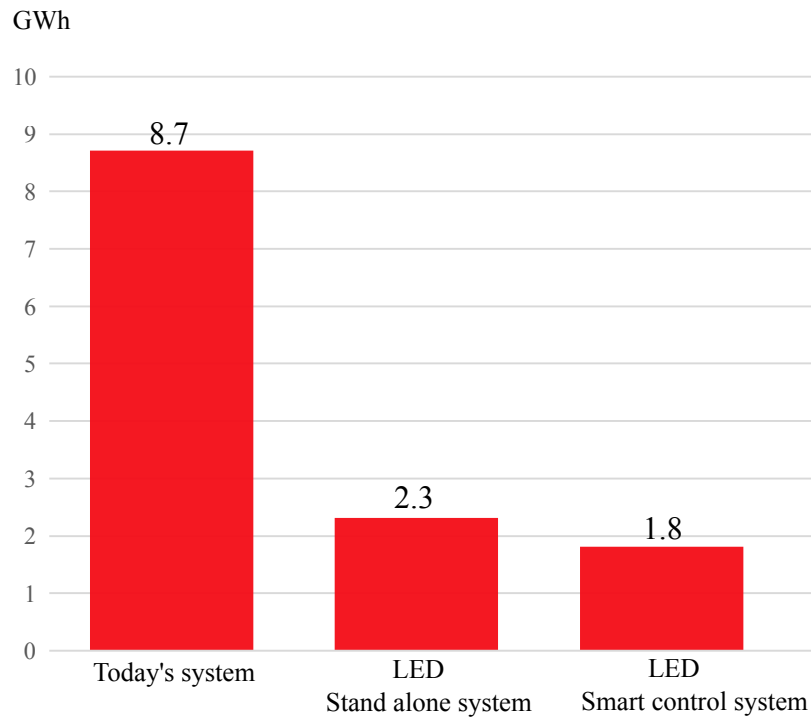
4.1 Energy savings

The daily energy consumption during one year is presented in figure 7 for the two different scenarios. The simulation starts in January and continues to the end of December.
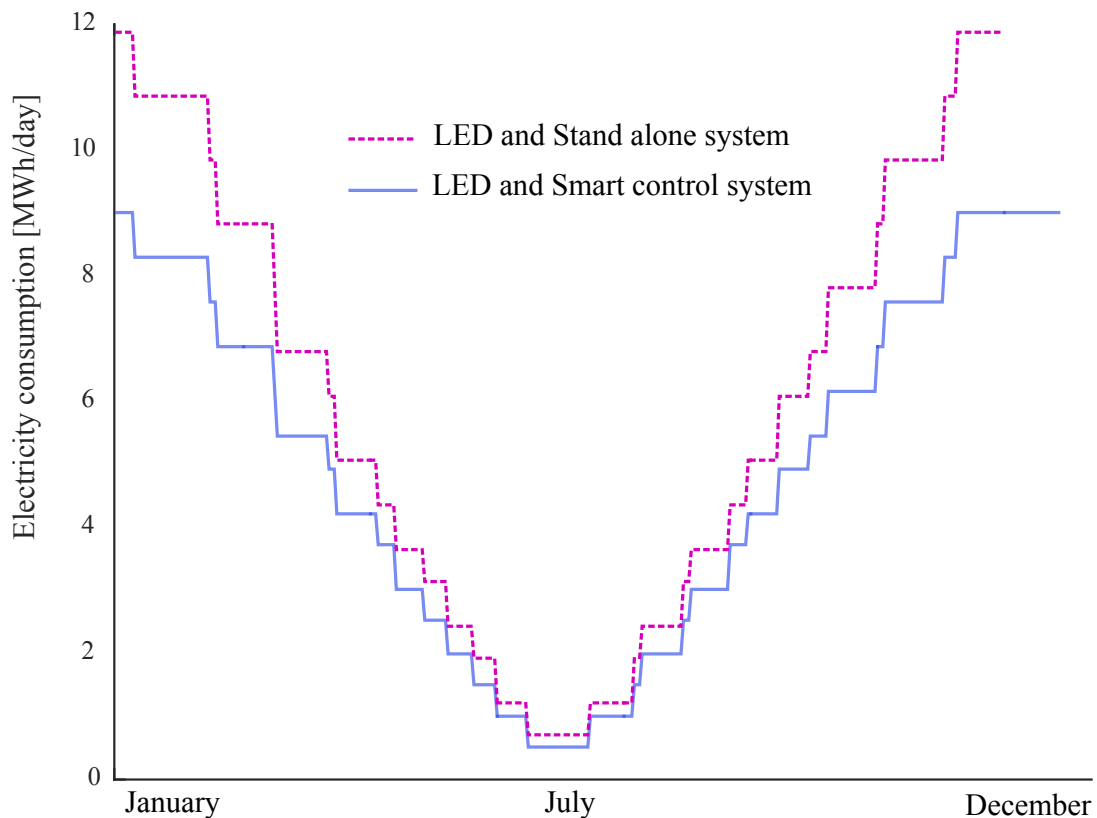
Figure 7. Energy consumption during one year for the two scenarios.

Figure 8 shows the total annual energy consumption for the two scenarios compared to the consumption today.

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Figure 8. Annual energy consumption for the two scenarios compared with the consumption today.

The energy savings in percent during one year are presented in table 7 for the two scenarios. The environmental savings in CO_2-e correspond to the energy savings since the only difference is the emission factor.

Table 7. Annual energy consumption and annual CO_2-e for the two scenarios. Energy and CO_2-e savings in percent for the two scenarios compared to the system today.

	Today's system	LED stand-alone system	LED smart control system
Annual energy consumption	8.71 GWh	2.31 GWh	1.81 GWh
Annual CO_2-e	1367 tonne	363 tonne	284 tonne
Energy and CO_2-e savings	-	73.5%	79.2%

4.2 Economic savings

The total cost during the life time of the system, 25 years, for the two scenarios is presented in figure 9 together with the total cost during 25 years for the system today. This is calculated with a fixed electricity price during the whole period.
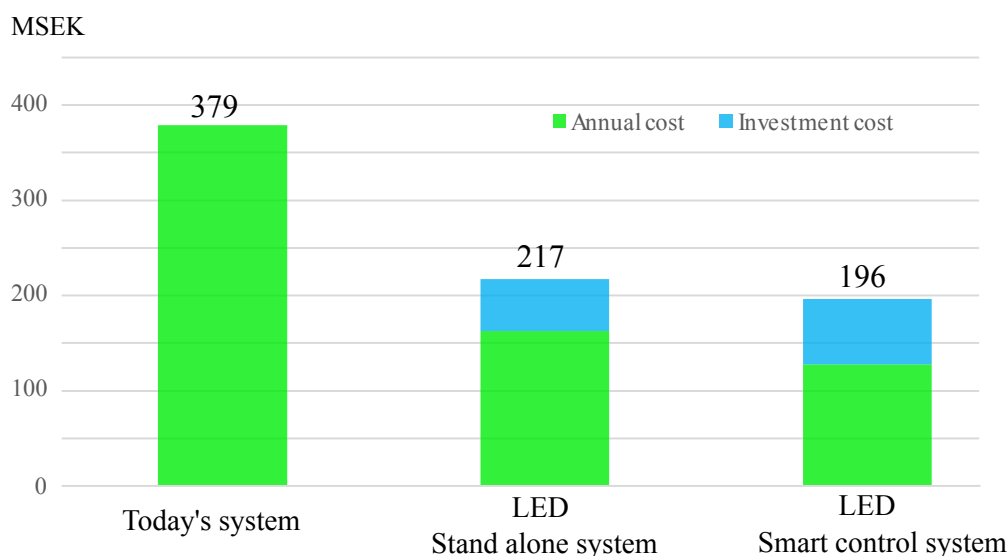
Figure 9. Total cost in Uppsala municipality during 25 years for the two scenarios compared with the system today. All numbers are excluding VAT.

The economic results for the two scenarios and the system today are presented in table 8. The system today does not have any numbers for savings, net income, pay-off time and investment cost since there is no investment and the other two scenarios are compared to this.

Table 8. Economic results for Uppsala municipality excluding VAT.

	System today	**LED stand-alone system**	**LED smart control system**
Annual cost	15.5 MSEK	6.5 MSEK/year	5.1 MSEK/year
Annual saving	-	8.6 MSEK/year	10.1 MSEK/year
Net income	-	6.5 MSEK/year	7.3 MSEK/year
Pay-off time	-	6.3 years	6.9 years
Total investment cost	-	54.3 MSEK	69.1 MSEK
Total cost during 25 years	381 MSEK	219 MSEK	199 MSEK
Total saving during 25 years	-	162 MSEK	182 MSEK

Figure 10 illustrates the pay-off time for the smart control system, and shows how the annual energy- and maintenance cost decrease within the new system. The reason why the total cost of 15.2 MSEK is the same before and after the investment is because the pay-off time is calculated as investment cost divided by the annual saving. The annual

saving is the difference between the maintenance and energy cost today and the maintenance and energy cost with the smart control system. Therefore, the annual saving is the same as the investment cost divided by the pay-off time.
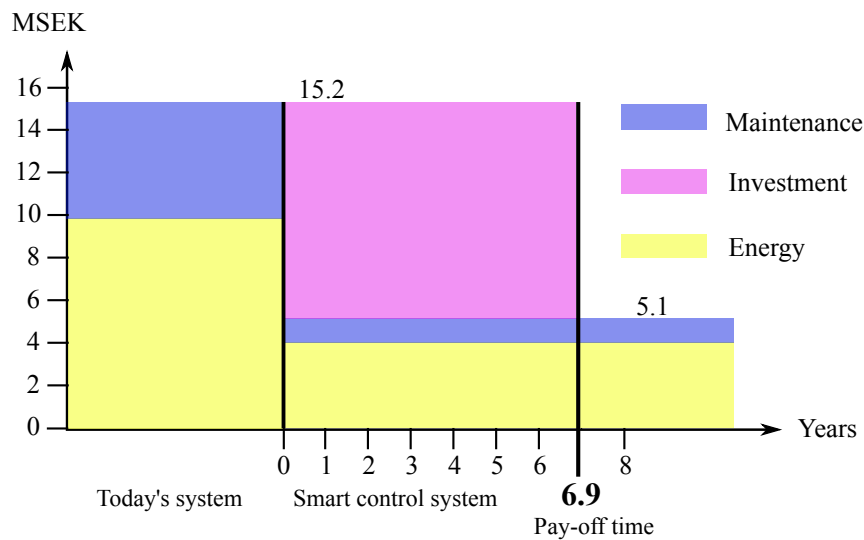

Figure 10. The annual energy- and maintenance cost for today´s system and the smart control system. Pay-off time for the smart control system is marked and calculated as the investment cost divided by the annual saving.

4.2.1 Sensitivity analysis

In this analysis, only the scenario with the smart control system will be investigated compared with the system today. The energy cost for the street light system depends on the electricity price, which varies over time. A sensitivity analysis of the economic calculation shows how the variation in electricity price affects the energy price. As mentioned in section 3.2.5, electricity price is a part of the total cost for electricity, together with grid fee and taxes. In March 2017 the electricity price was 0.368 SEK/kWh in Uppsala and that is considered the reference value for the sensitivity analysis. Table 9 presents the total energy cost during 25 years, with the fixed electricity price according to March 2017.

Table 9. Total energy cost during 25 years with a fixed electricity price.

|	Today's system	LED Smart control system
Energy cost	246 MSEK	99 MSEK

The electricity price varies from year to year and according to an electricity prognosis from the energy company Bixia AB (2015), the electricity price will increase with approximately 33 % from 2020 to 2030. That is approximately 3 % per year during 10 years. Considering Bixia's prognosis, the analysis investigates the energy cost over 25 years if the electricity price would increase with 1, 2, 3 or 4 % every year. The energy

costs are presented in table 10 and are compared with the energy costs in table 9. The percentage difference is presented in table 10 under "Difference".

Table 10. Total energy cost during 25 years for today's system and LED smart control system, with increased electricity price. The cost is compared to the energy cost with a fixed electricity price.

Increased electricity price/year	Today's system		LED Smart control system	
	Energy cost	**Difference**	**Energy cost**	**Difference**
1%	257 MSEK	4.6%	101 MSEK	2.4%
2%	270 MSEK	10.0%	104 MSEK	5.2%
3%	286 MSEK	16.4%	107 MSEK	8.5%
4%	304 MSEK	23.9%	111 MSEK	12.4%

Figure 11 shows how the total energy cost during 25 years varies for the two systems depending on the annual increase in electricity cost.
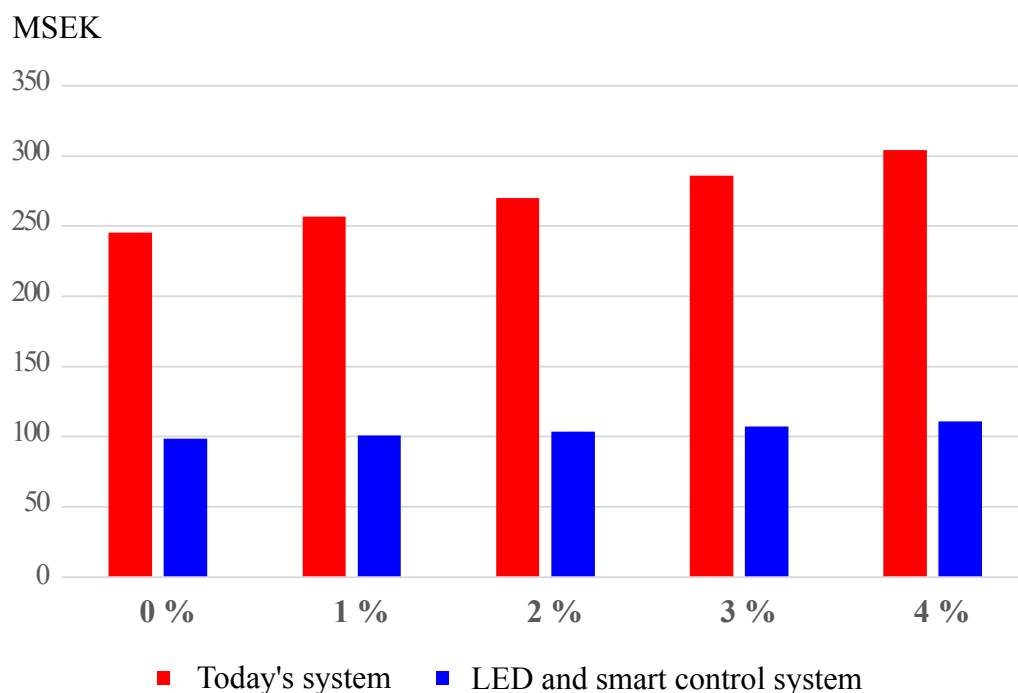
Figure 11. Total energy cost during 25 years if the electricity price would increase with 1, 2, 3 and 4 % every year.

5. Discussion

This section provides a discussion of the results in section 4, namely the effects of replacing all street lighting to LED armatures connected to a stand-alone system or a smart control system. The first part of this section focuses on the energy and environmental savings, followed by the economic results and a discussion of the sensitivity analysis and the validity of the model. This section is concluded with a general discussion about the possible advantages with the studied system.

5.1 Energy savings

The energy savings for the two scenarios compared to the energy consumption today are approximately 73.5 % and 79.2 %, thus it is profitable to invest in LED technology. The LED lights have lower power than therefore the energy consumption is reduced. An energy saving of 79.2 % seems reasonable since the energy saving in Sala is 77.8 %. There is a limitation in the calculations when looking at the amount of each armature type in Uppsala. The number of armatures are based on a distribution over the used armatures in Sala, which might be slightly different from the types and amounts that would be applied to Uppsala. Data over the types of armatures used today could have made the calculations more realistic for Uppsala. But limitations in data from Uppsala municipality about the 24 667 armatures advocated the usage of a distribution table.

The difference in energy savings between the two systems is approximately 5.7 % and is not very sensational. Especially compared to the performance tests made by Philips in Sala before the installation. In our calculations three different dimming curves were used and these might not be the most beneficial ones for the situation in Uppsala. The smart control system enables optimization of the street lights and the dimming curves can be further utilized depending on the situation in Uppsala. In our calculations, the same dimming curves are used during the whole year, while possibilities to develop the dimming curves according to snow or other external conditions are not taken into account. The smart control system gives an overview of the energy consumption and the errors in the street light system. The smart control system also enables the flexibility to adjust the intensities of the light in different parts of the municipality since the armatures are possible to regulate individually. If Uppsala municipality take advantage of the flexibility in the smart control system, the energy consumption can be even lower than calculated in this report. The savings in maintenance costs when using a smart control system compared to a stand-alone system further encourage the usage of a smart control system. Economic benefits are furthermore discussed in section 5.2.

Uppsala municipality are currently installing a stand-alone system which has a large impact on their energy consumption, see figure 8 and 9. But even more energy could be saved if installing a smart control system and as mentioned earlier the maintenance costs would be reduced.

Figure 7 presents the daily energy consumption for the two different scenarios during a year, where the smart control system consumes less than the stand-alone system. The savings are much higher during winter period than during summer. First and foremost, this is because the lights are turned on earlier and turned off later during winter. In addition to this, those "extra hours" in the afternoon during winter are when the dimming curves are on their highest intensity which increases the energy consumption.

As shown in figure 7, the consumption is the same a few days in a row during some periods. This is a result from the rounding to hours of when the civil twilight occurs. Even if the sun goes up/down different times in minutes, it is simulated as it goes up/down the same time in hours. The fact that the model simulates over hours is a delimitation in the model's accuracy and might affect the result, since the street lights switches on/off dependent on a dusk relay.

The percentage savings in CO_2-e are the same as the energy savings, thus only the operation time is considered. When saving energy, you consequently decrease the CO_2-e. If looking at the whole lifecycle of a LED armature, there could be more or less CO_2-e to be saved. A complete analysis of the differences in LCA for the two techniques could be an interesting investigation in a future project, where further environmental impacts of the armatures would be presented. Examples are material extraction and waste disposal. The content of mercury in the armatures and how this is handled is one aspect of this. The content of mercury is very little, but when summing up the content in for example
24 667 armatures as in the Uppsala case, the management of the material matters for the environment.

How the electricity mix is chosen is significant for the value of the CO_2-e. The difference between the Swedish, Nordic and European is large. But since the model focus on comparing different scenarios and the decrease in percent, the difference will still be the same.

5.1.1 Validity of the energy part of the model

The results from the validation in section 3.3 confirm the validity of the model. The numbers are similar and it is likely that the difference in energy consumption today (0.01 GWh) is because of the 200 armatures not included in the simulation. The data for when the light switches on/off is for the geographical location of Uppsala but the difference in Uppsala and Sala are negligible.

5.2 Economic savings

The energy savings for the two scenarios result in reduced annual energy cost for the two scenarios. That makes the total cost for the system today during the life time of 25 years higher than the total cost for the two systems with LED, 379 MSEK for the system today, 217 MSEK for LED with stand-alone system and 196 MSEK with LED and smart control system. Despite a high investment cost, both scenarios have a lower total cost during 25 years as figure 9 illustrates. Since it is calculated with a fixed electricity price, the number would probably vary in reality.

The life time of 25 years is an estimation from Daniel Ljung at Philips. If the savings are calculated with a different life time it would affect the result. The net income would also be affected if the life time and hence the depreciation time is changed. The net income for the smart control system is higher than the stand-alone system, even though the investment cost is higher, since the smart control system saves more energy.

The annual saving with LED smart system compared to the system today is 10.1 MSEK while the annual saving with LED stand-alone system is 8.6 MSEK. The difference

between the scenarios is 1.4 MSEK, which points to another advantage for the scenario with LED and smart control system. The pay-off time for the two scenarios is similar. The reason for this result is that the ratio of the investment cost and annual saving is similar in the both scenarios. A similar pay-off time supports the choice of a smart control system, since it is in addition to this more flexible, lower the energy consumption etcetera.

The reduction of maintenance costs is a big part of the annual savings for LED with smart control system. It is based on a prognosis from SHE-e and Philips which can be an optimistic number. The reduction of the maintenance cost for LED with stand-alone system is as described in section 3.2 an assumption based on the differences in workload for the two scenarios. Due to the limited data for LED stand-alone systems, the assumption is hard to verify. This may affect the result for the scenario.

Considering the reduced energy consumption for the two scenarios it might be possible to change subscription for grid fee to one with a lower fixed and varied transmission fee. That will decrease the cost for electricity and by that affect the economic savings, pay-off time and result year one in a positive way.

5.2.1 Sensitivity analysis

The sensitivity analysis shows how the LED smart control system and system today are affected if the electricity price increases with 1.00%, 2.00%, 3.00% or 4.00% per year during 25 years. Table 10 and figure 11 indicate that the system today is more sensitive for an increased electricity price compared to the smart control system. This is because the system today consumes more electricity and therefore the electricity price has a greater impact on the total energy cost. Thus, the smart control system is more reliable and stable in case of varying electricity price.

5.3 At last

When it comes to the system in general and the people that are directly affected by it, such as the users and the people that run the system, it seems like it satisfies the demands that it meant to according to the Sala case. SHE-e has a positive experience of it since it has worked well and saved as much energy as they expected. The only minor problem are the pucks that takes in water. The complaints from the inhabitants in Sala have been few and not more than they had with the old system.

The white light from a LED light is an advantage from safety and comfort perspectives. Dark walk- and bike paths where people feel unsafe is easy to light up, and crossings can be lightened to prevent accidents. The control system makes it possible to immediately see when something is malfunctioning. Investment in new street light system is relevant for many municipalities with outdated lights, and the solution presented in this report is beneficial from several perspectives and possible to implement anywhere.

6. Conclusions

The overall conclusion of this thesis is that installing LED and a smart control system decreases the energy consumption and CO_2-e extensively, and the economic consequences are beneficial. The results are compared with the system today and the stand-alone system the municipality is about to install.

The LED armatures contribute to a lower power usage, and the possibility to dim the lights decrease the consumption even more. The simulations generates the following results:

- Annual energy- and CO_2-e saving compared to system today: 79.2 %

In conjunction with a reduced energy consumption, the annual cost for electricity is reduced. The calculations generates the following results:

- Net income: 7.3 MSEK/year
- Annual saving compared to system today: 10.1 MSEK/year
- Annual saving compared to the system Uppsala municipality is about to install: 1.4 MSEK/year
- Pay-off time: 6.9 years
- Total saving compared to system today during 25 years: 182 MSEK

7. Acknowledgement

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