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Economic Feasibility for Solar PV in Swedish Office Buildings

A Case Study Approach

Master’s Thesis within the Sustainable Energy Systems programme

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MASTER'S THESIS

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Abstract

Boverket, a governmental agency in Sweden, has the goal to regulate so that all new buildings will be near zero energy buildings from 2020 and one way to reach this goal is to install a solar photovoltaic (solar PV) system on the building. Commercial buildings, such as office buildings, usually have a daily electricity use profile that is well matched with electricity generation from a solar PV system. The price for solar PV today is about a fifth of the price in 2006. Under these conditions, it is interesting to investigate the potential for using solar PV in Swedish office buildings.

The purpose of this thesis is to investigate the economic feasibility for solar PV in Swedish office building from a technical, economical and legal perspective. The purpose is also to investigate existing PV system installations in office buildings. These purposes are processed with help of a number of research objectives where load profiles were studied for buildings with different cooling systems, evaluation of existing PV systems and an economic analysis of PV systems with different locations, orientations, slope angles for different load curves were performed.

The research objectives were examined with a case study approach. Measured data for property electricity load and electricity generation from existing PV systems for five different office buildings was examined. An analysis of the matching of electricity load and electricity generation for existing PV systems for five buildings was made in order to investigate how the systems were sized and mounted with respect to the available roof space, roof conditions and electricity load for the buildings. The electricity load data was then used in the study where simulated electricity generation for different system configurations with different slope angles, orientations and azimuth angles were matched with the property electricity load profiles for the examined buildings. This matching was then used in an economic evaluation with today´s technical, legal and economic conditions to evaluate how different system configuration affects the profitability.

The conclusions that could be drawn from this study are that a PV system investment can be profitable with today´s conditions from a property owner’s perspective and that the choice of slope and azimuth angles for a PV installation is important for the profitability. There is an optimal system size in terms of profitability which is different for different electricity load profiles. At this optimum there was some percent of overproduction. An increased use of solar PV in Sweden is possible; the technical, legal and economic conditions are today good enough. However, a study including a larger number of buildings corresponding to typical Swedish office buildings is required to draw any general conclusions regarding the potential of solar PV.

Key words: Solar photovoltaics, Office buildings, Economic evaluation

Ekonomiska möjligheter för solcellsanläggningar på svenska kontorsbyggnader
Baserad på fallstudier
Examensarbete inom masterprogrammet *Sustainable Energy Systems*
NINA JOHANSSON AND JESPER KARLSSON
Institutionen för Energi och Miljö
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Sammanfattning

Boverket har satt målet att alla nya fastigheter efter 2020 ska vara nära-nollenergibyggnader. Ett sätt att nå detta mål är att installera solceller på fastigheterna, då den använda elen från en anläggning kan räknas bort i den specifika energianvändningen. Kommersiella fastigheter, såsom kontorsbyggnader, har vanligtvis en ellastprofil som stämmer väl överens med elproduktionen från solceller. Dessutom har priset på solceller sjunkit kraftigt de senaste åren och är ungefär en femtedel av vad priset var 2006. På grund av dessa förutsättningar är det intressant att undersöka vilken potential solceller på svenska konstorsbyggnader har.

Syftet med detta examensarbete är att undersöka potentialen för solcellsanläggningar på svenska kontorsbyggnader från ett tekniskt, ekonomiskt och lagmässigt perspektiv. Syftet är också att undersöka existerande solcellsanläggningar på kontorsbyggnader. För att uppnå dessa syften togs ett antal mål fram. Målen innefattar analys av lastprofiler för konstorsbyggnader med olika kylsystem, utvärdering av existerande solcellsanläggningar och en ekonomisk analys där simulerade solcellsanläggningar med olika orientering och lutningar utvärderades för olika fastighetsellastprofiler.

Målen behandlades med hjälp av ett antal fallstudier. Mätdata för ellaster och elproduktion från existerande solcellsanläggningar från fem kontorsbyggnader undersöktes. En studie hur elproduktion från existerande solcellsanläggningar matchar med ellasten för fem konstorsbyggnader gjordes för att undersöka hur solcellsanläggningarna var dimensionerade och installerade med avseende på takyta, takförutsättningar och ellaster för byggnaderna. Mätdata användes sedan i en annan studie där simulerad elproduktion för anläggningar med olika lutningsvinkel och orienteringar användes och matchades med fastighetsellastprofilen för de olika byggnaderna. Matchningen användes sedan i en ekonomisk utvärdering, där dagens tekniska, lagmässiga och ekonomiska förutsättningar inkluderades, för att undersöka hur olika systemkonfigurationer påverkar lönsamheten hos en investering i en solcellsanläggning.

Slutsatser som kunde dras från detta examensarbete är att en investering i en solcellsanläggning kan vara lönsam med dagens förutsättningar och att valet av lutningsvinkel och orientering för solcellssystemet är avgörande för lönsamheten. Det finns en optimal systemstorlek med avseende på lönsamhet som är olika för olika lastprofiler, vid detta optimum var några procent av den producerade elen överproduktion. En ökning av solcellssystemsinstallationer i Sverige är möjligt; de tekniska, lagmässiga och ekonomiska förutsättningarna är tillräckligt bra idag. Dock krävs en studie med fler byggnader som motsvarar ett typiskt kontor för att dra generella slutsatser kring potentialen för solcellsanläggningar i kontorsbyggnader.

Nyckelord: Solceller, kontorsbyggnader, ekonomisk utvärdering

Contents

Preface

Today the integration of solar photovoltaics (solar PV) is relatively small in Sweden compared to other European countries. The construction company NCC has the goal to gain deeper knowledge in this field to increase the usage of solar PV systems in their buildings and has therefore initiated a project, which is financed by Energimyndigheten, Elforsk, SBUF and NCC Construction Research & Development. The thesis has been a part of this project, in which the company wants to investigate how well the electricity load curves for existing office buildings with different cooling system solutions match the electricity generation from solar PV panels. They also wanted to investigate what conditions are needed to make a solar PV system investment profitable having a property owner's perspective.

In this thesis, the potential for building attached solar photovoltaic systems on Swedish office buildings have been investigated taking technical, legal and economic conditions into consideration. The study is based on a literature study and case studies of Swedish office buildings with PV systems. The project has been carried out from September 2014 to January 2015 at the Division of Building Services Engineering, Department of Energy and Environment, Chalmers University of Technology, Sweden.

The project has been carried out with Maria Haegermark as a supervisor and Professor Jan-Olof Dalenbäck as examiner. Two supervisors at NCC, Elsa Fahlén and Eva Grill have also followed the project from beginning until the end. Our supervisors Maria Haegermark, Elsa Fahlén and Eva Grill are highly appreciated for support while conducting the thesis. We would also like to thank Vasakronan, Akademiska hus, Skanska and Bengt Dahlgren for their help and input in the form of data for the case studies. Without this information the study would not be possible.

Göteborg January 2015

Nina Johansson and Jesper Karlsson

Notations

Roman upper case letters

A	Area of the PV system (m^2)
$C_{\%}$	Coverage (%)
C_t	Total costs per year (SEK)
D	Distance between the module rows (m)
E_t	Electricity generation per year (kWh)
F_{fee}	Fee for feeding electricity into the grid (SEK)
G_h	Generated solar electricity for the hour h (kWh)
G_{tot}	Generated solar electricity for one year (kWh)
$G_{tot,y}$	The total generated electricity from the solar PV system in year y (kWh)
I_o	Initial investment cost (SEK)
I_R	Cost for replacement of inverter (SEK
L_h	Property electricity load for the hour h (kWh)
$L1$	Length of the PV system (m)
$L2$	Width of the PV system (m)
N_{mr}	Number of modules in a row in a PV system
N_r	Number of rows in a PV system
N_{tot}	Total number of modules in a PV system
NPV	Net Present Value
$O_{\%}$	Overproduction (%)
O_h	Overproduction for the hour h (kWh)
O_{tot}	Total overproduction on hourly basis for a year (kWh)
O_y	Overproduced electricity from the solar PV system in year y (kWh)
$P_{ec,y}$	Price of green electricity certificate in year y (SEK)
$P_{gb,y}$	Grid benefit compensation given in year y (SEK/kWh)
$P_{P,y}$	Price of purchased electricity in year y (SEK/kWh)
R	Residual value (SEK)
S_h	Self-consumed solar electricity for the hour h (kWh)
S_y	Self-consumed solar electricity from the solar PV system in year y (kWh)
$U_{t,y}$	Payments in year y (SEK)

Roman lower case letters

a	Azimuth (degrees)
d	Module distance (m)
h	Height (m)
hyp	Hypothenuse (degrees)
k	Factor of investment costs that is operational an maintenance cost $(-)$
n	Life time (years)
s	Slope (degrees)
sa	Suns altitude (degrees)
r	Discount rate (-):

1 Introduction

The introduction chapter gives firstly a background of why it is interesting for the Swedish building sector to investigate the potential of PV investments for office buildings. After giving the reader a background to the subject, the purpose and objectives, method and boundaries and limitations are presented. Finally reading instructions of the report is given.

1.1 Background

The energy use in the building sector stands for almost 40% of the total energy use in Sweden, where the commercial buildings represented 15% in 2012 (IEA, 2014). Boverket, a governmental agency in Sweden, has the goal to regulate for all the new buildings to be near zero energy buildings from 31st December 2020 and all governmental building to be near zero energy buildings after 31st December 2018. Near zero energy building has not yet been quantified regarding energy performance, but will be investigated and reported the 15th of June 2015 (Boverket 1, 2014). The building sector is thereby constantly working with energy performance of buildings to meet new targets. One way to reduce the net use of energy could be to attach or integrate solar PV in the buildings, since the solar electricity can be subtracted from the specific energy of the building (Boverket 2, 2014).

Today the PV development is not yet wide spread and is driven mainly by a few countries. However, the growth of the Asian market in 2013 together with the declining prices in the last few years have made policymakers in numerous countries all over the world plan for PV development (IEA-PVPS, 2014). The price of a module today is about a fifth of the price in 2006 for a module with crystalline silicon cells (BSW-Solar, 2014). The Swedish solar PV market is still very small. In the end of 2013 the cumulative PV capacity in Sweden was 43.2 MW, which currently represents about 0.03 % of Sweden's total electricity use. The majority of the systems have been installed during the last 5 years (Lindahl, 2013).

In some parts of Sweden the solar irradiation on a yearly basis is equal to the irradiation in central Germany (Huld, 2012), in which regions new PV systems are rapidly installed. Sweden has about a thousand systems, while Germany has installed more than a million. Still it is commonly thought that Sweden is a country with poor sun and that the use of the energy produced by a solar PV system during summer is of little use. In fact this electricity from solar PV can reduce the demand of hydropower during summer, resulting in saving the energy to be used during other periods more efficiently (Paradis 1, 2013). According to a study about regulated power in Sweden, the existing regulating hydropower can manage a possible expansion of wind power and PV power of about a third of the electricity use (Söder, 2012).

Commercial buildings, like office buildings, that are operating during daytime usually have a daily electricity use profile that is well matched by the availability of solar radiation. Depending on the surface areas available, building integrated solar PV can generate considerable portions of the energy requirements. (Braun & Rüther, 2010) However, this study made by Braun was for Brazil and since no studies regarding Swedish conditions have been found for office buildings in Swedish conditions it is interesting to investigate the potential for solar PV in office buildings in Sweden.

The lowered PV module prices, the solar irradiation in Sweden and the matching of electricity load and electricity generation for commercial buildings together with the more strict energy performance standards for buildings makes it interesting to investigate the potential of having solar PV panels on office buildings from a property owner’s point of view.

1.2 Purpose and Objectives

The purpose of the thesis is to investigate the economic feasibility of solar PV in office buildings in Sweden. The feasibility will be investigated from a technical, economical and legal perspective and will be evaluated using a case study approach of existing office buildings. The purpose is also to investigate existing PV systems installations in office buildings with different cooling systems. In order to fulfill these purposes, the following research objectives were addressed:

- The first objective is to investigate if and how the electricity load profile varies for five existing office buildings with different cooling systems.
- The second objective is to investigate how the PV systems installations have been made and to investigate the matching of electricity generation from existing solar PV systems and load curves for these buildings.
- The third objective is to investigate how the size, orientation and slope of the PV system influence the matching of electricity generation and electricity load and how that influences the investment decision for office buildings with different electricity load profiles and cooling systems. Taking the current technical and legal conditions into account.

1.3 Method

The method evolved continuously through the thesis and can be divided into different parts with corresponding methods, which can be seen in Figure 1. These were most of the times conducted in parallel, but are for simplicity ordered according to the figure. In the chapter “Detailed Method”, the methods used in the thesis are described more in detail. This section gives an overview of the overall method used in the study.

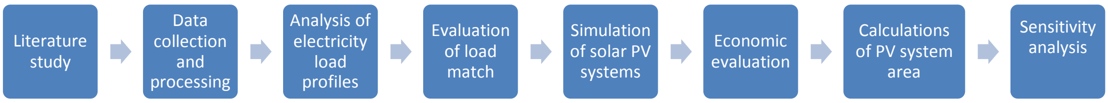


Figure 1.1 The different methods used in the thesis.

In order to answer the research objectives, this project is based on case studies for five office buildings with available measured data for electricity load and PV electricity generation. The first part of the project was an investigation of how the load profiles varies with different cooling systems for the five office buildings. In the second part the existing PV system installations on the five office buildings were investigated followed by an investigation of the matching of electricity load and electricity generation for the different office buildings. The third part was an investigation of how the slope, size and orientation are affecting the profitability for an investment in a solar PV system for some of the different office buildings with different load profiles. These case studies were made by simulating solar PV systems with different size, slope and orientation in computer software for the location where the examined building is located. A matching in terms of coverage and overproduction of measured electricity load and simulated electricity generation for different solar PV systems on the different office buildings were then made. With overproduction means the excess electricity that can´t be used within the property and that are feed into the grid or stored in for example batteries. This matching was then used in an economical evaluation for each solar PV system for three of the office buildings.

The project started with a literature study to gain deeper knowledge of the subject. Data for electricity loads and solar electricity generation was then collected for five buildings to be included in the case studies. The advantage of using measured data for office buildings instead of using simulated data is that the result will be reality-based and give the study more accuracy. The buildings that were chosen would preferably be buildings with similar sizes and that were recently built or renovated, but with different energy systems to be able to study how the load curve affects the suitability of a solar PV system on a building. The buildings included in this study were however differing a lot in size due to a limitation in available measurement data. The number of buildings examined was as large as possible that could be managed within the time frame of the thesis and was also depending on the availability of data. Data on an hourly basis was chosen to obtain accuracy of the study and to be able to study the effect of continuous changes in generation and usage over the days. It would be even more accurate to use smaller time steps than hourly, but there was few buildings measuring on shorter periods, which also was a reason why hourly basis was chosen.

To be able to study the effect of slope, orientation and size on the profitability of a solar PV investment, simulations of systems with the different system configurations were simulated to get different electricity generation data on an hourly basis. The simulations were made for three of the examined office buildings. The simulations were made by first choosing simulation computer software and then define a reference solar PV system that was used on all buildings.

The economic evaluation was then made by using a special developed Excel-tool, where input values in form of hourly electricity load for one year and simulated electricity generation for one year generated an economic result for a PV system size for a certain building. Finally, a sensitivity analysis for the economic result was made for critical input parameters.

The roofs for the examined buildings were all different regarding size, orientation and slope. To be able to study the impact of the size, orientation and slope of a PV system the roof was assumed to be flat and have unlimited area. For all systems simulated, an estimated area equivalent for a flat roof for the different sizes, orientations and slopes were calculated. The maximum installed peak power of solar PV that could fit on the existing roof area for the PV systems with different slopes and orientation was also calculated. This was made to be able to investigate if a simulated system would fit on the roof for the existing building assuming having a flat roof.

1.4 Boundaries and Limitations

The office buildings included in the study are office buildings which are recently built or newly renovated from 2007. The different cooling systems included in the study are limited to district cooling, electricity for cooling and free cooling. The matching of electricity generation and load curves will only be studied for one year, due to the availability of data.

A reference solar PV system will be used for all simulations, where a common polycrystalline PV module and a common inverter will be used. The PV system studied has roof attached PV panels, which means that the system does not replace other building material. Overproduced electricity is fed into the grid and no storage solutions, such as batteries, are included. The cost is assumed to be the same for PV systems with different slope.

When calculating the profitability of a PV system investment, the cost from loans in terms of interest rents is not considered. Instead it is assumed that the investment cost is paid the first year when the investment is made. The thesis does not consider different ownership alternatives of a PV system. The investor and owner in this study is the property owner, therefore is the property electricity of importance and not the business electricity.

In the evaluation of the potential for solar PV, environmental certificates, such as BREEM, are not included. Neither is the reduction of specific energy performance due to installing PV systems. A sensitivity analysis of the impact of the economic input parameters was made for only one system. This system was one of the economic optimal system configurations and was made to investigate if the estimated economic result is realistic and if it is sensitive to the estimations of the input parameters. A sensitivity analysis of the impact of the discount rate for an unprofitable system was performed as well to investigate how sensitive the economic result is to the required rate of return.

1.5 Reading Instructions

Chapter 2 is recommended to read if the reader is interested in the details of the methods used in the study. The methods are motivated why they are used and the equations and descriptions of how the calculations are made are included in this chapter.

Chapter 3 presents the office buildings electricity load profiles with different cooling system, which are used to study whether buildings with same cooling systems affects the load profiles similarly.

Chapter 4 describes the installation of the existing PV systems in the five office buildings. The matching of electricity generation from the existing PV system and the electricity load profiles presented in Chapter two are also presented in this chapter. The purpose of this chapter is to make it possible to investigate how existing PV systems installations on office buildings have been made.

Chapter 5 gives the input parameter for the simulations of electricity generation for the three different buildings that was chosen to be further studied. It also gives the preconditions for PV installations on office buildings owned by a company followed by the input parameters that are used in the economic evaluation of the PV systems.

Chapter 6 presents result for the matching of simulated electricity generation and electricity loads in terms of coverage and overproduction together with the economic result for the three office buildings. In the end of the chapter the result from a sensitivity analysis is given, which purpose is to investigate how large the impact some uncertain parameters have.

Chapter 7 is a chapter where the goals are discussed and where conclusions are drawn. The chapter starts with a discussion whether it is possible to draw any conclusions regarding the cooling systems impact on the electricity load profile of the electricity load profiles that are presented in Chapter 3. It discusses also the existing PV system installations and the load match, which was presented in Chapter 4. The result from the simulations and the economic evaluation that was presented in Chapter 6 is then discussed regarding what the impact of the size, orientation and slope of a PV system have on the matching and the economic evaluation. The impact of the input parameters studied in the sensitivity analyses is also discussed. Finally the technical, legal and economic conditions and the importance of these are discussed to be able to analyze a potential investment of a PV system on a Swedish office building.

Chapter 8 states a summary of the conclusions that can be drawn from the study.

2 Detailed Method

This chapter gives more detailed information about the methods that was used in the thesis. Firstly what was considered in the literature study and how it was conducted are presented. Secondly the collection and processing of data for the office buildings in the study is described. How the investigation of electricity load profile is performed is described thirdly. Fourthly, the calculations to evaluate the load match are described. These calculations are used both when evaluating the load match for existing office buildings with their corresponding PV systems and when evaluating the office buildings with PV system with different sizes, slopes and orientations. The selection of simulation software and the method how the simulations were made are then presented. The sixth section describes how the economic evaluation was conducted. The economic evaluation tools with corresponding equations that are used in the economic evaluation are described in detail. Finally the calculations of PV system areas is described, where both the calculations of peak power fitting the office buildings roofs and an approximated area for PV systems with different size, orientation and slope are included.

2.1 Literature Study

A literature was made to provide information to enable the analysis of the technical, legal and economic potential of a PV investment in Sweden. The literature study resulted in the chapter 3, which presents information that could be of interest for an owner of an office building interested in solar PV. Information was collected from databases, NCC and visiting relevant websites on the internet, but also study visits Sol i väst, WSP and Bengt Dahlgren. The information sources that were used were in first hand from original sources. The solar photovoltaic industry is rapidly growing and development is constantly moving forward, therefore sources with the latest information available have been used to a large extent as possible, since it makes the result and conclusion of the thesis more reliable and showing the true potential of today.

2.2 Measured Data for Office Buildings

Data for property electricity and electricity generation from solar PV system was collected on an hourly basis. The quality of the data was checked and analysed by looking for missing values and estimate if the data was reasonable before used. In the cases where there were missing data for some hours linear interpolation was used to approximate the missing values. In total, data for five office buildings was collected, whereof all of them had existing solar PV system on their roofs. These buildings had different size, levels and type of roof, which was not preferable, but since there were a lot of difficulties to get hold of measured data and the buildings had different cooling systems this was accepted. For each office building interpretation of the data was made with support from the supplier so that the data would be studied and used correctly. Information about the buildings energy/cooling system, size and other building specific conditions was also given by the supplier, energy declarations or found on the internet. The information is presented in Appendix A about the office buildings and has been verified by the data supplier.

Two of the buildings which were using district cooling were assumed, in an additional case, to have a cooling system with electricity driven cooling machines, to investigate what difference in electricity load profile curve there would be if the cooling system was changed. This additional case where two buildings had a replaced cooling system could be seen as two extra office buildings. The extra electricity load was calculated by division of a given hourly cooling load expressed in kWh/h by the coefficient of performance (COP) of the cooling machine. The coefficient of performance (COP) was assumed to 3, since Boverket uses this value as yearly average for air and water cooling machines (Boverket 3, 2015).

2.3 Analysis of Electricity Load Profiles

The electricity loads for the office buildings, as well as for buildings which had replaced district cooling with electricity for cooling, were plotted in diagrams on an hourly basis for a year to visualize the load profiles. Together with the information given about the buildings cooling systems and other information related to the buildings, the shape of the yearly load profile was analyzed. The average load per month during daytime 06:00-18:00 was plotted for all the electricity load profiles studied. The reason of to just take the electricity usage between the time 06:00-18:00 into account is because this time during the day when the solar insolation is biggest. It is during this time of the day the electricity demand is supposed to be covered with electricity from the solar PV system. This makes it possible to study how the cooling systems influence the electricity load profile during a year and what system that could possibly be preferable. In the analysis of the load profiles, the minimum base load of the buildings during day time was also estimated. This estimation was made by a calculation of the average minimum base load during day time between 6 am – 6pm, between March and October, because this is the time interval when most of the solar electricity production occurs. A comparison between the minimum base load and the size of the PV system was then made.

2.4 Evaluation of Load Match

The electricity loads and the solar electricity generations were plotted in the same diagrams to get an overview of the matching of electricity load and electricity generation for the existing solar PV systems for a year. To study and evaluate the matching more in detail it was chosen to calculate the overproduction and coverage on an hourly basis. The explanation of overproduction and coverage and how the calculations are performed is described below.

Overproduction is the generated electricity that cannot be used within the property that instead is fed into the grid or stored in for example batteries. For hours where solar electricity generation is larger than the electricity load there will be overproduction. By subtracting the electricity load from the solar electricity generation for these hours and summing those up per month or per year, the overproduction on an hourly basis for a month or a year are calculated. The calculations for the overproduction O_{tot} on an hourly basis for a year are shown in Equation 1. To make the number easier to compare to other solar PV systems the total overproduction O_{tot} is divided with the total generated electricity for one year according to equation X.

If $G_s > L_h$ then $O_h = G_h - L_h$ else $O_h = 0$

$$O_{tot} = \sum_{h=1}^{h=8760} O_h = \sum_{h=1}^{h=8760} G_h - L_h \quad (1)$$

$$O_{\%} = \frac{O_{tot}}{G_{tot}} \quad (2)$$

$O_{\%}$ = Overproduction (%)
O_{tot} = Total overproduction on hourly basis for a year (kWh)

O_h = Overproduction for the hour h (kWh)
G_{tot} = Generated solar electricity for one year (kWh)
G_h = Generated solar electricity for the hour h (kWh)
L_h = Property electricity load for the hour h (kWh)

The coverage is the share of the generated electricity that is used in a property in relation to the total generated electricity. The coverage per month and per year, on an hourly basis, was calculated by summing the hourly solar electricity used in the building for a month and dividing this by the electricity load for that month. The coverage on an hourly basis for a year was also calculated, which calculations are shown in Equation 3. The coverage on a yearly basis was simply calculated by dividing the total solar electricity production for a year by the total electricity load for a year.

If $G_h > L_h$ then $S_h = L_h$ else $S_h = G_h$

$$C_{\%} = \frac{\sum_{h=1}^{h=8760} S_h}{\sum_{h=1}^{h=8760} L_h} * 100 \quad (3)$$

G_h = Generated solar electricity for the hour h (kWh)
L_h = Property electricity load for the hour h (kWh)
S_h =Self-consumed solar electricity for the hour h (kWh)
$C_{\%}$ = Coverage in (%)

2.5 Simulation of Solar PV Systems

There are several softwares that can be used for estimating electricity generation for a PV system. Some software’s are using simple calculations and are used for rough estimations and some are more advanced used for designing a PV system. The simulation softwares available were IDA, Polysun and PVsyst. IDA is a software that is used in the building sector and can be considered as software using simple calculations, while the two other are specially developed for simulating PV systems. To select simulation software from these three an evaluation was made, which can be found in Appendix B. From the evaluation the software Polysun was chosen. The program had enough accuracy and was simple to use for a beginner. For all the simulations a reference solar PV system was used which components and input values are described in section 5.1.

Simulations of PV systems for three of the five office buildings were made. The two of the office buildings that was not simulated was either not considered a representative office building due to its very low electricity load or the property and the business electricity was not separated.

The electricity profile for the three office buildings was first studied to investigate how the orientation of the modules was suited to fit the generation to the load profile to increase the self-consumption. Self-consumption is the generated electricity that is used within the property. The load profiles studied can be seen in detail in section 4.3. Solar PV systems for the orientations chosen and with different slope angles were simulated. The orientations were chosen to be south and have a slope of 0°, 15°, 30° and 45° for all the office buildings studied. An orientation where half of the modules are facing east and the other half are facing west, with the slopes of 15°, 30° and 45° was chosen for one building that had a suitable electricity load profile. More of the selection can be read in section 5.1. From these simulation results, the generation from PV systems of different sizes was calculated by scaling the simulated result. Simulating a system for each size in Polysun would lead to difference in generation per kW_p installed due to the differences in configurations of PV arrays and inverters that will occur, which would make the results not fully comparable for different sizes. kW_p is the nominal power output during standard test conditions (STC) which is further described in section 3.1.2. By scaling up and down, the system will have the same percentage of losses. One limitation by using this method was that the area of the different PV systems was not given and had to be estimated. How these estimations were made are described in the next section.

2.6 Economic Evaluation Tools

To analyse the potential of solar PV in Sweden economical evaluations of solar PV investments has been made. The simulated hourly electricity production was used and has been matched with the load profile for the different office buildings to get data for the annual self-consumption, overproduction and coverage. The economical investigation was made by calculating a number of economical evaluation tools with use of the data for generation, self-consumption and overproduction. The main economical evaluation tools of use was net present value (NPV), payback period (PBP), life cycle costs (LCC) and cost of self-consumed electricity (CSCE). The investment evaluation tools were chosen to get a range of numbers which takes different aspects of an investment into account. NPV gives an indicator of the profitability of the investment, i.e. the net profit in the end of the economic lifetime of the system given in net present value. PBP tells how many years it will take to pay back the costs related to the investment for the solar PV system. This measure gives a number of how fast the investment will pay off which could be an interesting parameter to know even though it does not give any information about the profitability. LCC gives a number of the total costs related to the investment. CSCE gives a number of how much the own usage from the system costs per kWh. This number gives an idea of how profitable the investment is from a perspective when the produced electricity from solar PV replaces bought electricity from the grid. All economy calculations were made without including any VAT. A detailed explanation of how those economical evaluation tools are calculated is explained further in the following sections 2.6.1-2.6.4. Several economical input parameters had to be estimated to calculate the economical evaluation tools. The assumed values are described in section 5.2.

Using the economical evaluation tool developed in Excel the economical evaluation tools was calculated for PV systems with different slopes and sizes for a certain building with a measured electricity load profile. The load curve for the buildings was assumed to be the same for every year which in reality differs. The future could also imply improvements such as energy efficiency measures and by this change the load curves. This assumption was made since the available data were for one year for the office buildings used in the simulations. By selecting a size of a system as input value, resulting in upscaling or downscaling the simulated electricity generation, the economical evaluation tools was generated, see Appendix C for the interface. An overview of how the economical evaluation was conducted can be seen in Figure 2.

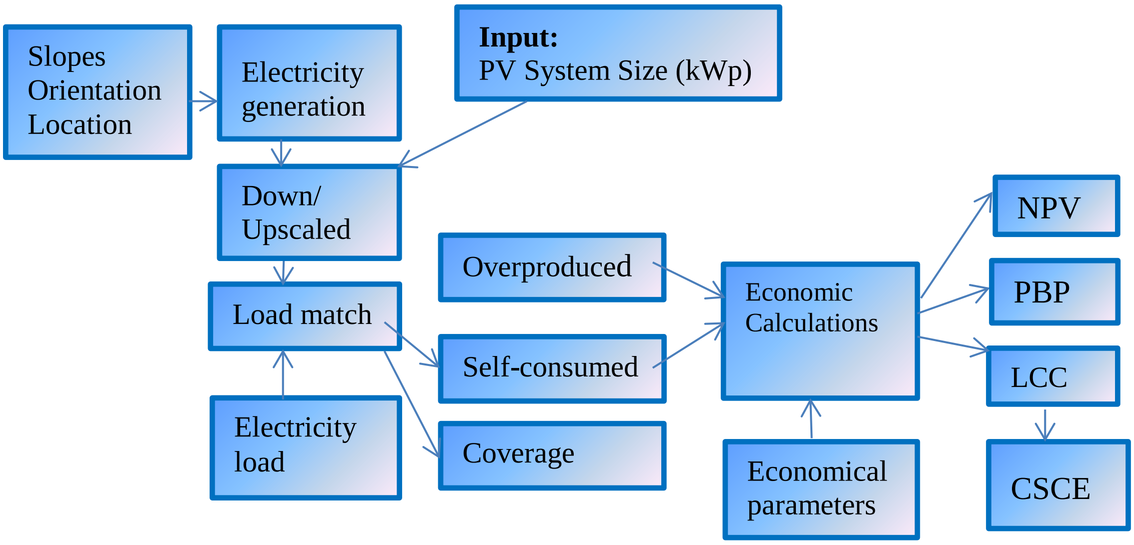


Figure 2.1 A structure over the Excel-tool. It shows that it from selecting a PV system size generates the economic evaluation tools, when simulated electricity generation for a year, electricity load for a year and economic parameters are given.

The methods used to calculate the economical evaluation tools and their corresponding equations are presented in the rest of the section. A short description of how the evaluation tools are used is also included in each section, together with theory of the common method if the method in question has been modified to suit the purpose of the thesis.

2.6.1 Net Present Value (NPV)

Net present value is a method to analyse the profitability for an investment by estimate how much the investment will yield during its life span. NPV is calculated by summing up the discounted cash flows that are related with the investment. The present cash flows for each year include all inflows and all outflows discounted with the discount rate for the investment. The inflows are calculated as positive values and the outflows are calculated as negative values. If the NPV is positive the investment is profitable and the greater positive value of the NPV it is the more profitable is the investment (Ong & Thum, 2013).

In this thesis the NPV was calculated by firstly calculating a net cash flow for every year and summing them up to a total net cash flow for the PV systems whole lifetime. This net cash flow is based on the estimated savings from avoided bought electricity, income from electricity certificates and grid benefit compensation and expenses related to operation and maintenance and costs for feeding electricity to the grid. The cash flow for every year was then discounted to present value. The net cash flow is expressed by Equation 4.

$$\text{Net Cash Flow} = \sum_{y=1}^{y=n} \frac{\left(S_y \times P_{P,y} + G_{tot,y} \times P_{ec,y} + O_y \times P_{gb,y} - k \times I_o - F_{fee}\right)}{(1+r)^{y-1}} \tag{4}$$

$=$ Self-consumed electricity from the solar PV system in year y (kWh)
$P_{P,y} =$ Price of purchased electricity in year y (SEK/kWh)
$G_{tot,y} =$ The total generated electricity from the solar PV system in year y (kWh)
$P_{ec,y} =$ Price of green electricity certificate in year y (SEK)
$O_y =$ Overproduced electricity from the solar PV system in year y (kWh)
$P_{gb,y} =$ Grid benefit compensation given in year y (SEK/kWh)
$k =$ Factor of investment costs that is operational an maintenance cost $(-)$
$I_o =$ Initial investment cost
$F_{fee} =$ Fee for feeding electricity into the grid (SEK/year)
$r =$ Discount rate (-)
$n =$ Life time (years)

It is assumed that the inverter needs to be replaced after 15 years and this cost is discounted to present value. The net present value was then calculated by subtracting the initial investment cost and the inverter cost in present value from the discounted net cash flow. The calculation is described in Equation 5 below.

$$NPV = \text{Net Cash Flow} - I_o - \frac{I_R}{(1+r)^{15}} \tag{5}$$

I_R = Cost for replacement of inverter (SEK)

2.6.2 Payback Period (PBP)

Payback Period (PBP) is a method to estimate the time it would take to pay off an investment. The method is suitable to use to fast compare different investment alternatives or to examine how fast, or if an investment pays off during its lifetime. The main uncertainty for a PBP analysis for a solar PV investment is to estimate the future electricity price. Another drawback is that this method does not consider the interest expenses which usually are a big part of the life cycle cost of a solar PV system (Paradis, 2013). Payback time evaluate capital recovery and do not say anything about the profitability for the investment. For example it does not account for the returns after its payback period. (Ong & Thum, 2013) There are different ways to calculate the PBP with different levels of complexity. The basic most straightforward method to calculate the PBP is to divide the initial project investment cost with an expected annual cash inflow. There are also methods for uneven cash flows from year to year and methods where the value of time is taken into account, so called “discounted payback period” (Calvin M Boardman, 1982).

It was chosen to use a method where the time value of money was taken into account, since this will give a more accurate payback period for the investment. The payback period used is using equation (4) for net cash flow same as for the net present value in section 2.6.1 above. The initial investment cost is starting as an initial negative cash flow and upon this is then the annual cash flow added year for year. After 15 years is the cost for replacement of the inverter discounted to present value and added as a negative value. A plot of this could look as in the Figure 3. When the graph intersects the x-axis at y=0 has the investment been paid off. The y-axis shows the cumulative economical result in net present value for a certain year (x-axis) after the investment. The point where the time is 30 gives the net present value, for a PV system with a lifetime of 30 years. Similarly would the point at 25 years give the net present value for a PV system with a lifetime of 25 years.

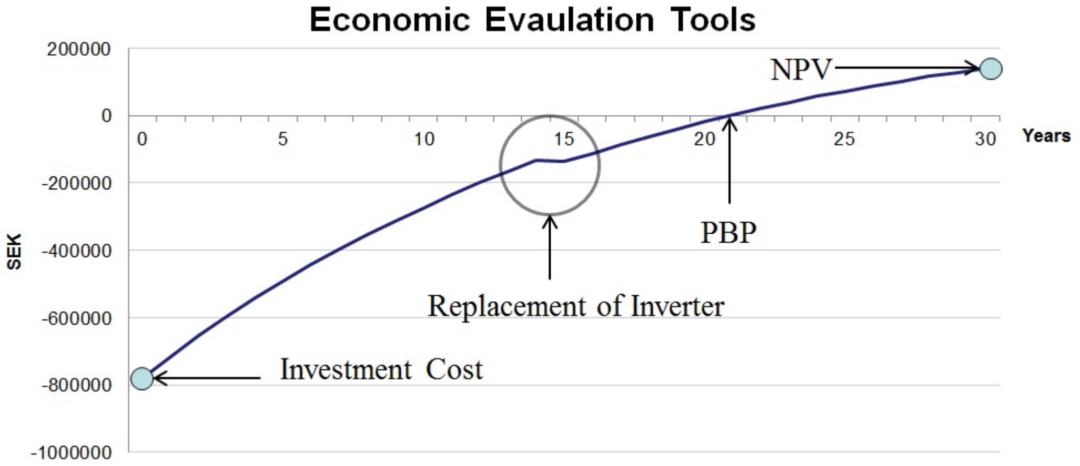


Figure 2.2 The economic result over the lifetime of a PV system investment. The initial investment cost, the replacement of the inverter, the PBP and the NPV are marked in the figure.

2.6.3 Life Cycle Costs (LCC)

The life cycle costs are all the costs that are related to the investment through its life cycle. The life cycle is a period of time between a start date and the disposal of the asset. It includes initial investment cost, the residual value and the payments every year during its lifetime, where these payments usually consist of operation and maintenance costs. (Davis Langdon, 2007) A general formula is shown in Equation (6).

$$LCC = I_o - \frac{R}{(1+r)^n} + \sum_{y=1}^{y=n} \frac{U_{t,y}}{(1+r)^{y-1}} \tag{6}$$

I_o = Initial investment cost (SEK)
R = Residual value (SEK)
r = Discount rate (-)
n = Life time (years)
$U_{t,y}$ = Payments in year y (SEK)

In this study the costs used are the initial investment cost, the cost for the replacement of the inverter after 15 years, operational and maintenance (O&M) costs and the costs for feeding electricity to the grid. The O&M costs are assumed to a percentage of the initial investment cost. The residual value and the disposal costs are assumed to cancel each other out and are therefore not included. All the costs have been discounted to present value. The equation for LCC used in this thesis is described in Equation (7).

$$LCC = I_o + \frac{I_R}{(1+r)^{15}} + \sum_{y=1}^{y=n} \frac{k \times I_o + F_{fee}}{(1+r)^{y-1}} \tag{7}$$

I_R = Cost for replacement of inverter (SEK)
k = Factor of investment costs that is operational and maintenance cost (-)
F_{fee} = Fee for feeding electricity into the grid (SEK)

2.6.4 Cost of Self-Consumed Electricity (CSCE)

The economical evaluation tool, cost of self-consumed electricity (CSCE) is similar to the economical evaluation tool levelized cost of electricity (LCOE). LCOE is a common method to estimate the cost of electricity from an electricity generating technology, expressed in for example SEK/kWh, to evaluate the relative cost-effectiveness compared to other electricity generating technologies. LCOE is calculated by the total lifetime cost divided by the total lifetime energy production, where the total lifetime costs are defined as the cash outflows minus the cash inflows. The cash outflows could be investments cost, interest payments (in case of loans), service and maintenance and grid connection costs in some cases. Cash inflows could be subsides and green certificates (LCOE paper). The assumptions that are made in the LCOE analysis is the choice of a discount rate, average system price, average system lifetime, n, and the degradation of the energy generation over the system lifetime(LCOE paper). A general formula for LCOE can be seen in Equation (8).

$$LCOE = \frac{\sum_{y=0}^{n} \frac{C_t}{(1+r)^y}}{\sum_{y=0}^{n} \frac{E_t}{(1+r)^y}} \tag{8}$$

r = Discount rate (-)
E_t = Electricity production per year (kWh)
C_t = Total costs per year (SEK)

The difference between CSCE and LCOE is that CSCE calculates the estimated cost of the own consumed electricity and not for the total electricity generated. The equation for CSCE is given by Equation 9, where LCC represent the net cash outflows and is the same as equation (4) described in the previous section. The net cash inflows consists of the green electricity certificates and the grid benefit compensation.

$$CSCE = \frac{LCC - \sum_{y=1}^{y=n} \frac{(G_{tot,y} \times P_{ec,y} + O_y \times P_{gb,y})}{(1+r)^{y-1}}}{\sum_{y=1}^{y=n} \frac{S_y}{(1+r)^{y-1}}} \tag{9}$$

LCC = Life cycle costs (SEK)
O_y = Overproduced electricity from the solar PV system in year y (kWh)
S_y = Self-consumed electricity from the solar PV system in year y (kWh)

The estimated electricity price that is calculated from LCOE is the price for the production of electricity. This measure is suitable when a comparison between different energy production facilities is compared. But for a solar PV system that is a part of a buildings energy system is the load profile for the building important when it comes to evaluate its profitability. CSCE calculates the price for the electricity that is consumed within the building including the income from selling electricity. A conclusion was made that CSCE is better suited to evaluate cost of electricity from a solar PV system that is a part of a buildings energy system.

2.7 Calculation of PV System Area

To relate the simulated PV systems sizes to an area, the distance needed between the panel rows for different slope angles to avoid internal shadowing must be calculated. The method used for calculating these distances are firstly described in this section. To relate the simulation and corresponding economic result to the office buildings the possible peak power was calculated for the PV systems. Therefore a method of how to calculate the possible peak power for PV systems with different slopes and orientations on existing roofs of the office buildings is presented secondly. Lastly a description of how estimations of a potential area needed for a PV system with a certain peak power are calculated is described. The purpose for having this area is to give a perception of how large area that might be needed for a PV system and to relate this area to the existing roof area.

2.7.1 Calculating the Distance between Modules

The rows for a PV system must have certain distance between the panels to avoid internal shadowing. The distance depends on the height, and the azimuth, of the system and the suns altitude. The height of the system can be calculated using the slope, and the hypotenuse. Equation (10) shows how the distance can be calculated (Nordic Folkecenter, 2012). See Figure 4 for notations of the constituting elements. In a report from Elforsk an estimation of distance for a slope of 30° are made by multiplying the hypotenuse with a factor, k of 2.5 (Noord & Ärlebäck, 2011). Using the previous Equation (10) and Equation (11), the suns altitude used in Elforsks estimation was calculated to 11.3°. Knowing the suns altitude, factors for the other two slopes, 15° and 45° was calculated to 1.3 and 3.5 respectively.

$$D = \frac{h}{\tan(sa)} \times \cos(a) = \frac{hyp \times \sin(s)}{\tan(sa)} \times \cos(a) \tag{10}$$

$$D = hyp \times k \tag{11}$$

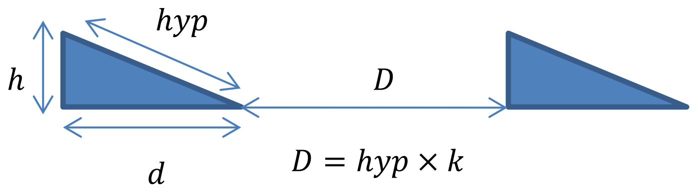


Figure 2.3 Shows the notations that are used for the calculations of the distance, D, that is needed between the rows to avoid shading.

D = Distance between the rows (m)

$h =$ Height (m)
$a =$ Azimuth (degrees)
$sa =$ Suns altitude (degrees)
$hyp =$ Hypothenuse (degrees)
$s =$ Slope (degrees)
$d =$ Module distance (m)

2.7.2 Estimating the Number of Modules on Existing Flat Roof

By using the calculated distance between panel rows for different slopes it is possible to calculate the number of modules and the corresponding peak power that fits onto the existing roof of the office buildings assuming the roof is flat. This was made for the PV systems with slope of 0°, 15°, 30° and 45° in the direction to the south. Calculating the number of modules in the east-west directions for slope 30° and 45° was not made since it is not likely to have these configurations on a flat roof. Instead it was assumed that these systems only are used if the roof has this orientation from the beginning. The number of modules for the east-west configuration with a slope of 15° was calculated, assuming no distance between the rows (D=0) since this is how the installations are made today, see Figure 2.4.

Figure 2.4 The layout for a solar PV system that has a slope of 15°.

Dividing the roof of the office buildings into blocks which internally are not shadowing each other the number of modules was calculated by using the distance and the dimensions and slope of the modules. For example, having a rectangular block it was first calculated how many modules that could be fitted into the width, by dividing the width, W with the side of a module, w. Then the number of rows was calculated using the distances D and module distance, d and the length L of the block. The modules were oriented using the short side as the hypotenuse. The orientation of the building that was not facing south was assumed not to be fixed to the original to make it easier to conduct the calculations. With this method it is possible to underestimate the number of modules, since it was assumed that the distance between the panels must be fulfilled. In real cases it might be reasonable to shorten the distance to some extent for making space for an additional row. Knowing the number of modules the peak power can be calculated easily.

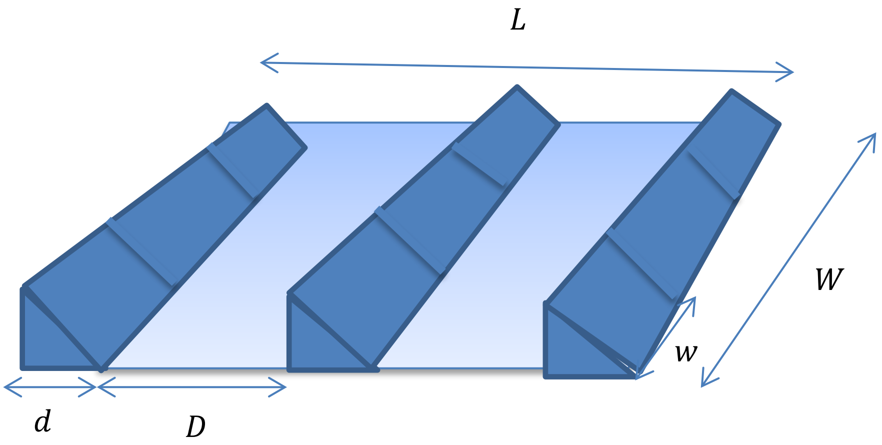


Figure 2.5 Shows the distances and respective notations that are used for calculating the number of modules on an office buildings existing roof dimensions which is assumed flat.

2.7.3 Estimating an Area of a PV System

Similar to the previous calculations estimating the possible peak power, the area for all PV systems beside the east-west PV system with slope of 30° and 45° was estimated. The square root of the total number of the modules, N_{tot} gives the number of modules in a row, N_{mr}. By dividing the total number of modules with the number of modules in a row the number of rows, Nr was calculated. With this information an estimated area, A, could then be calculated by calculating the length and the width of the system, $L1$ and $L2$ respectively. The length was calculated using the distance, D, the length under a module, d, and the number of rows, N_r. The width of the system was the length of the side of the module, w, multiplied with the number of modules in a row. The calculations are presented below in form of equations.

$$N_{mr} = \sqrt{N_{tot}}$$

$$N_r = roundup\left(\frac{N_{tot}}{N_{mr}}\right)$$

$$L1 = (N_r - 1) \times D + N_r \times d\ , where\ d = \frac{\cos(s)}{hyp}$$

$$L2 = N_{mr} \times w$$

$$A = L1 \times L2$$

N_{tot} = Total number of modules
N_{mr} = Number of modules in a row
N_r = Number of rows
D = Distance between rows (m)
d = Module distance (m)
s = Slope (degrees)
hyp = Hypothenuse (m)
$L1$ = Length of the system(m)
$L2$ = Width of the system (m)
A =Area of the PV system (m^2)

2.8 Sensitivity Analysis

A sensitivity analysis was made to investigate how sensitive parameters affect the economical result. Sensitive parameters are estimated parameters that for a small change in value might change the outcome of the result drastically. The sensitivity of the parameter was tested by keeping all the values fixed to its original assumed value and changing the studied parameter. The analysis was performed for the PV system that had the most profitable result for one office buildings. The result of the sensitivity analysis is showed in the section 6.6, where also the changes in parameters are described.

3 Literature Survey

The first section of this chapter, Solar Photovoltaics, gives a technical background of Solar PV in general. After this the section, Office Buildings, describes the energy distribution in office buildings and different cooling systems for buildings. This information is included in the thesis to evaluate if the office buildings in this study are representative. The section, Solar PV in Buildings, are describing the different types of PV installations in buildings and what to consider when implementing solar PV on buildings. Maintenance is also included in this part. In the last section, Conditions and Legislation for Solar PV Electricity Producers, information from the electricity law and other regulations influencing PV electricity producer’s investment are presented. It describes related costs and how electricity is sold.

3.1 Solar Photovoltaics (Solar PV)

In this section the fundamentals of solar photovoltaics (PV) and different PV technologies are firstly presented, followed by descriptions of solar PV systems and descriptions of the parameters that influences the electricity generation.

3.1.1 Fundamentals and Technologies

Solar PV is a technology that directly converts light radiation into direct current using a p-n junction incorporated in a semiconductor. An electric voltage is emerged between the electrodes when light shine upon this system due to the photovoltaic effect. Light is absorbed in the semi-conductor material at the surface of the solar cell. The absorption of light quanta is generating electron hole pairs from the semi-conducting material when light hits the cell. If the positive and negative side of the solar cell is connected, a current will flow in the circuit. Figure

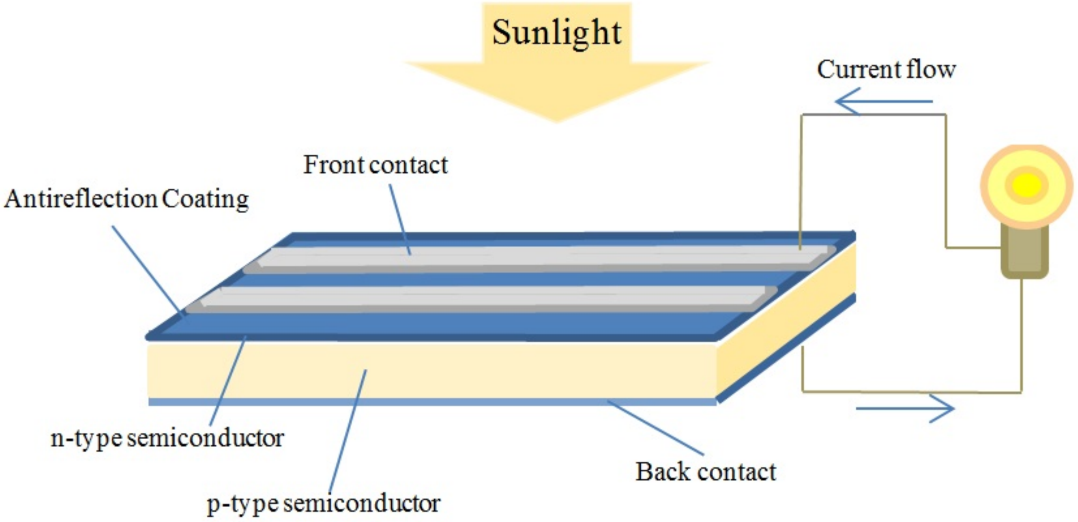


Figure 3.1 – A picture of a solar cell; n and p type semiconductor compound with antireflection coating and back and front contact connected to an electric load

The electric voltage generated over an individual solar cell is very low. To get a higher voltage, a number of crystalline cells are connected in series or for thin film PV, a thin layer of semi-conducting material are internally connected in series as a result from a pattering of the layer in the manufacturing (Stefan Haas, 2012). Solar cells are packed into modules with a casing to protect against environmental and mechanical impacts (A. Goetzberger, 2005).Solar PV can convert both the direct radiation and the diffuse radiation into electricity, compared to thermal solar system that can only use the direct radiation. Diffuse radiation is a major part of the total radiation in northern climate (Häberlin, 2012).

The most common commercially produced solar cells today are wafer-Si crystalline cells (single crystal- and poly crystalline), thin-film cadmium telluride (CdTe) cells, thin-film Si cells and thin-film copper indium gallium selenide (CIGS). Crystalline silicon accounted for 89% of the solar cell market in the world, 2012 (Tao, 2014). Figure 3.2 shows how difference poly and mono crystalline silicon cells look like. A module with an output of 200 W_p have an area of around 1.5 m^2 and a weight of around 18 kg. The largest mass-produced monocrystalline module 2012 had a rated power output of 300 W_p (Häberlin, 2012). Commercial monocrystalline silicon PV cells having a conversion efficiency of between 16-24%. The cheaper and more widely used is the poly crystalline silicon cell which has a slightly lower conversion efficiency of 14-17 % in average. The mean conversion efficiency is 16 % for commercial produced polycrystalline cells today (ISE, 2014). Some resellers of solar modules state a module lifetime of 30 years, others give a specified performance guarantee of 10-26 years (Häberlin, 2012). Measurements of the performance of 25 years old modules where made by Energibanken AB commissioned by the SolEl-programmet supported by i.e. Energimyndigheten and Elforsk in Sweden in 2007. No noticeable deterioration of the performance could be measured from 19 of the 20 modules after 25 years of operation compared to a new system. The old modules also had very few visible defects. The conclusion made was that 25 years life span of the solar modules is reasonable in Swedish weather conditions and that 25 years can be assumed to be underestimated (Hedström, 2007).

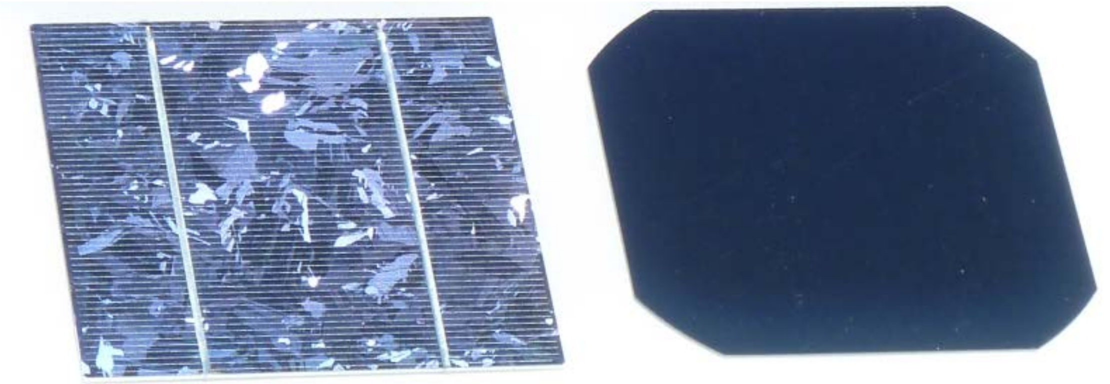


Figure 3.2 – Two crystalline silicon solar cells, poly crystalline silicon to the left and mono crystalline silicon to the right (Mueller, 2014).

In contrast to wafer based solar modules, the manufacturing of solar cell and the solar module are not separated in the production of thin film modules. The series connections between individual cells are made in the manufacturing process of the complete thin film solar module (Stefan Haas, 2012). The semi-conducting material required for full absorption of photons in a thin film solar module is only 0.5-2 µm (Häberlin, 2012),which reduce the need of material a lot compared to crystalline solar cells, which have a wafer thickness of 180-200 µm (Tao, 2014). The semi-conducting material in a thin film solar module can be attached onto a backing of some inexpensive material like glass, metal, plastic etc. (Häberlin, 2012). The drawback for thin film solar modules is the lower efficiency, and thus more area needed to produce the same amount of electricity compared to crystalline solar modules. Thin film cells have a module efficiency of around 7 % for amorphous silicon and 13 % for CIGS (IEA-PVPS, 2014). Because of the manufacturing method and the less material use the manufacturing cost for thin film solar modules could be substantially lower than for crystalline solar modules, but to be competitive more development are needed to reach a stable, higher efficiency (Häberlin, 2012) Thin film solar PV cells accounted 2012 for around 11 % of the world market (Tao, 2014). Amorphous thin film solar cells experience a significant degradation of the efficiency, up to 10-30%, during its first month of operation and the lifetime could be shorter than for crystalline solar cells (Häberlin, 2012).

PV cells with a conversion efficiency of 40% or more have been developed (III-V compound semi-conductor triple-junction tendem cells), but due to their higher cost, those cells are mainly used in special applications (IEA-PVPS, 2014).

3.1.2 Systems and Components

A Solar PV system consists of modules, cabling, mountings and inverter to regulate and/or modify the electrical output. A solar PV system is rated in kilowatt peak (kW_P) which is the nominal power output during standard test conditions (STC). STC is defined as a solar radiation of 1000W/m^2, solar spectrum that follows AM 1.5 (air mass 1.5, solar spectrum similar to when the sunlight hitting the earth´s surface at 42° over the horizon) and a module temperature of 25 °C (Parida, et al., 2011). It is possible to design the solar PV system get any required power output (IEA-PVPS, 2013).

Solar PV Systems

Solar PV systems could act as a stand-alone system or being connected to the power grid, with or without storage. Stand-alone system means that the Solar PV act independent of the power grid. Solar PV as a stand-alone system is suitable in settings where it is less important to have electricity available all the time, such as irrigation systems and fan operation during summer. A stand-alone system could also be used together with a storage system, most commonly battery storage, to get an electricity supply when the sun is not shining. The battery storage in a stand-alone solar PV system typically accounts for about 10-40% of the investment cost and up to 30-60% of the operating costs. Grid-connected PV systems are connected directly to the grid using an inverter to convert DC current to AC current at a frequency of the grid. A grid connected solar PV system is suitable where the public power grid is extensive and available, to reduce the storage cost and get more reliable electricity supply. (Häberlin, 2012)

Most of the solar PV installations in Sweden are grid connected due to a governmental capital subsidy for grid-connected Solar PV systems that have been active since 2009 and that will be active thru 2016 (IEA-PVPS, 2014).

Inverters for Solar PV systems

Inverters for solar PV are labelled in maximum power output (kW) and maximum DC voltage from the solar panels. Conversion efficiencies of inverters are typically in a range of 95-97%, with a maximum of 98% (IEA-PVPS, 2014).

Inverters are usually equipped with a solar tracker that constantly adjusts the load to reach the maximum power point (MPP) with a maximum power point tracker. MPP is a point of operation where the relation between the voltage and the current has a relation that gives the maximum power output. The MPP is different for different irradiance, cell temperature, manufacturing tolerance and aging. The life span of an inverter is around 15-20 years (Häberlin, 2012).

3.1.3 Electricity Production Parameters

The electricity production from a solar PV system is depending on several factors. The location, the orientation of the modules and the efficiency of the solar PV, inverter and remaining components are some of the factors. Other factors are weather conditions, snow and dirt.

The location determines the performance due to climate and obstacles surrounding the system. The climate in turn decides available irradiation and ambient temperature, while nearby obstacles might reduce production due to shading of the system. Important before installing solar panels are to consider the shading, since shading of the panels may decrease the production significantly (Masa-Bote & Caamaño-Martín, 2014). It is enough for one solar cell to be shadowed in a module to limit the module current resulting in reduced production. The electricity production is further decreased if the modules are connected in series, therefore must a PV modules have by pass-diodes to reduce the effect of shading (Papadopoulou, 2012).

The orientation of a module is given by the angles for azimuth and slope. These two parameters will affect when and how much of the solar irradiation the module area will receive. The azimuth angle decides in what direction the module is facing, for example if it is facing south the angle is usually 0^{o} while for north means an angle of 180^{o}. Installation against east and west results in more production during the morning and the evening respectively, while installation facing south gives the highest generation at the middle of the day. The slope gives the angle for the solar PV related to the horizon, where 0^{o} means horizontal and 90^{o} is vertical. For example will a vertical placement of a PV system on a facade facing south give a yearly production 20-30% lower than the system with optimal inclination and same orientation to the south (Stridh & Hedström, 2011). Small deviations on the slope have low sensitivities for energy loss (Masa-Bote & Caamaño-Martín, 2014).

The solar PV efficiency is affected by the type of technology and by the cell temperature where increased temperature lowers the efficiency. It is therefore important to cool the panels with enough ventilation (Noord, 2010).

Snow and dirt will also have a negative impact, 2-6% is lost in insolation on a yearly basis during a snowy winter in south of Sweden (Solelprogrammet, 2015).

3.2 Office buildings

This chapter aims to provide information about office buildings regarding energy systems and how energy is distributed in the buildings.

3.2.1 Energy in office buildings

Buildings energy use is divided into property and business electricity (or other energy) use. The property electricity is defined as the electricity or other type of energy that is used to operate the central systems in the building that is required for the building to be used as intended. This energy is paid by the owner of the property. Examples of this electricity are the electricity used for fans, pumps, elevators, fixed mounted lights etcetera. The business electricity is defined as the electricity and other type of energy that is used for the activity in the buildings premises. This energy is paid by the tenants of the property. Example that is counted as operational electricity is lighting, computers, copiers and similar (Rosenqvist, 2015).

In a study commissioned by Energimyndigheten the energy use in office buildings and administration buildings was examined by studying the distribution of the electricity to various areas of usage, such as lighting, fans and cooling machines. This study involved 123 buildings where the mean specific electricity use was 53% for operational electricity and 47% for building electricity. The average specific electricity use for property electricity for the studied buildings was on average 44.5 kWh/m^2, where fans had a large share of 17.9 kWh/m^2 (40.2 %) followed by cooling machines using 10.6 kWh/m^2 (23.8 %) (Hellberg, 2007).

3.2.2 Cooling systems in office buildings

A commercial building generally generates a heat surplus most of the time of the year from internal heat sources, with heat deficit generally only at night and weekends. There are several cooling systems to remove the heat surplus from buildings; the most used is air based cooling (with constant or variable air flow), water based cooling or a combination of those. A combination is mainly used when the cooling demand is too big for only air based cooling, because of comfort problem when draught getting too big. Depending on the cooling system of the commercial building, the electricity demand for the building will be different (Nilsson, 2001). In average, the cooling demand in Swedish office buildings over 3000 m^2 is 24 kWh/m^2/year tempered area (Sahlin, 2014).

The most used method to produce cooling is from electrical driven compressor, which is a thermodynamic refrigeration cycle. Another method to produce cooling is with evaporative cooling which cool down air by humidification of the air when it passes a wet surface. A variant of evaporative cooling is sorption cooling which dries the air before the humidification to be able to add as much moisture as possible before the air gets saturated. Sorption cooling needs added heat. District cooling and free cooling are other methods to cool down a building. District cooling supplies cold water which has been cooled down in facilities. The cooling in a water based cooling system is supplied to the room with for example; chilled beams, cooling panels and fan coils. Free cooling are cooling that can be provided with outdoor air without using a cooling machine. Usually the supply air in an air based cooling system is supplied at 16-18

°C, this means that outdoor air can supply the whole cooling demand when the outdoor temperature is below this temperature (Nilsson, 2001).

3.3 Solar PV for Buildings

Solar photovoltaics can be mounted on buildings, but also integrated in the building envelope serving two functions, power generation and replacing building material. Mounted PV is called Building attached PV (BAPV) and if the system is integrated it is called Building integrated PV (BIPV). These two concepts are firstly described in this chapter, and then factors to consider when implementing solar PV systems are explained.

3.3.1 BAPV and BIPV

The BAPV are seen as add-ons to the building and can be categorized as standoff and rack-mounted arrays. Standoff arrays are mounted parallel above the roof surface of a pitched roof and the rack-mounted arrays are installed so that optimal orientation and tilt of the modules are achieved for the application. The rack-mounted system is usually mounted on flat roofs. Conventional framed modules for both categories are supported by a superstructure that is attached to the building through brackets or other solutions that are mechanically fastened (Peng, et al., 2011). Depending on the roof type, pitched or flat roof and the roof material, there are different solutions in how to attach the solar PV system. In a report commissioned by Sol i Väst several attachment techniques are described (Paradis 2, 2014).

The BIPV replaces conventional element material, for example for roof, facades, balconies and shading devices for windows. Some define BIPV as PV installations that are a part of the architectural design creating desired appearance and visual effects, without necessarily replacing conventional building material (Peng, et al., 2011). The fact that the cost of conventional material is avoided the BIPV systems can potentially have lower overall cost compared to a mounted PV system (Kylili & Fokaides, 2013).

3.3.2 Implementing Solar PV in Buildings

The roof must last as long as the PV system, which is around 30 years. Therefore an evaluation if roof refurbishment is needed must be made before installing a system. Wind and snow loads must be considered as well when designing a system. The mounting system must be adapted to the local conditions, for example a mounting requirements different from the north Sweden compared to the south Sweden, since the mounting system installed in the north might need to be more robust (Paradis 2, 2014). The available area for the solar PV system must be considered to investigate how large the PV system can be. The installation area for a certain effect (kW) needed depends on whether the roof is pitched or flat. The area is larger for a flat roof since the panels must be spaced for preventing shading. The available areas should be simulated regarding generation so that the electricity cost can be calculated (Paradis 1, 2013). Solar PV system´s, especially grid-connected systems, are requiring very little maintenance during operation, but there should be space to enable this (Parida, et al., 2011). In environments when the PV system is visible from the ground or surrounding buildings a building permit should be applied for (Paradis 1, 2013).

3.4 Conditions for PV Electricity Producers

The conditions for a solar PV electricity producer are different from case to case and the situation is rather complex. Smaller producer of electricity have certain advantages compared to bigger producers in Sweden. Producers of electricity are classified with respect to the size of the system and the size of the main fuse. Two concepts that seem to be widely used in Sweden are small scale producer and micro-producers. In the law of electricity (1994:854, chapter 4 10§) it is a distinction between producers smaller than 43.5 kW and 63 A and a producer with a maximum installed power of 1500 kW, but the terms micro-producer and small scale producer is not defined in the law (Näringsdepartementet, 2014). The actual terms are used by energy companies and other organizations with different definitions. Small scale producers of electricity are often defined as producers with a maximum installed power of 1500 kW. Several energy companies and some organisations has been studied and micro-producers are often defined as producers with a maximum installed power of 43.5kW$_p$ and a maximum size of the main fuse of 63A, some energy companies accept a size of the main fuse of maximum 100 A to being defined as a micro-producer. Micro-producers are in most cases private persons that producing electricity mainly to their own use at their private houses because commercial buildings have in most cases a main fuse bigger than 63 A (and 100 A) (Sundsvallelnät, 2012) (Vattenfall 1, 2015) (GöteborgEnergi, 2015) (Khaffaf, 2014) (Energimyndigheten 1, 2014) (TekniskaVerken, 2013).

This chapter describes conditions and which legislations there are and what costs these legislations means for a small scale producer and a micro-producer. Legislations regarding feeding electricity to the grid, energy tax and grid benefit compensation are explained. Tax credit, direct capital subsidy, green electricity certificates influences also the conditions for a solar PV system investment and are therefore also explained. Guarantee of origin is not used today for solar PV generation, but might in the future be and is therefore also described in this section. Finally the conditions for selling overproduced electricity for small scale and micro-producers are explained.

3.4.1 Feed in Fee

According to the law of electricity (1994:854, chapter 4 10§) a small scale electricity producer that is feeding electricity to the grid is obliged to pay a grid tariff to the grid owner that covers the cost for measurement, calculation and reporting to the grid owner. A micro producer (main fuse bigger than 63 A, installed power over 43.5) is not obliged to pay anything for feeding electricity to the grid with the condition that the micro producer consumes more (electricity from the PV system) than feeding to the grid annually (Näringsdepartementet, 2014).

3.4.2 Energy Tax

All consumed electricity in Sweden is normally taxable. This tax varies depending on where in Sweden the use occurs, the tax is lower at some municipalities in north

Sweden. In 2014, the energy tax was 0.294 SEK/kWh exclusive VAT in and 0.194 SEK/kWh exclusive VAT in the lower price regions (Vattenfall 2, 2014). However, there are exemptions in the law about energy tax. One exemption relevant for a solar PV installation is that, electricity from an electricity producer that disposes over facilities with an installed generator output that is smaller than 100 kW and that is not producing electricity commercially is not taxable according to the law about energy tax (1994:1776, chapter 11 2§) (Finansdepartementet, 2014). An addition to this exemption is that the Swedish tax agency 2011 made a statement that electricity produced from solar PV or other facilities without a generator is not obliged to pay energy tax. This means that there is no upper limit in size for a solar PV system. However, to avoid energy tax the produced electricity cannot be transferred for any kind of compensation, since the generation then becomes commercial. A producer is considered as commercial when:

- Feeding electricity to the grid and get compensation
- Charge tenants or base rents on measured use from the PV system
- Count off overproduction for a certain time with bought electricity another time, so-called net metering charging

If a producer is considered as a commercial producer, the producer needs to be registered as a taxable electricity producer to the Swedish tax agency. The commercial producer needs to pay energy tax on all own use and sold electricity from the production. But if the electricity is sold to another electricity supplier energy tax is not paid, if this actor also must pay energy tax. The energy tax is just charged in the last selling stage. (Wallberg, 2014)

The situation is different for private persons that are producers than for a company. In an addition to the energy law it is declared that the Swedish tax agency accept an income of maximum 30 000 SEK from sold electricity from a solar PV system per year to be exempt to be considered a commercial producer and thereof be exempt from energy tax. In practice this means that the addition to the law is only relevant for private persons because most companies have a bigger income from the business and then exceed this limit. (Skatteverket, 2014)

In summary, a company will be exempted to pay energy tax on all produced electricity if it can avoid to be considered as a commercial producer according to what mentioned above. A private household can sell electricity without being obliged to pay energy tax if the compensation is below 30 000 SEK per year.

3.4.3 Grid Benefit Compensation

The entitlement to get grid benefit compensation for feeding electricity to the grid is based on the law about electricity (1994:854, chapter 3 15§). This law says that a producer of electricity has the right to get compensation from the grid company due to reduces of losses in the grid. This compensation differs between different grid companies and where the generation occurs (Näringsdepartementet, 2014).

3.4.4 Tax credit

A law proposal regarding tax credit that is relevant for micro-producers of renewable electricity were submitted by government came into force the first of January 2015. This entitles both private persons and companies a tax credit of 0.6 SEK/kWh (maximum 18000 SEK/year) as long as they fulfil the following criterions.

Firstly the electricity should be fed into the same point as the producer takes out the electricity. Secondly the fuse at the connection point should not exceed 100A. Thirdly the number of kWh fed into the grid during a year must not exceed the amount of purchased kWh. The fourth criteria are that the electricity producer must notify to a grid company that the producer produces renewable electricity. The grid company register the production to the Swedish tax agency (Skatteverket, 2015).

3.4.5 Direct Capital Subsidy

The direct capital subsidy has been active since 2009 and has been extended until 2016 with a budget of 210 million SEK for the years 2013-2016. The subsidy covers from 1 February 35% of the installation cost of PV systems which includes material and labour costs that costs less than 37 000 SEK excluding VAT/kW_p up to 1.2millions per PV system (Gustafsson, 2014). Since there are more applications than funding and the waiting time for the subsidy decision in general is 1-2 years in average has constituted in an upper cap of the Swedish PV market (Lindahl, 2013).

3.4.6 Electricity Certificate

A producer of renewable energy is entitled to electricity certificates from the government for each MWh of produced electricity. The electrical certificates can be sold on the market for electrical certificates to generate an income to the producer. New facilities that are producing renewable energy and that have been taken into operation after the introduction of the electrical certification system are entitled to get electrical certificates for 15 years. The system of electrical certificates has been in use in Sweden since 2003 and aims to increase the amount of renewable energy in the system. All users and suppliers of electricity are obliged to buy a certain quota of electrical certificates in their trade, which creating a demand for the certificates (Energimyndigheten 2, 2013).

Only about one-eighth of the electricity generation from PV systems in Sweden received a green electricity certificate. The major reason for this low share is the due to the placement of the meters that register the electricity produced. The meter is usually placed between the grid and the building, which means that it is only the surplus electricity that generates certificates. With an extra internal meter and an extra yearly measurement fee payment it is possible to get certificates for all production. The extra costs that this implies are for building with small systems not profitable today (Lindahl, 2013).

3.4.7 Guarantees of Origin

Guarantees of origin are intended to provide the energy customer the ability to choose electricity suppliers from an environmental perspective. The state gives the producers these guarantees in form of electronic document for each MWh electricity produced, which shows the type of energy the electricity origins from. These can then be sold on the open market. There is no real market for trading PV guarantees of origin, since the volumes of today are too small. Instead some utility companies buy PV electricity higher than the spot price and offer their customer a given percentage of delivered electricity mix to be from solar (Lindahl, 2013).

3.4.8 Selling Overproduced Electricity

The conditions and the relevance for selling overproduced electricity are different for different circumstances. This study divides the cases as selling electricity as a micro-producer or as a small scale producer. All selling of electricity is liable to pay VAT of 25 %. (Wallberg, 2014)

Micro-producers

To get economical compensation for the electricity that are fed into the grid, the owner of the PV system must find an electricity trading company willing to pay for the excess electricity and establishing a contract. The trend in Sweden is that for micro-producers more and more electricity trading companies offer compensation schemes for buying over-produced electricity. There are various options that a micro-producer can choose between and some of them are listed in IEA PVPs latest report for Sweden and includes net metering on yearly and monthly basis, fixed compensation ranging from Nord Pool spot price to 1.35 SEK/kWh (Energimyndigheten 3, 2014) (Lindahl, 2013). The spot price varies from hour to hour and from year to year. In 2013, this price was in average 39.4 öre/kWh for Sweden (Nord Pool Spot, 2014).

Small Scale Producers

Small scale producers do often not have the same type of compensation schemes as micro-producers. Some large energy trading companies has been studied and the compensation is different for different electricity trading companies but usually consists of the spot price during the hour of trade from Nord Pool spot market plus grid benefit compensation. To sell electricity the producer need to establish a contract with the energy trading company (Fortum, 2015). The producer can also get compensation from selling electrical certificates.

4 ELECTRICITY LOAD PROFILES

This chapter presents the electricity load profiles for the five examined office buildings. In addition to the five studied buildings two additional cases are presented where the district cooling in buildings with district cooling is replaced with electric cooling with a COP of 3. Information and technical data for all the examined buildings can be found in Appendix A. The load curves on an hourly basis are presented for all the examined office building divided into different cooling systems. After this presentation an analysis comparing the office buildings with different cooling systems is made. Finally the electricity load profile for a typical summer day is presented for the office buildings that are further used in the selection of orientations in the simulations.

4.1 Electricity Load Profiles for different Cooling Systems

In this section, the electricity load profiles for all the examined buildings, inclusive the two additional cases mentioned above, divided into their different cooling system is presented. The purpose is to investigate if and how the cooling system affects the electricity load profile. The electricity load profiles for office buildings with district system are firstly described followed by the electricity load profiles for the office buildings with district cooling. Finally one building that uses demand controlled ventilation with free cooling from bore holes in the ground is presented. The air supply with cooled air from outdoor is increasing if there is a cooling demand and if the supply air temperature is too high free cooling from bore holes is used.

4.1.1 District Cooling

The electricity load profiles, together with a brief explanation of its shape, for buildings using district cooling are presented in this section.

A-huset Linköping

The electricity load profile for “A-huset Linköping” is shown in Figure 4.1. “A-huset Linköping” has its highest electricity load during the first and last month of the year, when it can be as high as 250kWh/h. The load profile is the rest of the year more or less constant ranging from 50kWh/h to 160kWh/h. The shape of the load profile can be explained by that the energy system consists of district heating and district cooling i.e. heating and cooling demand do not affect the electricity use. “A-huset Linköping” is the largest building in the study, hence the high energy load compared to the other office buildings. The minimum average base load for the summer half-year for “A-huset Linköping” was estimated to 80 kW. “A-huset Linköping” are used for offices purposes, but also classrooms and laboratories and had 2013 a property electricity use of 24.7$\text{kWh}_{el}/\text{m}^2_{year}$.

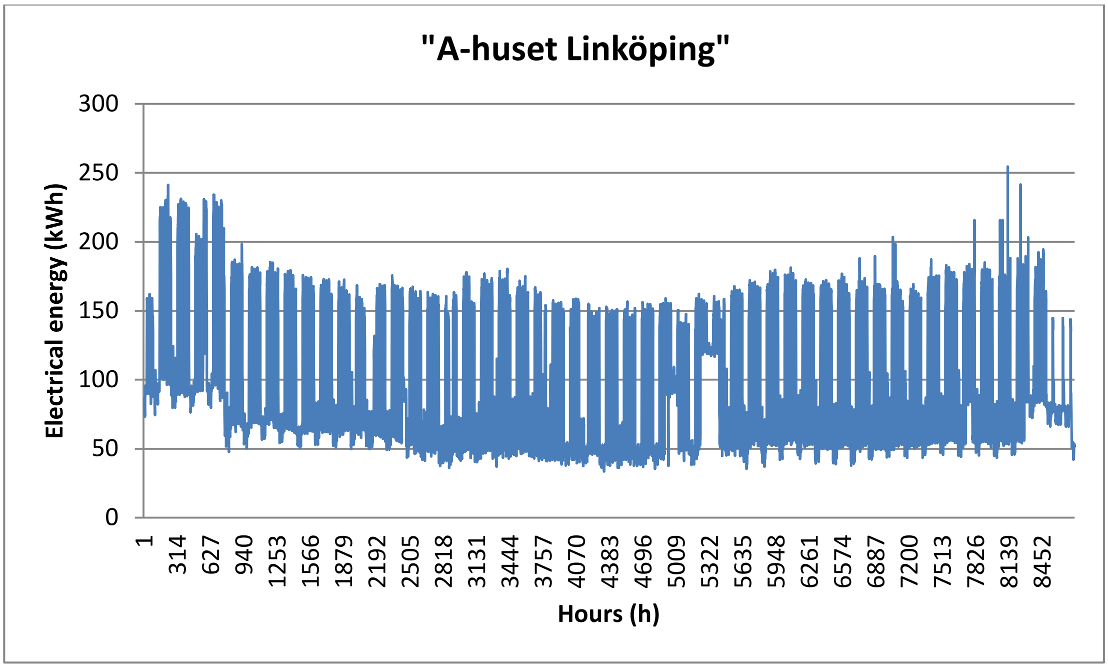


Figure 4.1 – Hourly property electricity load for "A-huset Linköping" during 2013.

Akademiska hus Solna

The electricity load profile for "Akademiska hus Solna" is shown in Figure 4.2. The electricity load for "Akademiska hus Solna" includes both the property electricity and the business electricity. The load is decreased during the summer which might be explained by that the building is not used as normal due to less activity, which is influencing both the property electricity and the operational electricity. "Akademiska hus Solna" is used solely for office purposes and had in 2013 a total electricity use of 77.4kWh$_{el}$/m^2.

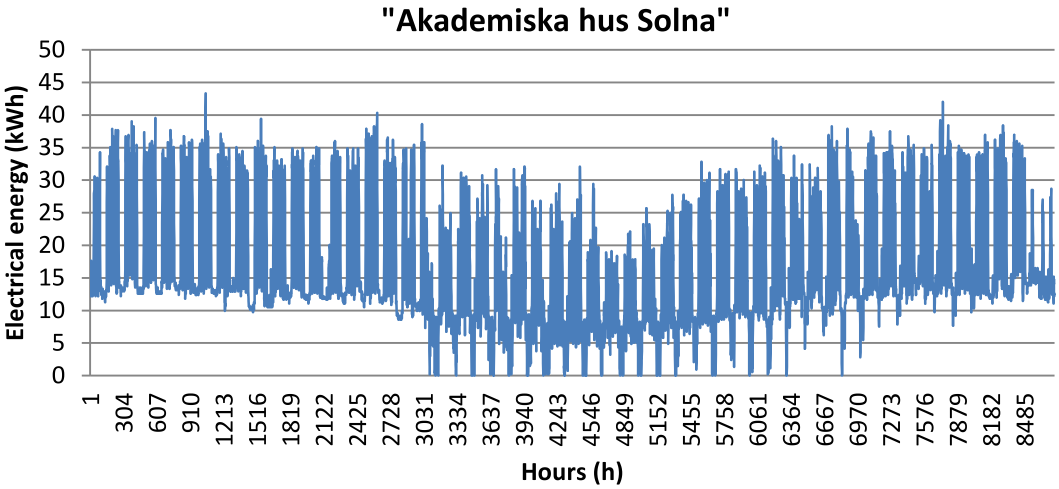


Figure 4.2 – Hourly electricity load during 2013 including property and business electricity for "Akademiska hus Solna".

4.1.2 Electrically driven cooling

The electricity load profiles for buildings using electric cooling inclusive the buildings with replacement of district cooling with electric cooling are presented in this section. The load profiles are presented together with a brief explanation of the shape of the profile.

Vasakronan Uppsala

The electricity load profile for “Vasakronan Uppsala” can be seen in Figure 4.3. The electricity load for “Vasakronan Uppsala” is between 30-45kWh/h during the winter months and is increased during the summer months where the peak can be as high as 100kWh/h. The increased electricity usage during summer is explained by the increased need for cooling. The minimum average base load for the summer half-year for “Vasakronan Uppsala” was around 34 kW. The building is used solely for office purposes and had in 2013 an electricity use of 59.2kWh_{el}/m^2.

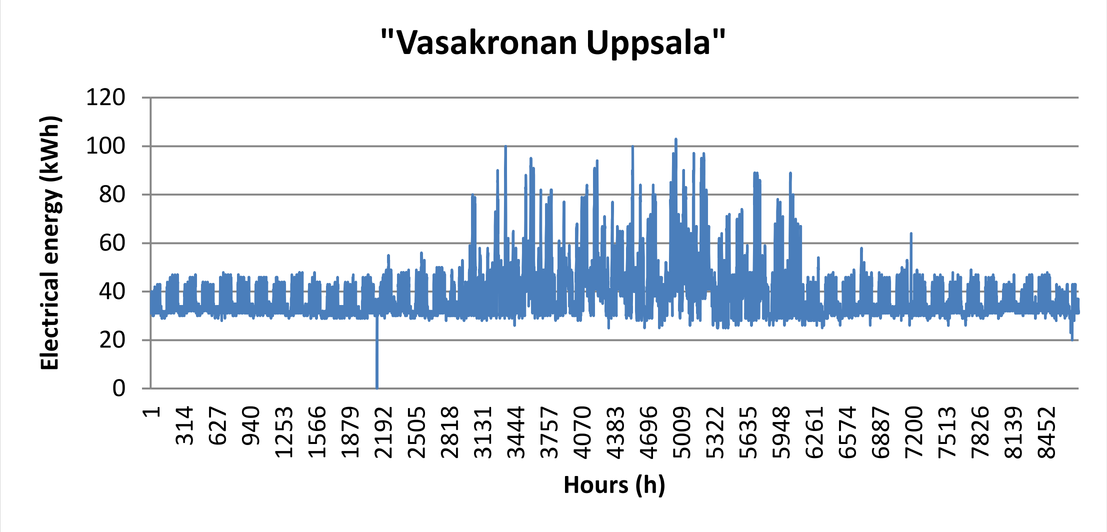


Figure 4.3 – Hourly electricity load for “Vasakronan Uppsala” during 2013.

Bengt Dahlgren Mölndal

The electricity load profile for “Bengt Dahlgren Mölndal” can be seen in Figure 4.4. The electricity use for “Bengt Dahlgren Mölndal” is bigger during winter and summer and smaller during spring and autumn. The biggest electricity use is during the summer months. This electricity load profile can be explained by the use of reversible heat pump in the buildings energy system that are used to produce heat when it is cold and provide cooling when it is warm. The minimum average base load for the summer half-year for “Bengt Dahlgren Mölndal” was around 3.3 kW. The building is used solely for office purposes and had in 2013 an electricity use of 13.6kWh_{el}/m^2, which indicates that Bengt Dahlgren has a high energy performance. It is also classified as a low energy building.

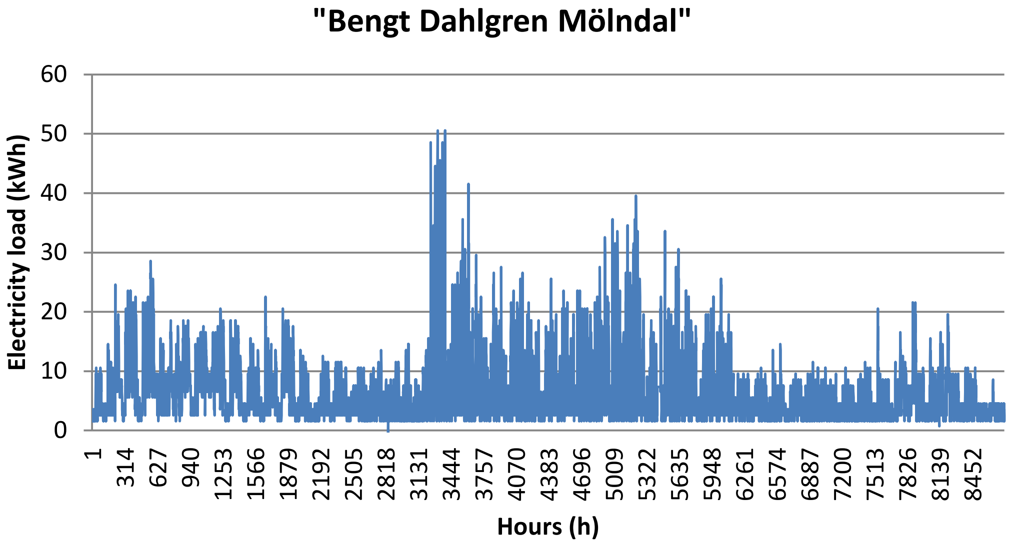


Figure 4.4 – Hourly electricity load for "Bengt Dahlgren Mölndal" during 2013.

A-huset Linköping with Electric Cooling

The electricity load profile for "A-huset Linköping" with electrical cooling can be seen in Figure 4.5. To be able to easily compare how the replacement of cooling system is affecting the load curve, the load curve for district cooling is plotted in blue and the load curve for electric cooling is plotted in red. In figure X it is clearly shown how the electricity demand during summer is increasing with a replaced cooling system. The minimum average base load for the summer half-year for "A-huset Linköping" with electric cooling was around 132 kW. The peak demand is now above 300kWh/h and the electricity use is 36.2kWh$_{el}$/m^2, which corresponds to an increase of 11.5kWh$_{el}$/m^2.

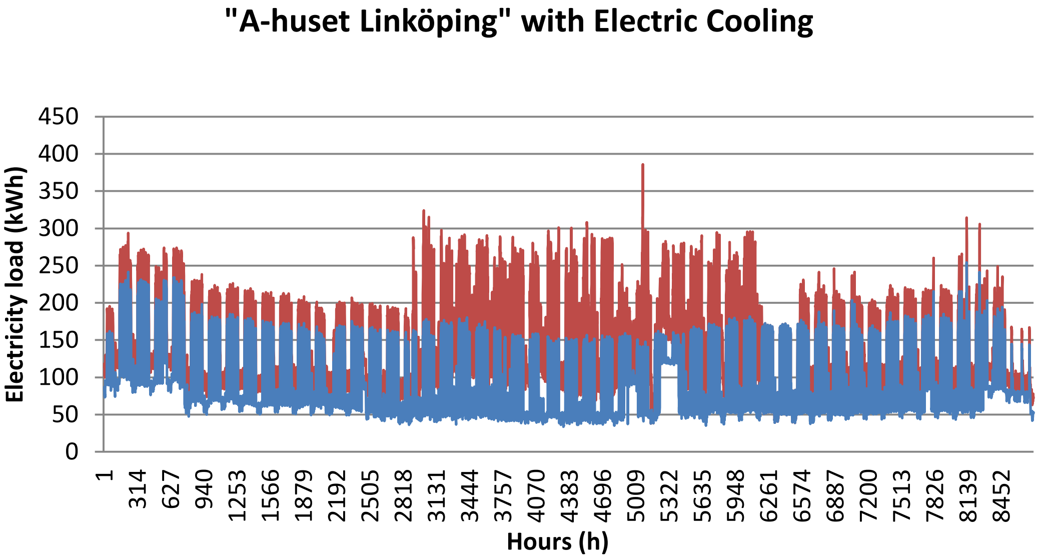


Figure 4.5 – The red curve is the hourly electricity load for "A-huset Linköping" with electric cooling and the blue curve is the original hourly electricity load during 2013.

Akademiska hus Solna with Electric Cooling

The electricity load profile for "Akademiska hus Solna" with electrical cooling can be seen in Figure 4.6. To be able to easily compare how the replacement of cooling system is affecting the load curve the load curve for district cooling is plotted in blue and the load curve for electric cooling is plotted in red. It can be seen in Figure 4.6 that it is not as clear as for "A-huset Linköping" that the electricity demand during summer is increasing with a replaced cooling system. The electricity demand is larger during the whole year with a larger increase during summer. The peak demand is not changed significantly and the electricity use is now 84kWh$_{el}$/m^2, which is an increase of 6.6kWh$_{el}$/m^2.

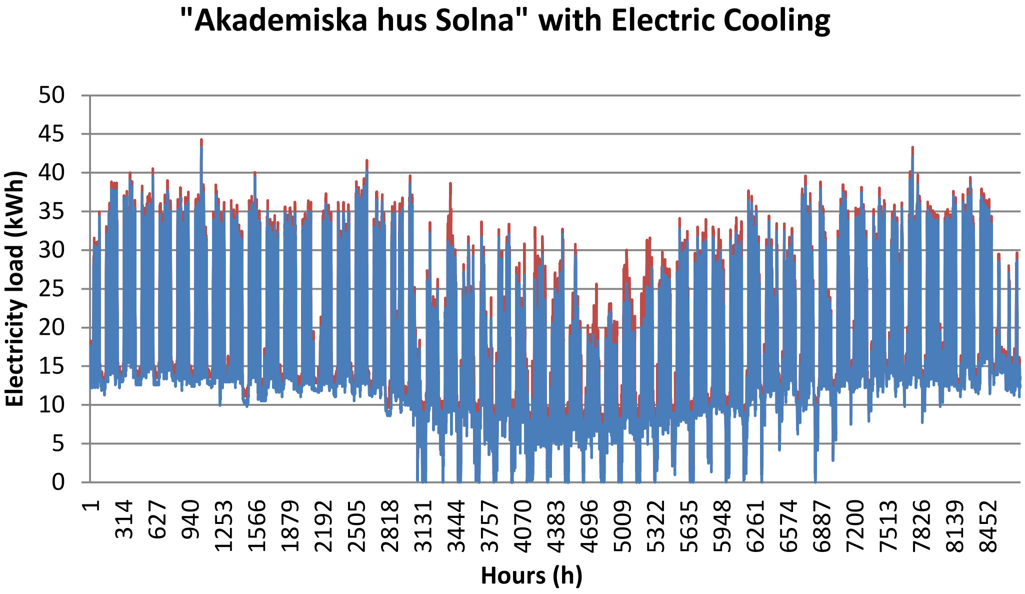


Figure 4.6 – The red curve is the hourly electricity load including property and business electricity for "Akademiska hus Solna" with electric cooling and the blue curve is the original hourly electricity load including property and business electricity during 2013.

4.1.3 Free Cooling System

The only office building with free cooling is "Väla Gård Helsingborg". The electricity load profile which includes both property and operational electricity for the office building can be seen in Figure 4.7. "Väla Gård Helsingborg" uses demand controlled ventilation to increase the supply air from outdoor with cooled air when the cooling demand is increasing. If the supply air is too high, free cooling from bore holes in the ground that lowering the air temperature in the cooling coils is used and hence electricity is not directly used for cooling but only for pump and fans. The load profile can be explained by an increased electricity use during winter months from the ground source heat pump and apart from that has a rather even electricity use during the year. The electricity use is 15.784kWh$_{el}$/m^2, whereof the property electricity was measured to around 7kWh$_{el}$/m^2.

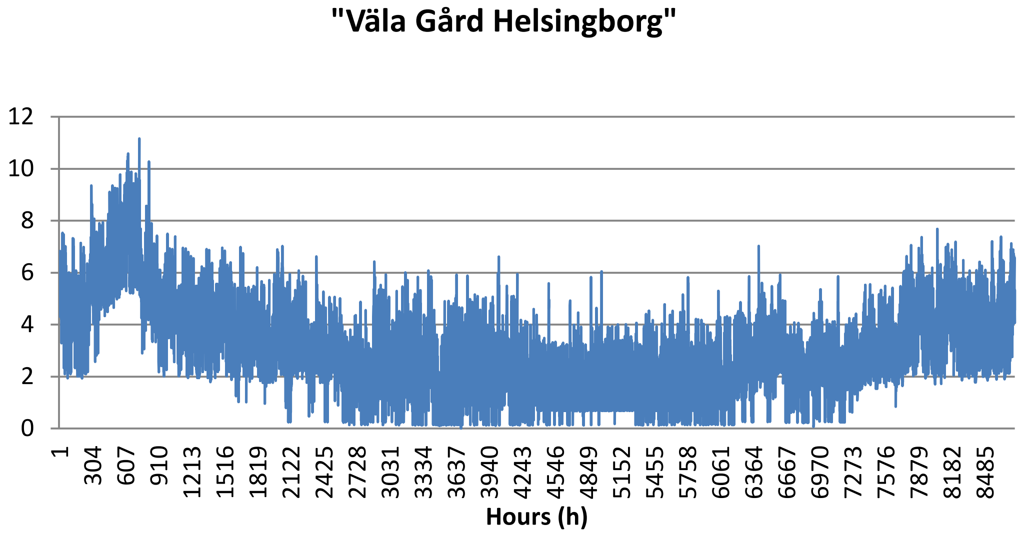


Figure 4.7 – Hourly electricity load including property and business electricity for "Väla Gård Helsingborg" during 2013/2014.

4.2 Comparison of Electricity Load Profiles

The Figure 4.8 below shows the average electricity load for the time 06:00-18:00 per month in kWh/h and it is possible to see the trends in electricity use during the year. The purpose of this summarised graph is to get an overview of how the electricity use differs during the year for buildings with different cooling systems. The Figure 4.8 below shows that that the office buildings with district cooling have a drop in electricity use during the summer, while the buildings with electrical cooling have an increase in energy use during summer. The shape of the curve for A-huset Linköping looks rather unregularly. "A-huset Linköping" uses both district heating and district cooling and the shape could be explained by an uneven activity in the building. "A-huset Linköping" that uses electricity for cooling has a significant higher electricity demand during summer. The same significant increase in electricity demand cannot be seen in "Akademiska hus Solna" using electricity for cooling. The property and operational electricity demand is low for "Akademiska hus Solna" during summer (according to Figure 4.2), indicates that the activity is low during summer. This could explain why the graph shows that the electricity demand does not seem to increase noticeably while using electricity for cooling.

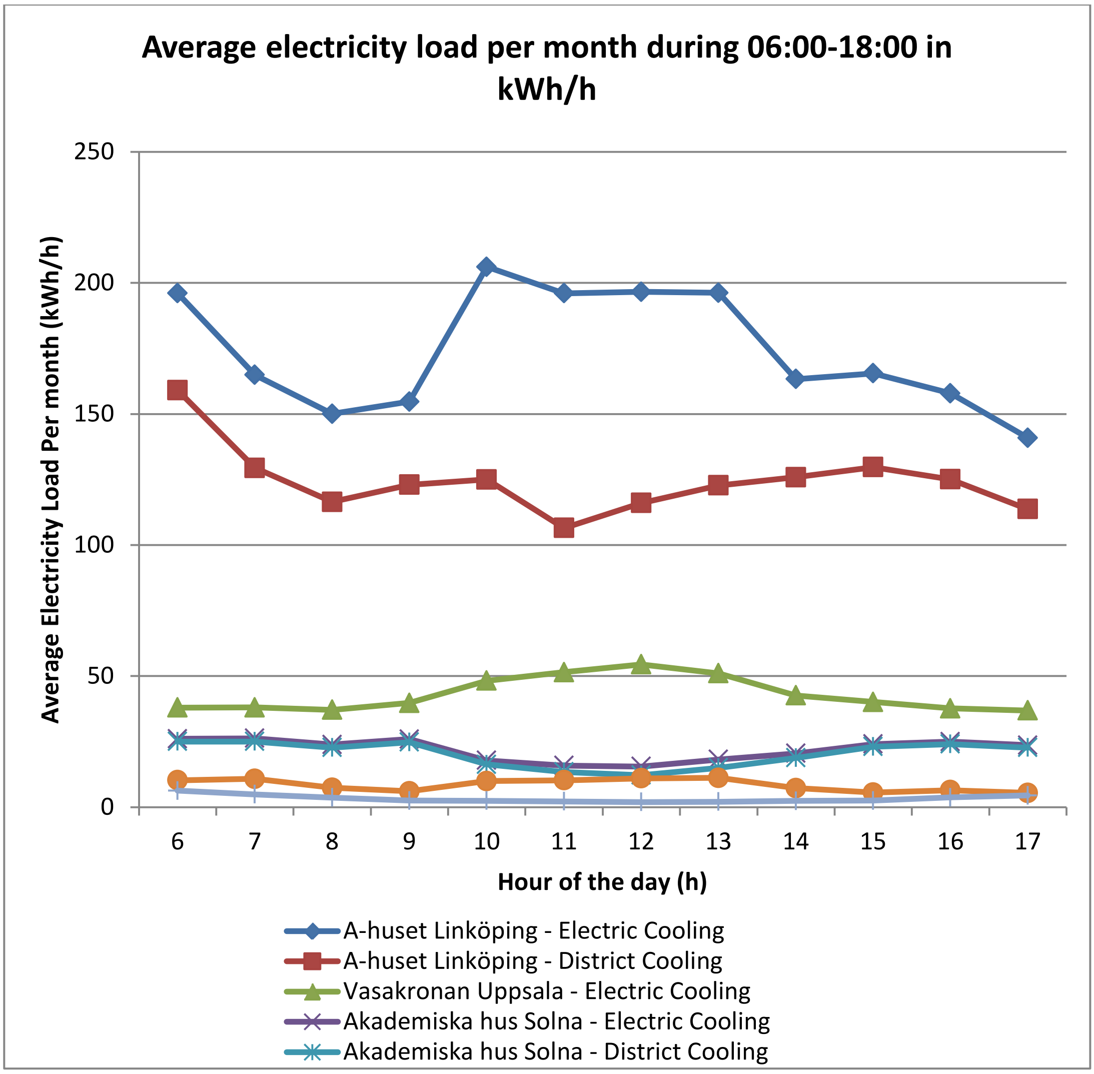


Figure 4.8 – Average electricity load per month during the hours 06:00-18:00 given in kWh/h for the different electricity load profiles studied.

4.3 Average Load Profiles for One Day in July

The load profiles for an average day in July are presented in Figure 4.9 for the examined buildings which PV systems are simulated on later in this thesis. The graph is scaled by the peak use during the day to be able to compare the buildings. An average day in July is studied to investigate how the electrical load is distributed during the hours of the day when the potential electricity generation from a solar PV system is large. The purpose of the graph is to analyze how the load is varying during the day to identify possible relevant orientation and slopes for a PV installation to better match the electricity generation with the load curve. The graph shows the load profile for the office buildings “Uppsala Vasakronan”, “A-huset Linköping”, “A-huset Linköping” with electrical cooling and “Bengt Dahlgren Mölndal”. The X-axis shows the hour of the day and the Y-axis shows the average electricity use scaled with the maximum use.

The load profiles for an average day in July is different for the examined office buildings as could be seen in the figure. There is no detailed information available of how the buildings are used during the days. Only the cooling and heating need and type of cooling and heating system is available. “Bengt Dahlgren Mölndal” has a significant peak during the morning hours and a peak during the day. The peak for all the office buildings is occurring at almost the same time, which is in the afternoon around 16:00. After this peak the demand is reduced quickly, while the load before the peak is higher for a longer period of time, which starting point is different for the buildings but is around 07:00. The PV system should therefore not only be oriented regarding the peak, the load before and after the peak is important to consider.

To increase the load match for “Vasakronan Uppsala” and “Bengt Dahlgren” a way could be to place the panels so that they receive more insolation during afternoon instead, which means an azimuth between south and west. “A-huset Linköping” has unlike to the other buildings an even energy use during the whole day with a significantly lower base load compared to its peak load. A possible relevant orientation to increase the matching could in this case be to place the panels towards south to get the insolation to the panels concentrated in the middle of the day. But the shape of the load curve shows that there is no significant peak during daytime but a fairly even electricity use during the day. Considering this, a relevant orientation to get a good match could be to place the panels towards east and west, to get a higher insolation during mornings and afternoons and in turn flattening out the peak production during the day. “A-huset Linköping” will get a peak in electricity use in the afternoon if using electricity for cooling instead of district cooling. In this case a better load match could be reached by orienting the panels, so that they can receive a larger insolation during the afternoons. Similarly to “Vasakronan Uppsala” and “Bengt Dahlgren”, the orientation would be between south and west, but preferably more to the south compared to the other PV system due to the larger load in the mornings.

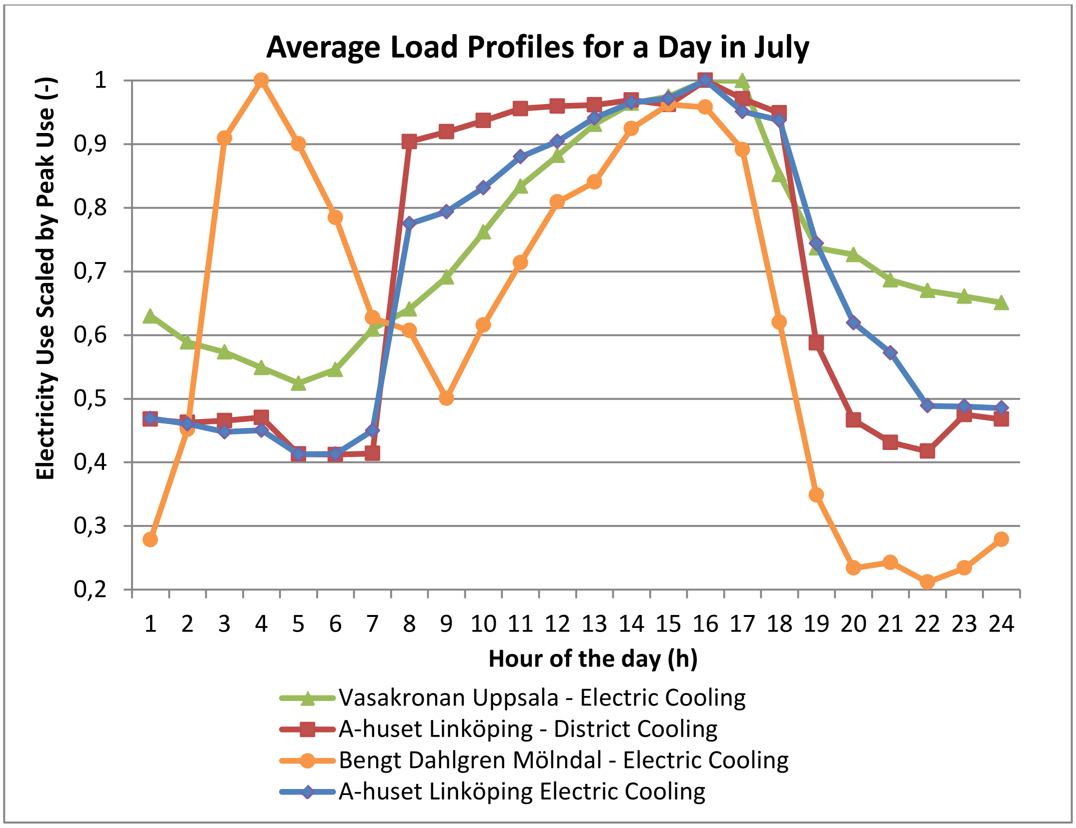


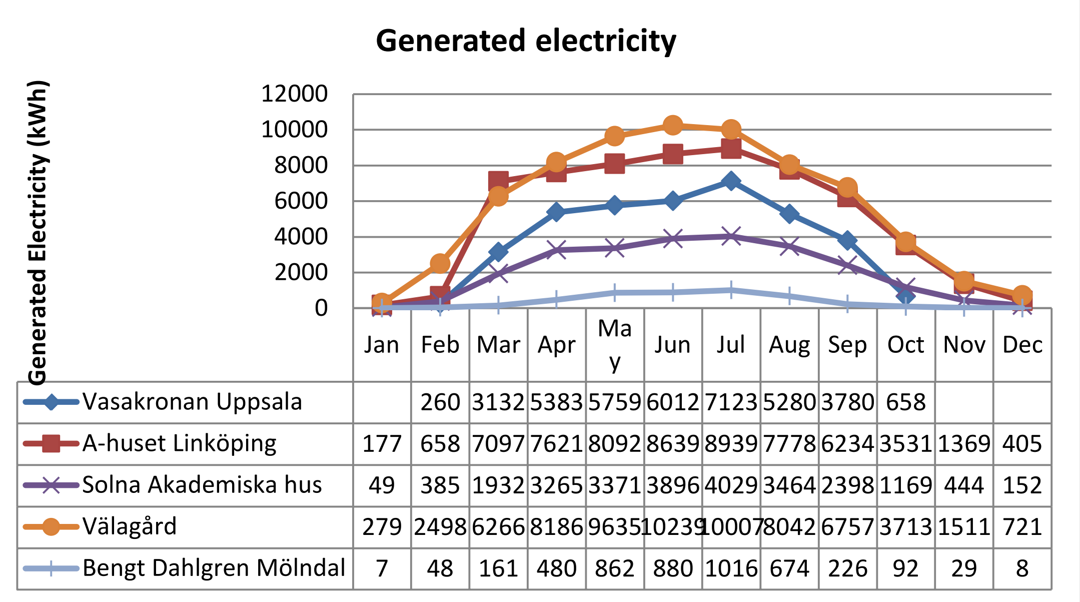
Figure 4.9 – Average load profiles for a day in July for those buildings and electricity load profiles that solar PV systems are simulated for.

5 Existing Solar PV Systems

In this chapter, existing solar PV systems installed on the studied office buildings are described and analysed in terms of coverage and overproduction. The first section of this chapter gives information about the PV systems installations on the five office buildings. This section also includes the electricity generated from the solar PV system for the year the load match is investigated for. The second section presents the result for the load match in terms of coverage and overproduction. In addition to the five studied buildings the load match for two additional cases are presented, where the district cooling in buildings with district cooling is replaced with electric cooling.

5.1 Electricity Generation from Existing PV Systems

The office buildings have different sizes of PV systems that are installed with different slopes and azimuth orientation, which have been installed different years. The installations of the PV systems take the roof conditions into account, where roof with orientations between southeast and southwest are used. The slope of the PV systems is for the buildings with pitched roofs the same as the slope of the roof. “Bengt Dahlgren Mölndal” is the only building with flat roof, where the PV systems have been selected to have a slope of 20°. Why this slope was chosen is not known. For “Vasakronan Uppsala”, “Akademiska hus Solna” and “Väla Gård Helsingborg” the PV systems filled the suitable roof areas within the range of orientations described above. For example, “Vasakronan Uppsala” filled the roof in the direction to the southeast, but left area around obstacles to avoid shading and the roofs to east and west without PV installations. “A-huset Linköping” and “Bengt Dahlgren Mölndal” did not fill the whole area that was suitable for having a PV system. It was approximated that less than 50% of the saw-toothed area is used for PV systems. The solar PV system for each building regarding sizes, azimuth, slope, generation per year and generation per kW$_p$ installed are presented in table 1. The generated electricity per month for each building is presented in Figure 5.1.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Vasakronan Uppsala		260	3132	5383	5759	6012	7123	5280	3780	658		
A-huset Linköping	177	658	7097	7621	8092	8639	8939	7778	6234	3531	1369	405
Solna Akademiska hus	49	385	1932	3265	3371	3896	4029	3464	2398	1169	444	152
Välagård	279	2498	6266	8186	9635	10239	10007	8042	6757	3713	1511	721
Bengt Dahlgren Mölndal	7	48	161	480	862	880	1016	674	226	92	29	8

Figure 5.1 – Generated electricity for different years from the existing PV systems given per month for the five office buildings.

Table 5-1

	System Size (kW_p)	Azimuth	Slope (°)	Generation per year (kWh)	Generation per kW_p
Vasakronan Uppsala	43	11° towards east	8	37 387	869
A-huset Linköping	65	0°	30	60 541	931
Solna Akademiska hus	26	south - southwest	9	24 555	944
Välagård	70	45° to west	45	67 857	969
Bengt Dahlgren Mölndal	7.05	0°	20	4 483	636

According to table 1 and Figure 5.1, intuitively, is the generated electricity higher for the larger system and is lower for smaller system size by size. The office buildings also have different locations, which influence the incoming global and diffuse radiation.

5.2 Matching of Electricity Load and Electricity Generation

The matching of load and electricity generation in terms of coverage and overproduction is presented in this section for each building. The coverage and overproduction is expressed on an hourly basis.

5.2.1 Vasakronan Uppsala

The data for "Vasakronan Uppsala" was only available from the installation date which was 19th of February 2014 till mid-October when the data was provided; therefore there are no values for January and not for the last months of the year. The matching of load and generation can be seen in Figure 5.2. "Vasakronan Uppsala" has a total coverage and overproduction of 12 % and 1 % respectively. The coverage is highest in April when it is 20% and is decreasing every month after that, which can be explained by the larger increase of electricity load than electricity generation. The overproduction is largest in June, when 2.5% of the electricity generated is fed into the grid. Since the input data is not for a whole year it is most likely that the coverage will be decreased when including the final winter months in the calculations. "Vasakronan Uppsala" has a significant increase in electricity demand during summer (according to Figure 4.3), and a quite large PV system of 43kW$_p$. The overproduction is small; this can be explained by the significant increase in demand the same months when the electricity generation is big.

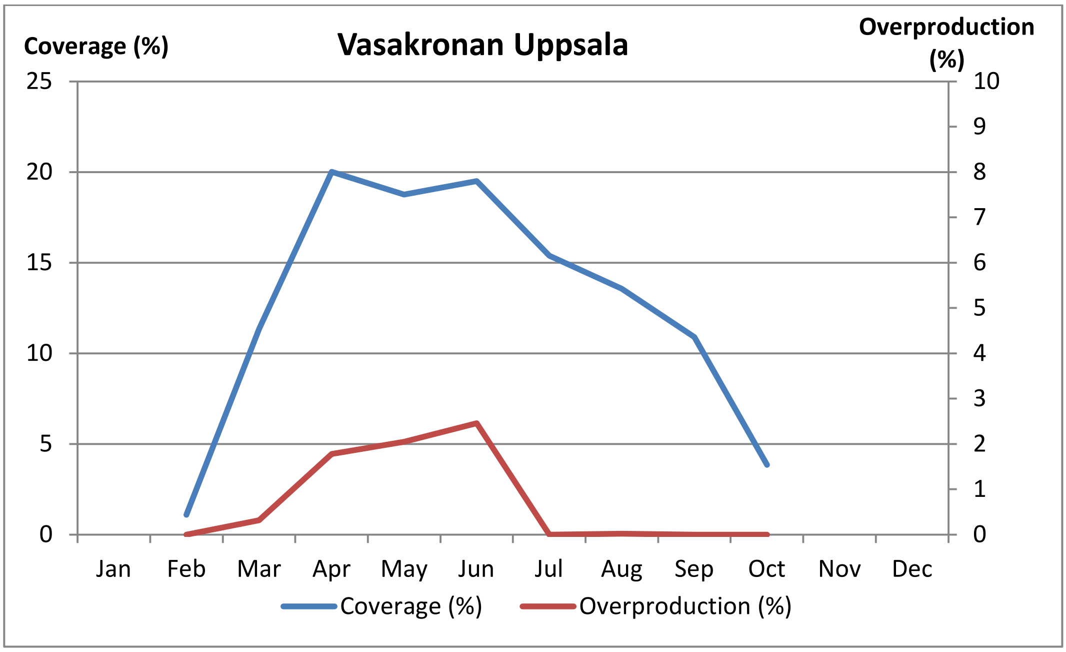


Figure 5.2 – Coverage (blue) and overproduction (red) for "Vasakronan Uppsala" per month.

5.2.2 A-huset Linköping with District Cooling

The matching of load curve and solar electricity generation was made for the year 2013 and can be seen in Figure 5.3. "A-huset Linköping" has a total coverage and overproduction of 7.1 % and less than 1 % respectively. The coverage was between

March and September equal or above 9% and had a maximum in June of 15.1%. There was only overproduction in May to July, where the highest overproduction occurred in July. “A-huset Linköping” has high electricity use (according to Figure 4.1) and the solar PV system is small considering the demand. This can explain why the coverage is fairly low with almost no overproduction.

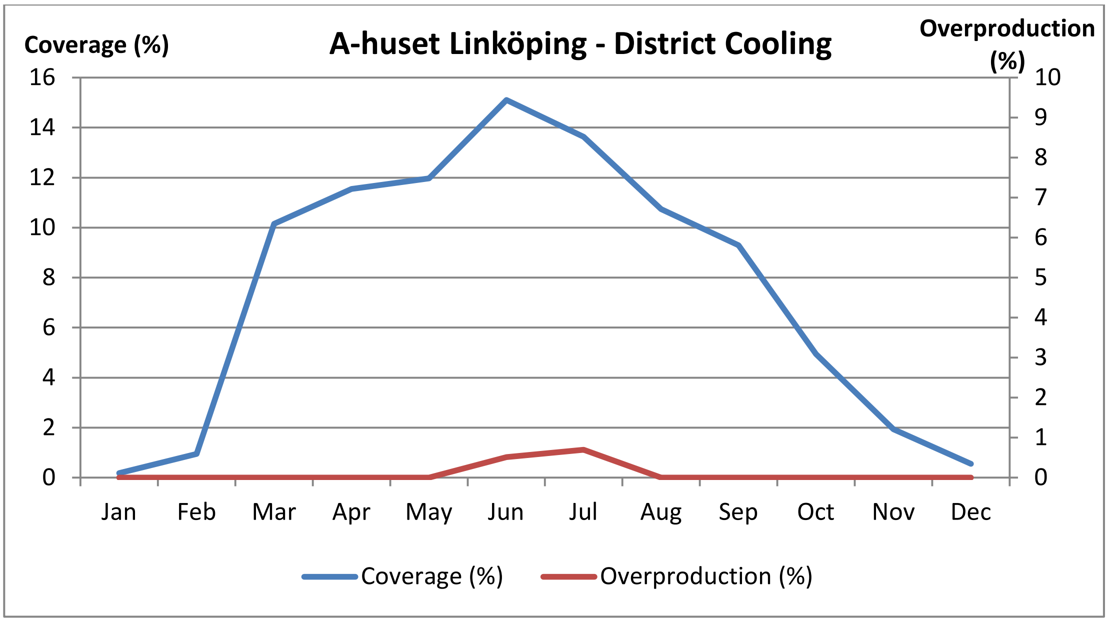


Figure 5.3 - Coverage (blue) and overproduction (red) for “A-huset Linköping” with district cooling per month.

5.2.3 A-huset Linköping with Electric Cooling

If the cooling system is replaced from district cooling to electric cooling, the coverage for A-huset is decreasing and the small overproduction is close to zero. The matching of load and generation can be seen in Figure 5.4. The annual coverage is decreasing from 7.1 % to 4.9 % and the annual overproduction is decreasing from 0.2 to 0%. This could be explained by a significant increase in electricity demand (as can be seen in Figure 4.5) during summer and an already small overproduction.

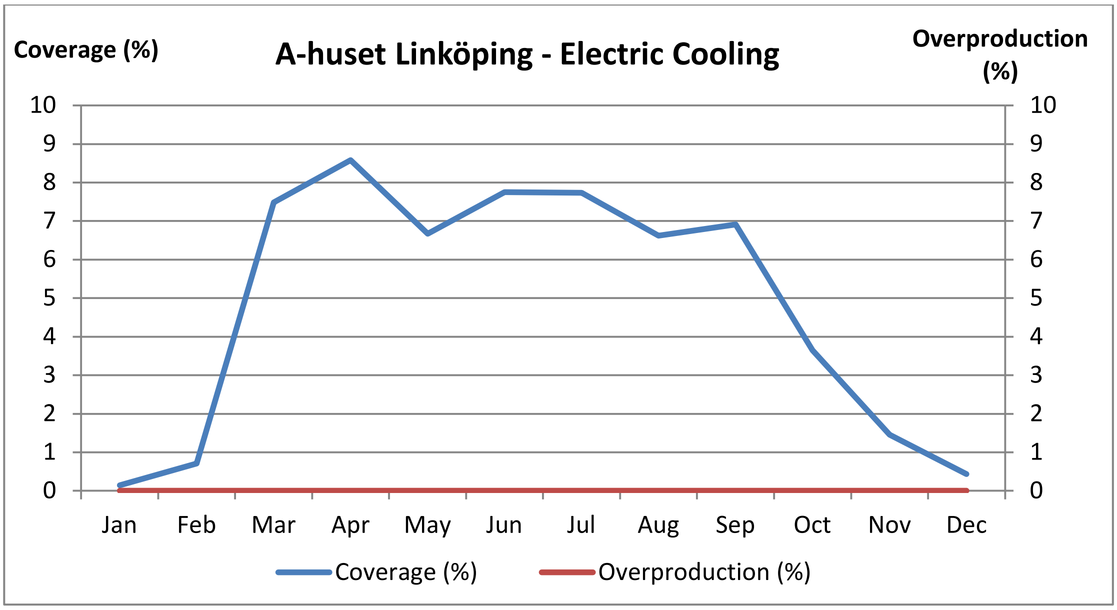


Figure 5.4 - Coverage (blue) and overproduction (red) for "A-huset Linköping" with electric cooling system per month.

5.2.4 "Akademiska hus Solna" with District Cooling

The matching of load curve and solar electricity generation was made for the period May 2013 – May 2014 because availability of data. The matching of load and generation can be seen in Figure 5.5. "Akademiska hus Solna" has a total coverage and overproduction of 13 % and less than 27 % respectively. The electricity load is decreasing during the summer months (according to Figure 4.2), which leads to a high overproduction.

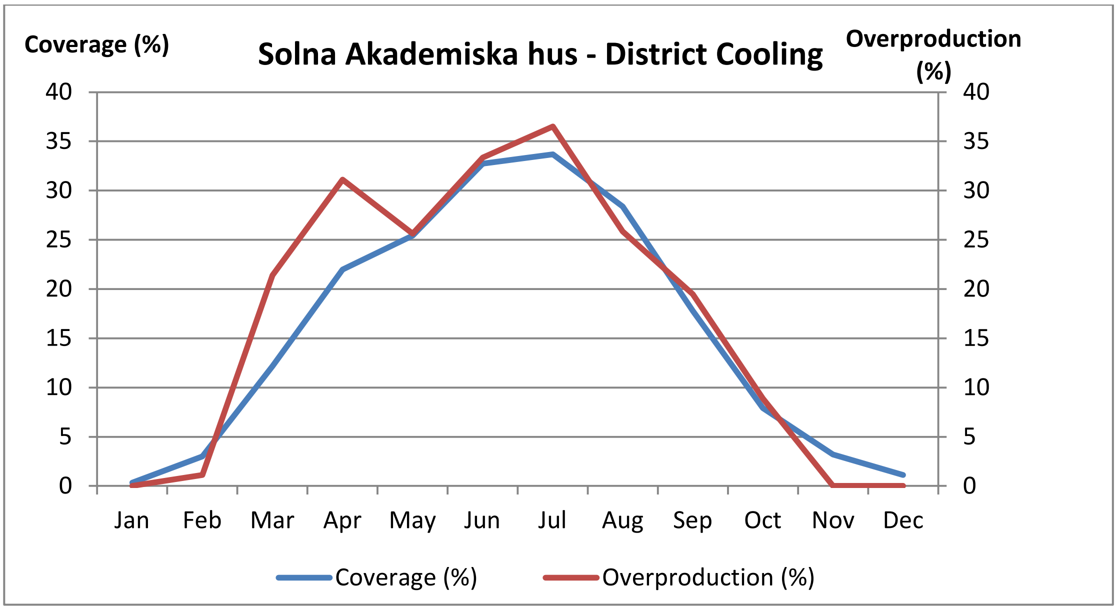


Figure 5.5 - Coverage (blue) and overproduction (red) for "Akademiska hus Solna" with district cooling per month.

5.2.5 Akademiska hus Solna with Electric Cooling

For “Akademiska hus Solna” is the coverage remaining the same and the overproduction is decreasing if the district cooling is replaced with electric cooling. The matching of load and generation can be seen in Figure 5.6. The annual coverage is 13.2 % with district cooling and 13.3 with electric cooling. The annual overproduction is decreasing from 27% to 20%. This could be explained by that the increase in electricity demand in summer partly is covered by the earlier overproduction. The increase in electricity demand where a bigger part of the earlier overproduction is covered leads to a smaller overproduction but the total coverage is not affected much.

“Akademiska hus Solna” is located on a campus area with an own electricity grid which makes it possible for the overproduced electricity to be transferred to other buildings that consumes the electricity. This is resulting in that no overproduction is fed into the grid.

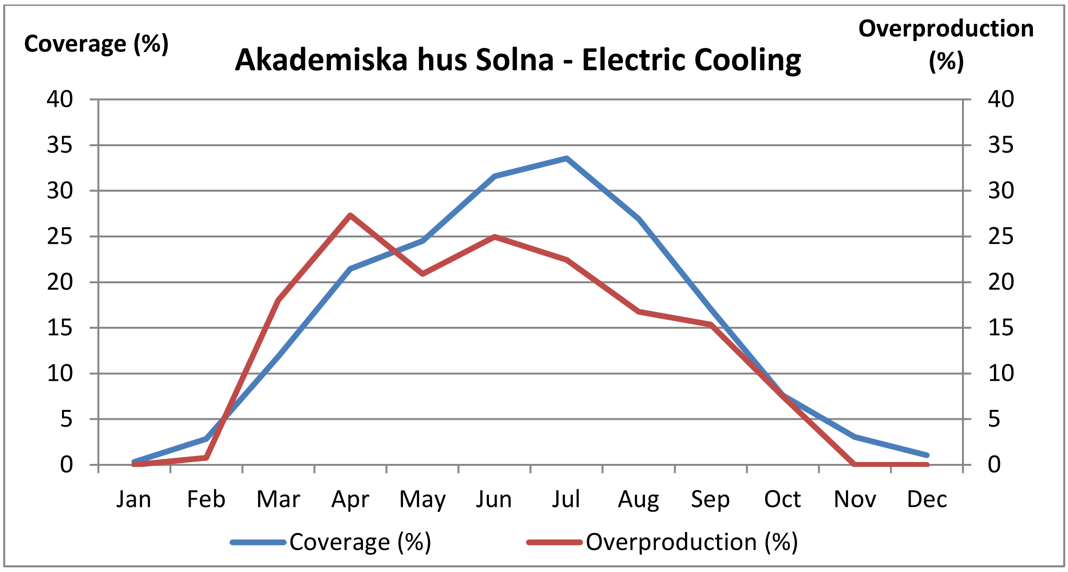


Figure 5.6 – Coverage (blue) and overproduction (red) for “Akademiska hus Solna” with electric cooling per month.

5.2.6 Väla Gård Helsingborg

The matching of load curve and solar electricity generation was made for the period May 2013 – May 2014 because availability of data. “Väla Gård Helsingborg” has a total coverage and overproduction of 33 % and 86 % respectively. The matching of load and generation can be seen in Figure 5.7. “Väla Gård Helsingborg” has a large solar PV system compared to the building needs (according to Figure 4.7 and Figure 5.1) which leads to a big overproduction. The overproduction is big from March till October and the biggest overproduction for one month is 91 % and occurs in July. The matching is made on an hourly basis which makes the coverage low considering the large overproduction. A coverage calculated on an annual basis is over 240 %. “Väla Gård Helsingborg” is designed to be a plus energy building that generates more electricity on an annual basis than it uses. The building is also the only of the studied building that sells their overproduced electricity, whether this is economically feasible is not known.

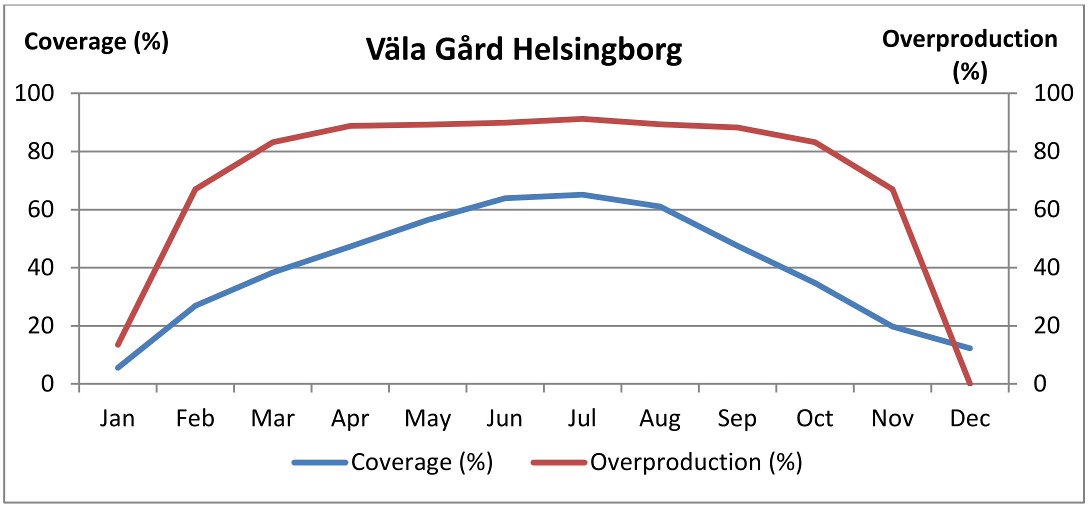


Figure 5.7 – Coverage (blue) and overproduction (red) for "Väla Gård Helsingborg" per month.

5.2.7 Bengt Dahlgren Mölndal

The matching of load curve and solar electricity generation was made for the year 2013 and can be seen in Figure 5.8. "Bengt Dahlgren Mölndal" has a total coverage and overproduction of 7.8 % and 0.05 % respectively. The solar PV system at "Bengt Dahlgren Mölndal" is small considering the size of the building and just 0.05 % of the total generated electricity is fed to the grid. The biggest overproduction for one month is 0.4 % and occurs in April. This is a month with low electricity need and fairly high electricity production. The biggest coverage for one month is 16.2 % and occurs in June. June is also a month with low electricity demand (according to Figure 4.4) which make the coverage higher.

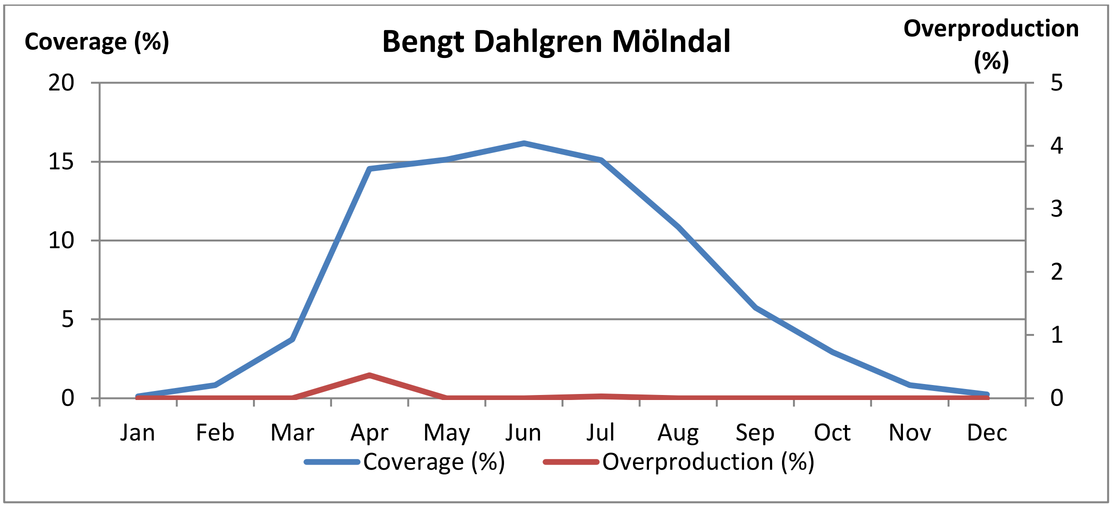


Figure 5.8 – Coverage (blue) and overproduction (red) for "Bengt Dahlgren Mölndal"per month.

6 Input Parameters for Simulated PV Systems

In this chapter, the input parameters that are used in the thesis is described and motivated. The preconditions for a solar PV system used for office buildings are also presented. It is divided into two sections, where the first part treats the technical parameters used for the simulations of PV systems. The second part describes firstly the preconditions given by legislations that are applicable for installations of PV systems on office buildings. These conditions influences what economical input parameters that are included in the calculations. The second part gives also all the input parameters that are used in the calculations of a number of economic decision tools.

6.1 Technical parameters for simulation of PV systems

There were several parameters that had to be chosen before making the simulations. These were location and orientation of the PV system and a reference PV system. The simulations that were made in Polysun used a reference PV system corresponding to a typical PV system in 2014. The components that had to be selected were type of module, type of inverter and other technical parameters. The size and configuration of the reference PV system had to be selected as well.

6.1.1 Location

The location was set according to the office buildings longitude and latitude. This in turn means that weather data is used for the exact location, which is preferred, since this gives a more precise evaluation of the matching of electricity load and generated electricity. The weather data was chosen to be for a normal year as the PV system will be evaluated for its whole lifetime. It was assumed that there were no shading effects from the surroundings and obstacles on the roof.

6.1.2 Orientation

By studying the electricity profile for an average day in July (Figure 4.9) it was chosen to simulate a system for each building in direction to the south, since it maximizes the generation and generates electricity during the hours when there is activity in the office. An east-west configuration of a PV system was made and simulated for one of the office building which was “A-huset Linköping”. In this configuration the generation during the day is evened out and there is no high peak at noon, which could increase the load matching since A-huset had an even load during the day.

The simulations were made with the slopes of 0°, 15°, 30° and 45° for both the south and the east-west configurations. The slope angles were varied to enable the analyses of the impact on load match in terms of coverage and overproduction.

6.1.3 Reference PV system

The reference solar PV system used consisted of modules from the manufacturer Yingli Green Energy Holding Co. Ltd. which for 2012 and 2013 was the world's largest producer of modules (IEA-PVPS, 2013). The polycrystalline module YL260P-29b was chosen since it has an efficiency of 15.917%, which is close to the average of polycrystalline cells in 2014 that was 16%. The module has a length of 1.65m and a width of 0.99m corresponding to an area of about 1.6m^2 and a power of 260W, which is close to the typical size in 2014 which was 255W.Yingli has a 10-year limited product warranty and promise a limited power warranty for 10 years at 91.2% of the minimal rated power output and 25 years at 80.7% of the minimal rated power output (Yingli, 2015). The annual degradation for the 25 year time period was calculated to 0.854%.

The reference system used the inverter Sunny Tripower STP 9000TL-20 from SMA which has an efficiency of 97.6%. This efficiency is higher than the common that is 95-97% but lower than the highest possible which is 98%. Inverters from SMA are commonly used in Sweden and SMA was ranked as the number one market leader of the PV inverter suppliers in 2013 (IHS, 2014).

The technical parameters were kept to initial default values except the degradation, which was set to 0%. The parameters and their corresponding value are listed in Table 6.1.

The decrease in performance due to the degradation is changing the output of the system and this leads to a decrease in self-consumed and overproduced electricity from year to year, which in turn influences the economic performance. The degradation was therefore set to zero in the software, since the simulation result generated would be a yearly average for the whole lifetime. The degradation is treated in among the economical inputs in section 6.2.2.

Table 6-1 – Technical Parameters That Were Used As the Default Value in the Simulation Software

Parameter	Value
Soiling	2%
Cable losses	4%
Mismatching	4%
Degradation	0%
Rear ventilation	Medium (Poor, Medium, Good)
System	Fixed system

6.1.4 Size and Configuration of Reference PV Systems

A PV system according to the specifications of the reference system was simulated for a size of 20 kW_p in the south direction using two inverters where there were two strings with 20 modules and two with 19 modules. Figure 6.1 shows the two strings connected in parallel in series of N modules, which in this configuration were 20 or 19 modules connected to an inverter. The east-west configurations were simulated by implementing two roofs and simulate $10kW_p$ in the east direction and $10kW_p$ in the west direction. In this simulation one inverter was used for two strings with 19 modules in each. The two PV systems of 10 kW were separate. Adding the generation by hour for the two orientations the total generation was calculated for the east-west case.

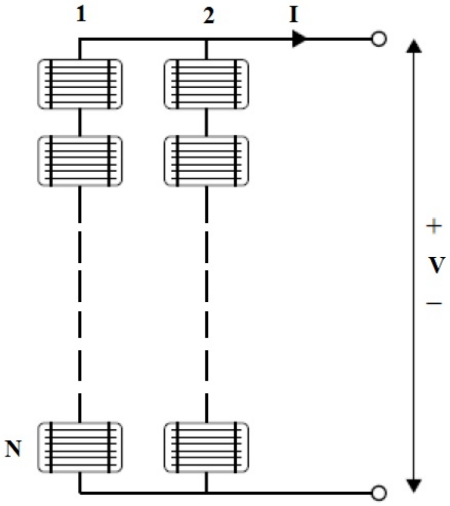


Figure 6.1 – Circuit diagram of PV system; two strings with N modules in each string. The figure is based on (Soteris, 2009)

6.2 Parameters for Economic Evaluation

Office buildings have in general a main fuse bigger than 63A (and bigger than 100A), and are therefore not counting as a micro-producer. Instead, companies are usually considered to be small scale producers and need then to pay a fee for feeding electricity to the grid and will usually only get paid the spot price from Nord Pool spot market, electrical certificates and a grid benefit compensation. Companies that decide to sell overproduced electricity from a solar PV system at their property are today, in most cases, obliged to pay energy tax on all the self-consumed electricity. This is because they are considered to be commercial producers of electricity once they start to sell. With this background it was chosen not to sell the overproduced electricity, since it was assumed that the main part of the electricity generated will be for self-consumption.

There is still some income for the overproduced electricity, which is the grid benefit compensation that the grid company must pay. Also, the electricity certificate brings an income for all the generated electricity. These and a number of other parameters have been estimated for the economical calculations. The parameters are presented in the following order: system life span, discount rate, solar PV system price, inverter cost, operation and maintenance cost, electricity prices, feed in cost, price of green electricity certificate, and grid benefit compensation. This section aims to explain how the values of the parameters were chosen.

6.2.1 System Life Span

A fundamental parameter for the economic evaluation is the system life span. The estimation of the life span of a PV system is crucial for the economical outcome, as could be seen in Figure 2.2. From the literature study it was known that the life span for a solar PV system could be longer than 25 years in Swedish conditions. It was also observed that the technical lifetime used in other investigations was 30 years (Arvind Chel, 2009). A Swedish study also showed that 25 years life time can be assumed to be underestimated (Hedström, 2007). In this study is a life time of 30 year used.

6.2.2 Degradation

The degradation was set to 0.854% which is what the guarantee stated was the maximum. The calculation of the effect from degradation was made by calculating the hourly output year for year while including an annual percentage of the degradation. The overproduction and self-consumption was then calculate on an hourly basis and summed up for every year.

6.2.3 Discount rate

The discount rate is a rate that is used during investment evaluations and reflects the required rate of return but also the risk that is associated with the investment. The discount rate can be real or nominal (Martland, 2011). The real discount rate is the discount rate without taking the inflation into account, while the nominal takes inflation into account. For all calculations of the economic evaluation tools used in this thesis the real discount rates was used and therefore were all the other values in the study without inflation. The level of the real discount rate was set to 6 % in the base case during this study. The discount rate is chosen from a property owner point of view and aims to be comparable to the discount rate for other investments.

6.2.4 Initial Investment Cost of a Solar PV System

It was observed that the prices per installed kW are different for different system sizes. The price is decreasing with increasing size and the price difference is bigger between small systems than for bigger systems. The estimated price for different sizes of PV systems in this thesis is based on a combination between statistics and prices from different Swedish retailers.

Turnkey prices for different system sizes provided by the Swedish Energy Agency (Lindahl, 2013) and the Bundesverband Solarwirtschaftin (BSW) (BSW-Solar, 2014) in Germany was used to investigate the current price level. The prices from the Swedish Energy Agency were available for 2013 and the presented prices were 16 SEK/W_p for systems up to 10 kW_p, 15 SEK/W_p for systems from 10 kW_p to 250 kW_p and 14 SEK/W_p for system sizes over 250 kW_p. The statistics from BSW were available for the third quarter in 2014 and the presented price was 12.6 SEK/W_p (1324 Euro/kW_p) for systems between 10 kW_p and 100 kW_p.

The transition in price between different system sizes is in reality not clearly defined jumps but rather smoother transition between prices from smaller to larger systems. To get a picture of how the prices are changing, the prices from Swedish retailers were collected. Prices were collected for different system sizes and a graph was plotted by an interpolation between the given values. The given prices were given including VAT and without installation costs. The prices were therefore modified to exclude VAT and the installation cost was estimated to be 25 % of the system cost based on a report from the European Commission (Jäger-Waldau, 2013), which was added to the total system costs.

The graph was used to get an approximately shape of the curve of how the prices are changing. The graph was verified and modified to represent the price level according to the statistic. The mean price level in the final graph is 16 SEK/W_p for system sizes between 5-10 kW_p, and 13.4 SEK/W_p for systems sizes between 10-100 kW_p which is a value between the values given in the statistic for the corresponding sizes. An assumption was made that the price decrease is flattening out for bigger system sizes and that the prices for 200 kW_p and more have the same price, 12 SEK/$W_{p.}$ The price of 12 SEK/W_p is motivated by real examples for bigger systems installed in Sweden: 172 kW_p for 12.6 SEK/W_p and 312 kW_p for 11.5 SEK/ W_p in 2013 (Stridh, 2014).

The graph of the total investment cost per kWp is illustrated in Figure 6.1.

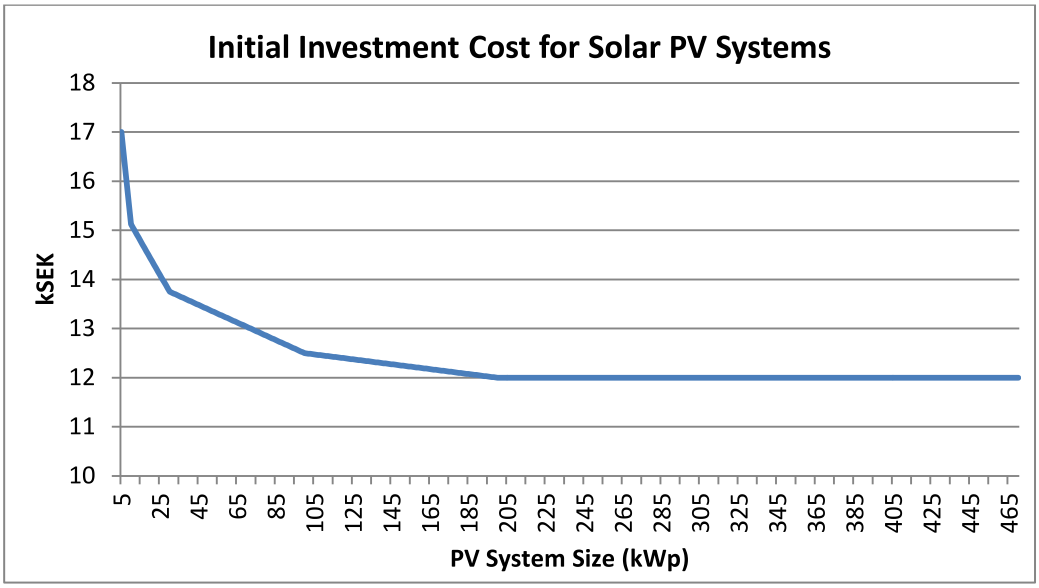


Figure 6.2 – Initial investment cost for a solar PV system given in kSEK for PV system sizes ranging from 5 to 470 kW_p.

6.2.5 Inverter Cost

Average inverter price differs between rated power and whether it is manufactured in EU or in China. The price is decreasing with increased rated power and is cheaper for inverters manufactured in China. It was assumed that the inverter was manufactured within EU. Wholesale prices for a rated power of 10-20kW was in a range from 120-180Euro/kW and for 20-30kW 100-130Euro/kW (GmbH, 2014). Since it is whole sale price it was assumed a price of 1500SEK/kW. This assumption was also based on the fact that a report made by the European Commission assumed 150Euro/kW$_p$ (Jäger-Waldau, 2013). Even though the cost for a new inverter will occur 15 years after the investment, it was assumed to have a value based on today’s market conditions since the market development is hard to predict.

6.2.6 Operation and Maintenance Costs

The operation and maintenance (O&M) costs are an uncertain post in the economic evaluation. No definition of what actual costs the O&M includes could be clarified from the literature study. Imaginable cost that is associated with O&M could be payment to a service technician to check the facility and surrounding equipment to detect potential faults in the system etc. The costs for running a solar PV system are low. The cost for operation and maintenance over the system life time is a rough estimation and it has been varied between 0.5 and 1.5 % of the investment cost per year for other studies (Jäger-Waldau, 2013) (Paradis 1, 2013). The higher value also included the cost for future replacement of inverters. The O&M costs used in the economic calculations were chosen to be 0.75% of the investment cost per year.

6.2.7 Electricity Prices

The development of the price of purchased electricity in the future is an important parameter when it comes to evaluate the profitability of a solar PV investment. The economic model for a solar PV investment calculates for many years in the future, and it is important that the estimation of the future electricity price is reasonable. The analysis of the future electricity market is complex and it is not obvious how the price will develop. One way to estimate the future electricity price is to assume an annual percentage of increase of the price. An analysis of the spot price from Nord Pool spot market showed however that this kind of assumption would not be reasonable.

The conclusion that was made was that to increase the accuracy in this economical evaluation, a model to predict the future electricity price should be used. Instead of using an annual percentage of increase to predict price, the price development for the electricity used in this study is based on three different scenarios drafted by Nelson Sommerfeldt (PhD student at applies thermodynamics and refrigeration at KTH). The different scenarios used comprise a development of the price that is low, middle or high. The electricity price development are predicted using historical trends and current market conditions for the near-term prices, while normative scenarios are used for mid- to long term prices. The shape of the curves are based on that near term energy systems stays in balance and keeps the prices low and that when the nuclear electricity generation is replaced it is by cheap, middle and expensive technologies. The curves are also based on a fundamental economic theory that people find replacement when products get too expensive. The estimated spot price and bought price year for year from Nelson´s study is used from a table directly in the economic model for this study. In the base case for the economic evaluation the middle price development is used where the values used are yearly average values to simplify the calculations.

6.2.8 Feed in Cost

The cost for feeding electricity to the grid for producers that are bigger than micro-producers differs for different grid companies in Sweden. The feed in cost used in this study corresponds to the actual feed in cost charged by the grid companies for the different locations of the examined office buildings. The feed in cost for the area for the office building A-huset Linköping was found to be 3600SEK/year exclusive VAT for a main fuse larger than 63A and with a max generated power of 1500kW (Linköping, 2013). The feed in cost for the area for Vasakronan Uppsala was found to be 2400SEK/year exclusive VAT, which was valid for a generation of max 300kW (Vattenfall 3, 2014). For this cost the size of the main fuse was not defined. The feed in cost for the area for Bengt Dahlgren in Mölndal was found to be 3000 SEK/year. The specified feed in costs is assumed to be the same over the whole economical life time of the PV system.

6.2.9 Price of Green Electricity Certificate

The price for electricity certificates has been in average 230 SEK/MWh the last 10 years. But a bit lower the last three years, with a value around 200 SEK/MWh. The price of green electricity certificate was in this study set to a fixed value of 200 SEK/MWh for the 15 years it is given (Energimyndigheten 4, 2015).

6.2.10 Grid Benefit Compensation

Grid benefit compensation differs for different grid companies operating in the regions where the office buildings are located. The value of the grid benefit compensation used in this study corresponds to the actual value that is paid where the reference is located. For “A-huset Linköping” in Linköping the grid benefit compensation was found to be 3.5 öre/kWh (Linköping, 2014). For “Vasakronan Uppsala” in Uppsala the value was found to be 4.1 öre/kWh (Vattenfall 3, 2014). The value for “Bengt Dahlgren Mölndal” in Mölndal was found to be 3 öre/kWh (Dahte, 2014). The value was assumed to be constant through the lifetime of the PV system, since it is unknown how it will change in the long term.

7 Simulations Result and Economic Evaluation

This chapter shows the result for load match in terms of coverage and overproduction for different sizes of PV systems and corresponding result for the economical evaluation tools of investments for the three office buildings that was further studied. The NPV is presented for all PV system sizes simulated, while PBP and CSCE are presented only for the economical optimum of NPV and the optimal PV system for the office buildings taking the available roof area into account. The chapter is divided into four parts, where the result for “Vasakronan Uppsala” is presented first followed by “A-huset Linköping” with district cooling, “A-huset Linköping” with electricity for cooling and “Bengt Dahlgren Mölndal”. To get an overview of the results for the different office buildings a summary is given in the end of this chapter.

7.1 Vasakronan Uppsala

The simulation for Vasakronan Uppsala was made for one angle of azimuth; south. The maximum size of the solar PV system is limited by the available roof area and the needed area is different for different slopes of the panels. The maximum size of a solar PV system assuming a flat roof with same dimensions and no obstacles is for Vasakronan Uppsala approximately; 168kW$_p$ for 0°, 88kW$_p$ for 15°, 82kW$_p$ for 30° and 47kW$_p$ for 45°.

Figure 7.1 shows how the coverage and overproduction differs with different PV system sizes for the different slopes for a PV system facing south. The coverage and overproduction is influenced by the same parameters, the electricity generation and the electricity load profile. When the coverage is decreasing the overproduction is increasing. The coverage is increasing with a constant rate up to a PV system size of 60kW$_p$, with a larger size the rate of increase is decreasing. Up to a PV system size of 60kW$_p$ there is zero or very low overproduction. From 60kW$_p$ the overproduction is increasing steadily for all slope angles. The larger the angle the larger is the overproduction for each system size.

Figure 7.2 shows how the net present value differs with PV system sizes for the different slopes for a PV system with a discount rate of 6%. It can be seen in the figure that a size above 20kW$_p$ and below 130kW$_p$ is profitable for the slopes of 30° and 45°, since the NPV is positive for these systems. PV systems with a slope of 15° are profitable above 30kW$_p$ and below 120kWp. A PV system with the slope angle of 0° never becomes profitable. For a slope angle of 45°, 30° and 15° the net present value has its maximum at a PV system size of 80kW$_p$, with the values 155 000 SEK, 134 000 SEK and 51 000 SEK respectively. It can be seen that the result for slope angles of 45° and 30° does not differ significantly. It only differs about 24 000 SEK at the largest for PV system sizes between 30kW$_p$ and 90kW$_p$.

For the economically optimum size of the system the CSCE is 1.02 SEK/kWh and the PBP is 22.1 years for a slope angle of 45°. For this system the coverage is 25.9% and the overproduction is 5.4 %. This PV system uses 188% of the existing roof area. With the dimensions and size of the roof for the existing office building the PV system would maximum be around 47kW$_p$ for a 45° slope, which corresponds to a NPV of approximately 104 000 SEK. The maximum size for a system with a slope of 30° is 82kW$_p$ and the optimum NPV value was 80kW$_p$ and has a higher NPV than the system of 47kW$_p$, means that this system is the most profitable taking the roof dimensions and size into account. This system has coverage of 25.4% and an overproduction of 4.1%. The PBP is 22.6 years and CSCE is 1.03 SEK/kWh.

The payback time is ranging from 21.4 years to no payback for the different PV system sizes. If the net present value is negative it means that the investments will never payback during the PV systems lifetime, hence gives no payback time. The shortest payback time of 21.4 years is found for system size of 60kW$_p$ and 45° slope angle. The payback time is increasing with decreased slope angle.

The cost of self-consumed electricity (CSCE) is ranging between 1.01 to 1.16 SEK/kWh for the systems that have a positive NPV. The lowest CSCE of 1.01 SEK/kWh is found for system size of 60kW$_p$ and 45° slope angle.

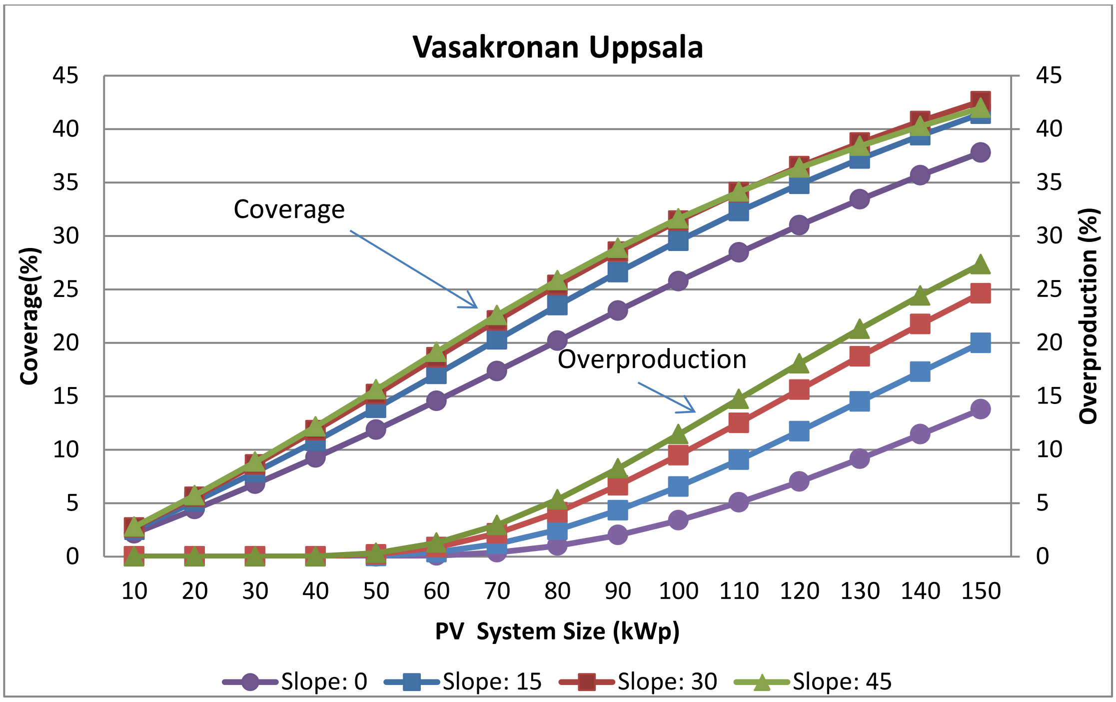


Figure 7.1 - Coverage and overproduction for different system sizes ranging from 10-150kWp for the office building, “Vasakronan Uppsala”, with a PV system facing south.

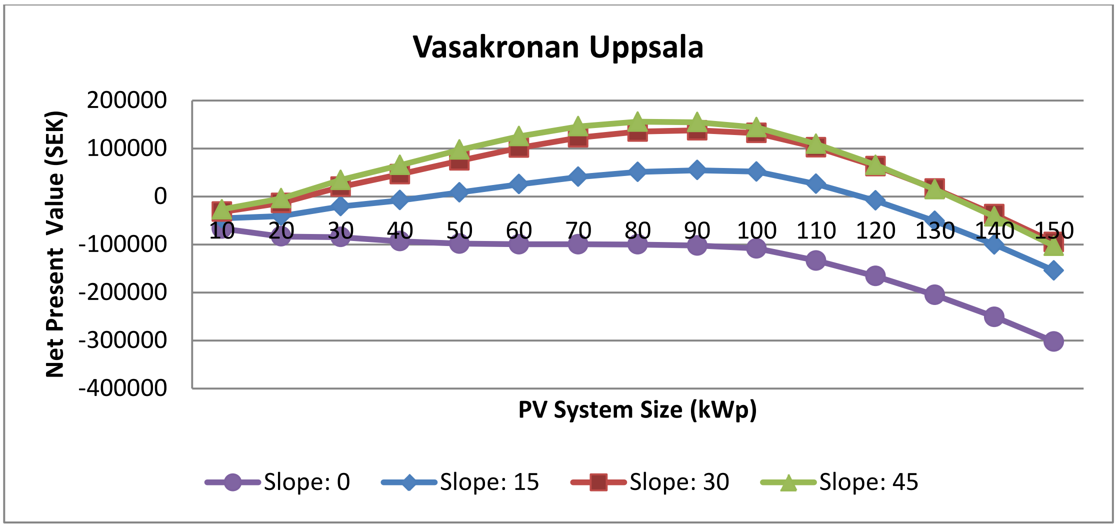


Figure 7.2 - Net present value for different system sizes ranging from 10-150kW$_p$ for the office building, “Vasakronan Uppsala”, with a PV system facing south.

7.2 A-huset Linköping with District Cooling

The simulation for A-huset Linköping with district cooling was made for two different angles of azimuth; one case where all panels are facing south and one case where half of the panels are facing east and half of the panels are facing west. The case with east and west configuration was made only for this building, due to its shape of the daily electricity load profile. The simulation for A-huset Linköping with electricity for cooling was made for PV systems facing south. The maximum size of the solar PV system is limited by the available roof area and the needed area is different for different slopes of the panels. The maximum size of a solar PV system facing south is for A-huset approximately; 2400 kW_p for 0°, 1170 kW_p for 15°, 730 kW_p for 30° and 570 kW_p for 45°. The maximum size of a solar PV system for an east –west configuration was not calculated for A-huset due to the generated economic result for this case.

7.2.1 PV System Facing South

Figure 7.3 presents the coverage and the overproduction for different PV system sizes ranging from 20 to 300 kW_p. The coverage is more or less increasing with a constant rate up to a size of 100kW_p and the rate of increase is from this value slightly decreasing. The overproduction is zero or close to zero for the size up to 100kW_p PV system size and is after this increasing steadily.

Figure 7.4 shows how the net present value differs with PV system sizes for the different slopes for a PV system. It can be seen in the figure that a size of above approximately 30kW_p and some sizes larger than 130kW_p are profitable for the slopes of 30° and 45°. PV systems with a slope of 15° are profitable above approximately 50 kWp and below 300kW_p. A PV system with the slope angle of 0° never becomes profitable. For a slope angle of 45°and 30° the net present value has its maximum at a PV system size of 220kW_p, with the values 461 000 SEK and 413 000 SEK respectively. For a slope angle of 15° the net present value has its maximum at a PV system size of 200kW_p, which results in a value of 225 000 SEK. The profitability is higher for higher slope angles. The PV system size of 220kW_p with a slope of 45° corresponds to coverage of 26.9%, an overproduction of 8% and uses 39% of the available roof. This system has a payback period of 21.5 years and a CSCE of 0.99SEK/kWh. With the dimensions and size of the roof for the existing office building the PV system would maximum be around 566kW_p for a slope of 45°, which means that the optimum system fits on the existing roof.

The payback time is ranging from 21 years to no payback time for the different PV systems. The shortest payback time of 21 years is found for the system size 140 kW_p and 45° slope angle. The payback time is shortest for all slope angles with a system size between 120 and 200 kW_p.

The cost of self-consumed electricity (CSCE) is ranging between 0.98 to 1.16 SEK/kWh for the systems with positive net present value. The lowest CSCE is found for system sizes between 120-200 kW_p and 45° slope angle.

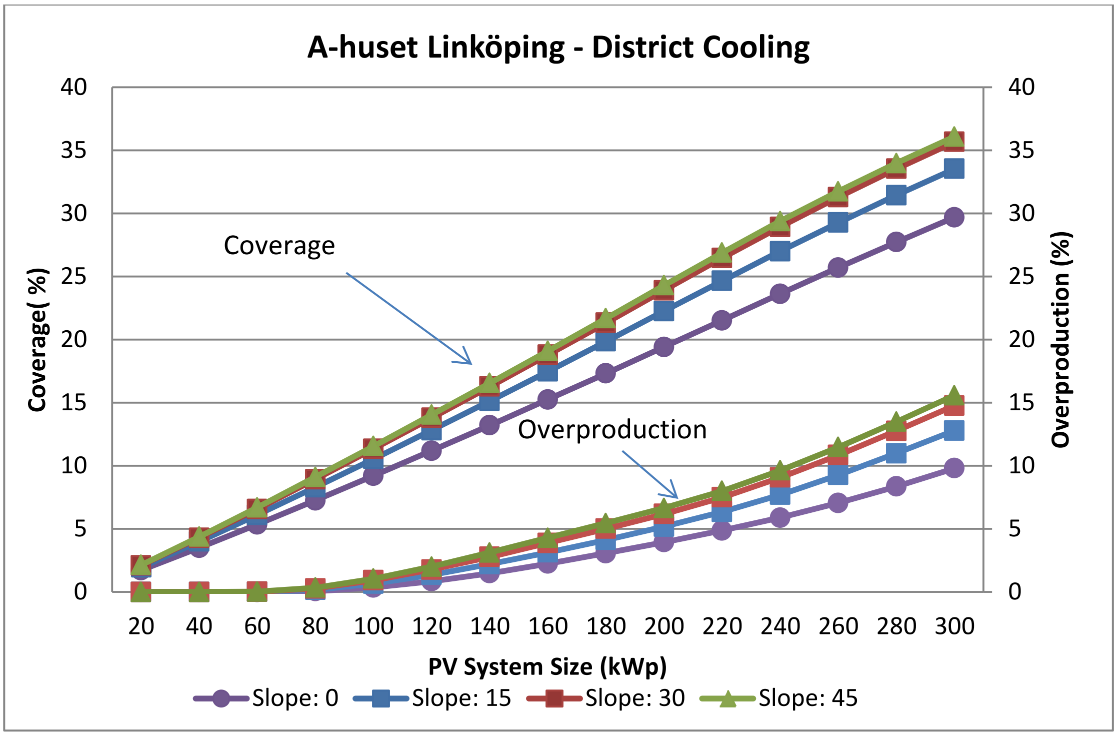


Figure 7.3 - Coverage and overproduction for different system sizes ranging from 20-300kW$_p$ for the office building, “A-huset Linköping”, with a PV system facing south.

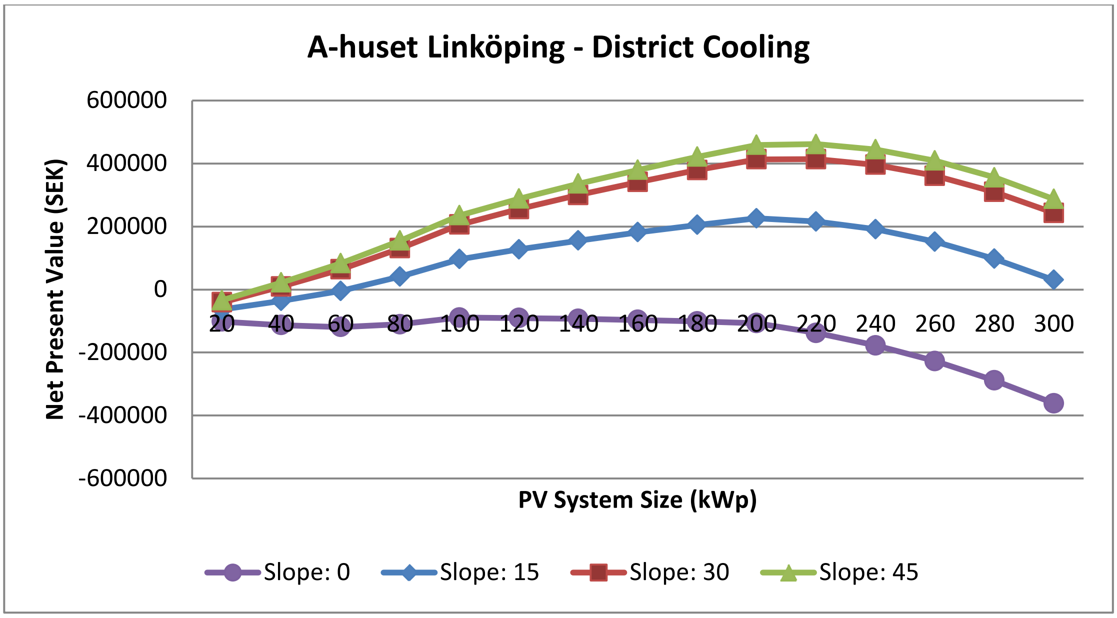


Figure 7.4 - Net present value for different PV system sizes ranging from 20-300kW$_p$ for the office building, “A-huset Linköping”, with a PV system facing south.

7.2.2 PV System Facing East and West

Figure 7.5 shows the coverage and the overproduction for different PV system sizes ranging from 20 to 300kW$_p$. Compared to the south facing system the coverage and overproduction is lower with a lower slope the larger is the coverage and the overproduction.

Figure 7.6 shows how the net present value differs with PV system sizes for the different slopes for a PV system. The east and west facing system resulted, compared to the south facing system, in a significantly lower economic performance and never reach profitability in terms of net present value during default economic assumptions. The net present value is decreasing for all investigated slopes with increased system size. A lower slope angle gives a slightly better result than a bigger slope angle. None of the simulated system gives a payback time during the lifetime of the system. The CSCE is ranging between 1.23 and 1.77 SEK/kWh. The highest CSCE is found for small system and 45° slope angle and the small CSCE is found for system sizes between 180-200kW$_p$ and 15° slope angle.

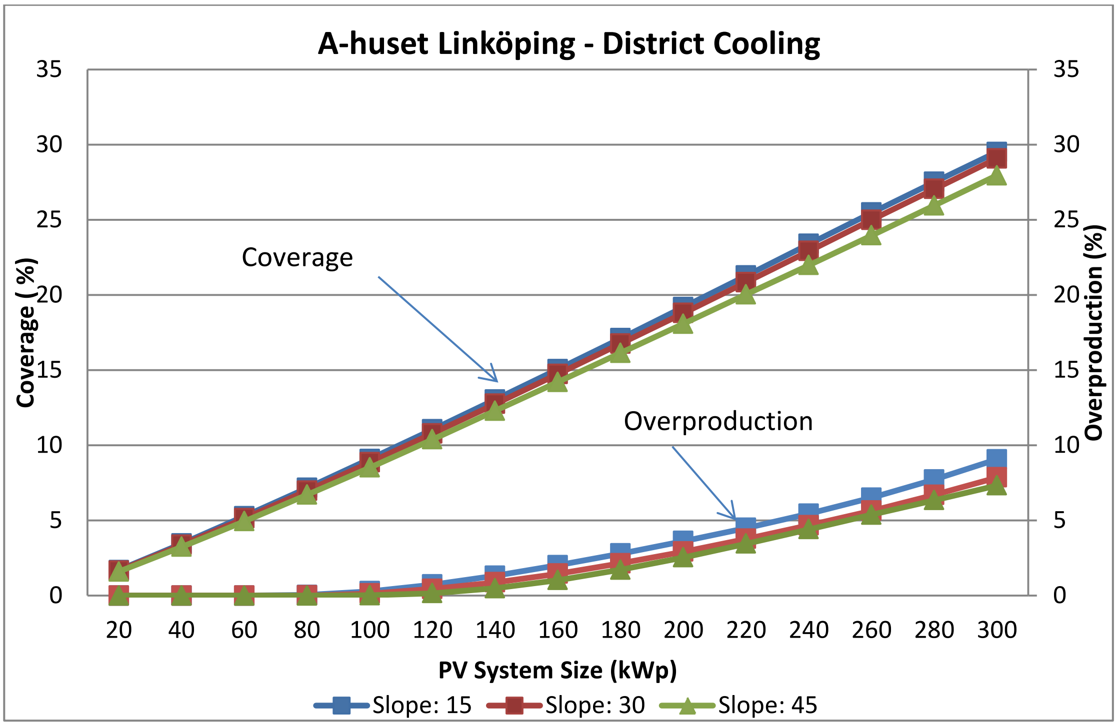


Figure 7.5 - Coverage and overproduction for different system sizes ranging from 20-300kW$_p$ for “A-huset Linköping” with an east-west orientation of the PV system.

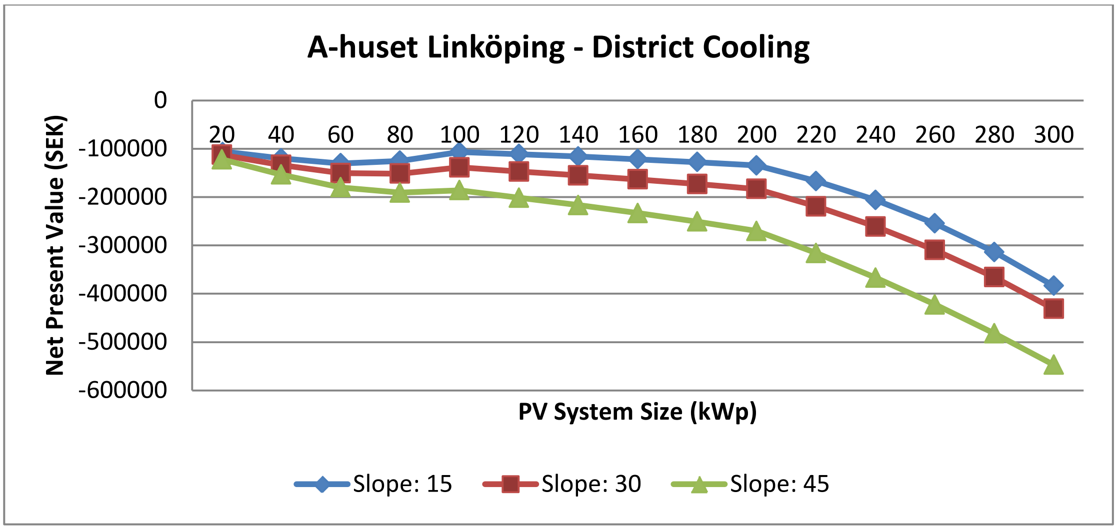


Figure 7.6 - Net present value for different PV system sizes ranging from 20-300kWp for "A-huset Linköping" with an east-west orientation of the PV system.

7.3 A-huset Linköping with electric Cooling

Figure 7.7 shows the coverage and the overproduction for different PV system sizes ranging from 20kW$_p$ to 400kW$_p$. Compared to result for the original office buildings A-huset with district cooling with the same azimuth the coverage and overproduction is lower. For example comparing a PV system of 300kW$_p$ and 45° slope, the coverage and overproduction for "A-huset Linköping" with district cooling is around 36% and 16% respectively. A cooling system using electricity gives coverage of around 26% and 6% for the same size and slope. This is explained by the increased electricity load throughout the year.

Figure 7.8 shows how the net present value differs with PV system sizes for the different slopes for a PV system. It can be seen in the figure that a size of above approximately 40kW$_p$ and up to more than 400kW$_p$ (systems larger than 400 kW$_p$ have not been simulated) is profitable for the slopes of 30° and 45°. PV systems with a slope of 15° are profitable above approximately 50 kW$_p$. A PV system with the slope angle of 0° never becomes profitable, but has an optimum at 200kW$_p$ corresponding to a loss of 35 000 SEK in the end of the investment.For a slope angle of 45°and 30° the net present value has its maximum at a PV system size of 320kW$_p$, with the values 728 000 SEK and 682 000 SEK respectively. For a slope angle of 15° the net present value has its maximum at a PV system size of 300kW$_p$, which results in a value of 413 000SEK. A PV system with a slope angle of 0° is never profitable.

It can be seen in Figure 7.8 that the NPV does not vary a lot for the sizes between 260kW$_p$ to 340kW$_p$ for the systems with positive NPV. The NPV does not also vary a lot for PV systems with a slope of 30° and 45°. The PV system size of 320kW$_p$ with a slope of 45° corresponds to a coverage of 27.4% and an overproduction of 7.3%. This system has a payback period of 21.2 years and a CSCE of 0.98 SEK/kWh. With the dimensions and size of the roof for the existing office building the PV system could maximum be around 566kW$_p$, which means that the optimum system uses 57% of the available roof. The payback time is ranging from 20.0 years to no payback time for the different PV systems. The shortest payback times of 20-21 years are found for system sizes between 120-300 kW_p for 45° slope angle and for system sizes between 160 and 280 kW_p for 30° slope.

The cost of self-consumed electricity (CSCE) is ranging between 0.94 to 1.16 SEK/kWh for the systems that have a positive NPV. The lowest CSCE of 0.94 SEK/kWh is found for system sizes of 200-220kW_p with a 45° slope angle.

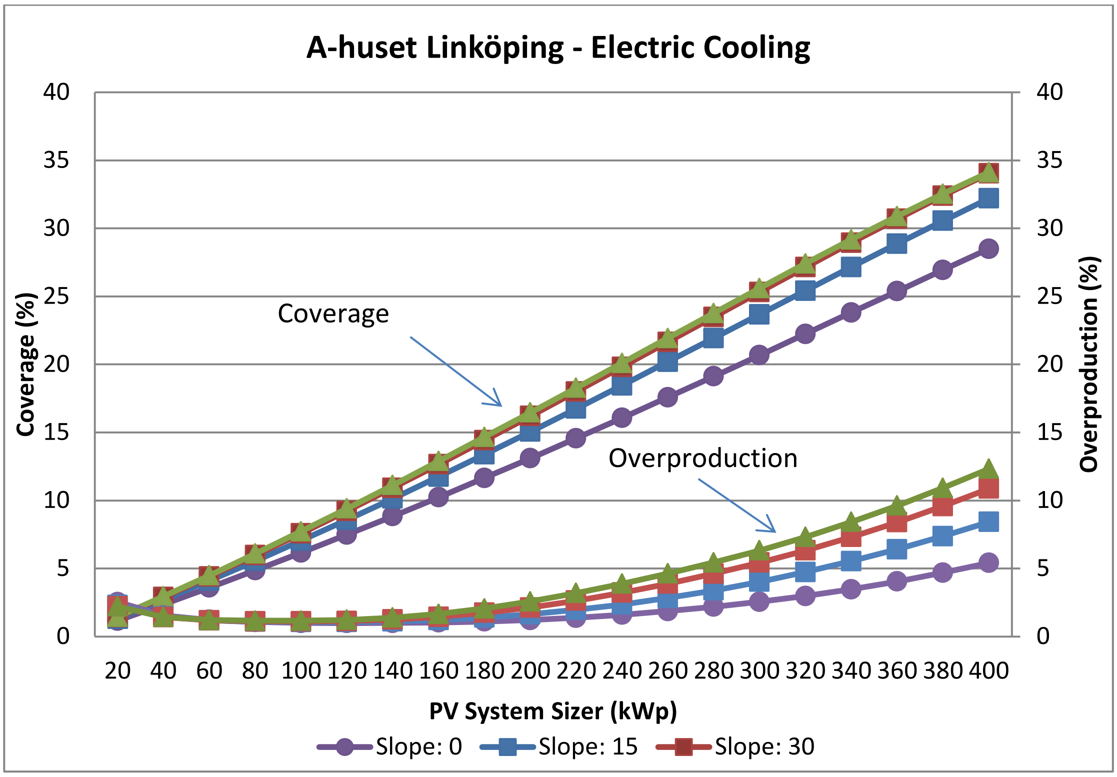


Figure 7.7 - *Coverage and overproduction for different system sizes ranging from 20-300kW_p for "A-huset Linköping" with electricity for cooling, with a PV system facing south.*

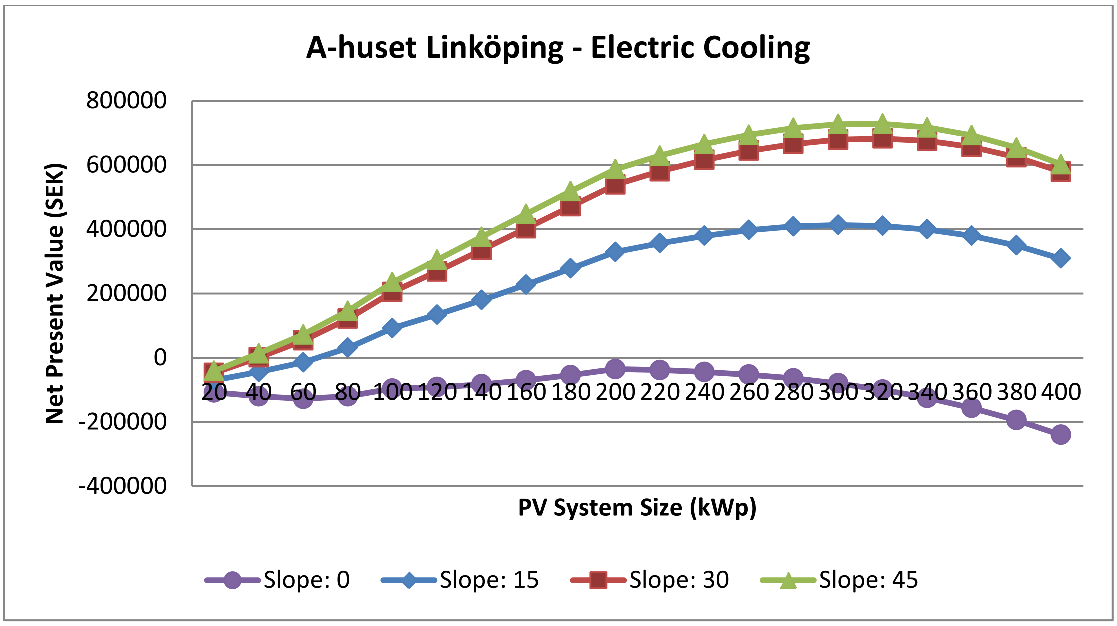


Figure 7.8 - *Net present value for different PV system sizes ranging from 20-300kW$_p$ for "A-huset Linköping" with electricity for cooling, with a PV system facing south.*

7.4 Bengt Dahlgren Mölndal

The simulation for "Bengt Dahlgren Mölndal" was made for one angle of azimuth; south. The maximum size of a solar PV system facing south that can fit on the roof is for "Bengt Dahlgren Mölndal" approximately; 54kW$_p$ for 0°, 26kW$_p$ for 15°, 16kW$_p$ for 30° and 12kW$_p$ for 45°.

Figure 7.9 shows the coverage and the overproduction for different PV system sizes ranging from 5kW$_p$ to 50kW$_p$. The larger the PV system size is the rate of change for the coverage is decreasing and the overproduction is increasing. If a PV system of 35kW$_p$ were to be installed the coverage could be as large as 50% depending on the slope, but this system would also result in an overproduction above 30% for the same slopes. Comparing the curve with the other buildings the overproduction curve does not follow the same shape. Already at 5kW$_p$ and above there is overproduction which is steadily increasing. This could be explained by the low electricity load that Bengt Dahlgren in Mölndal has, which can be seen in section 4.3.

Figure 7.10 shows how the net present value differs with PV system sizes for the different slopes for a PV system. "Bengt Dahlgren Mölndal" never reaches profitability in terms of net present value during default economic assumptions and is lower the larger the size is. None of the simulated system gives a payback time during the lifetime of the system. The CSCE is ranging between 1.59 and 2.24 SEK/kWh for the sizes studied. The lowest CSCE is found for 15kW$_p$ system and 45° slope angle and the highest CSCE is found for 5kW$_p$ system with a slope of 0°.

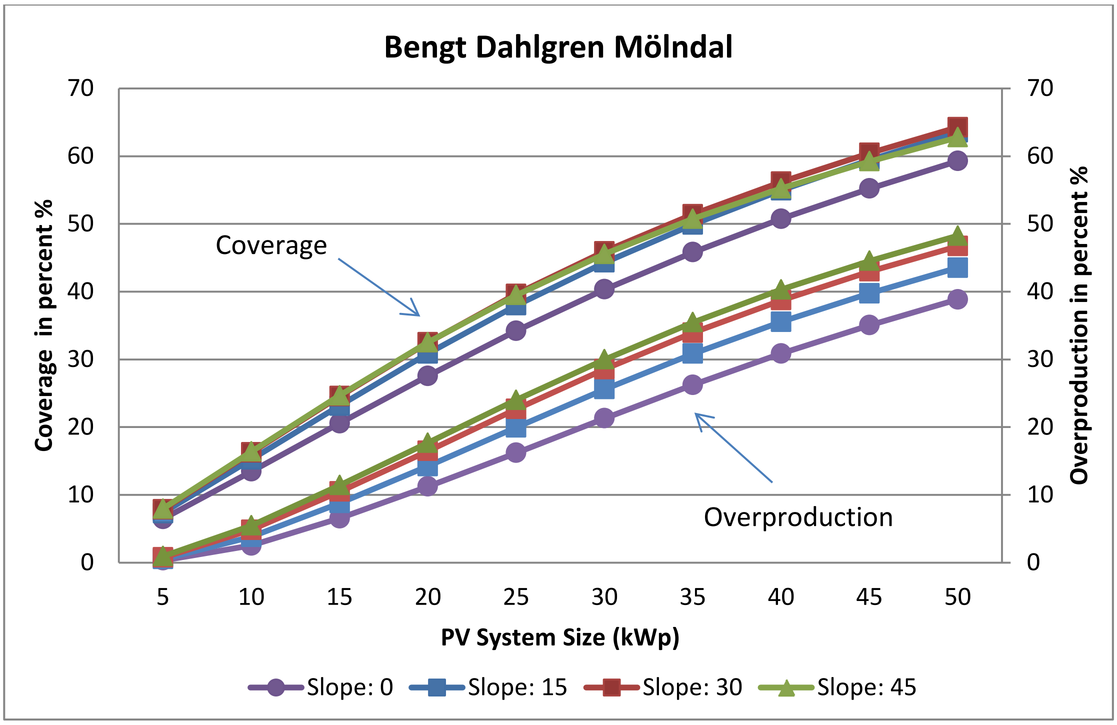


Figure 7.9 - *Coverage and overproduction for different system sizes ranging from 5-50kW$_p$ for "Bengt Dahlgren Mölndal" with a south facing PV system.*

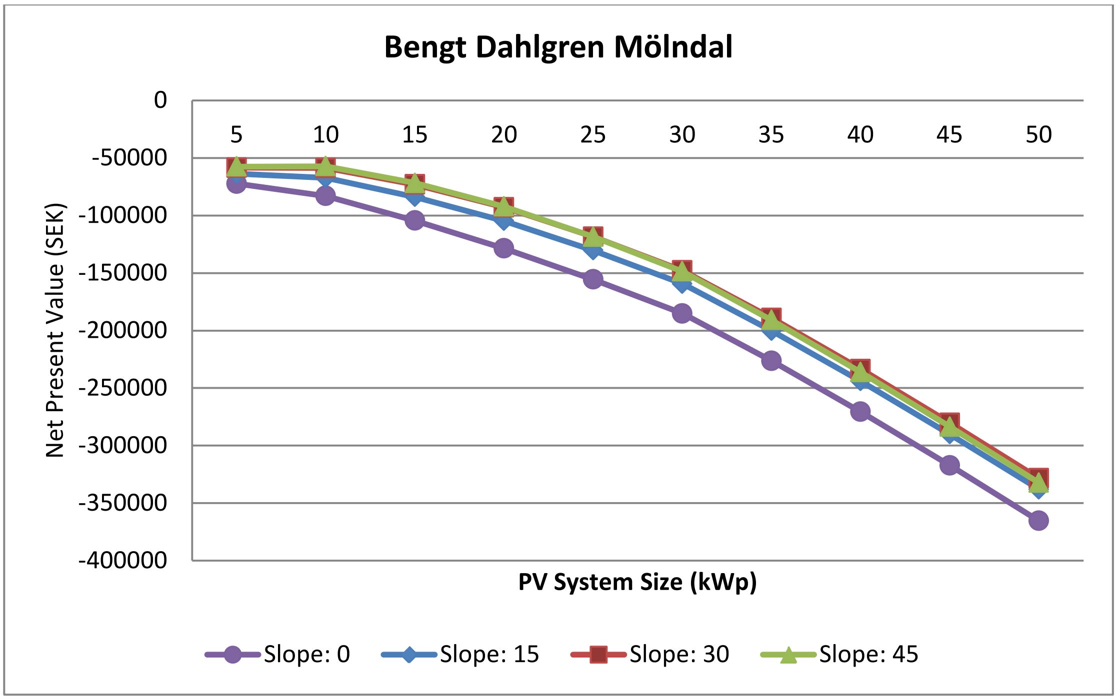


Figure 7.10 - *Net present value for different PV system sizes ranging from 5-50kW$_p$ for "Bengt Dahlgren Mölndal" with a south facing PV system.*

7.5 Summary of Result

Table 1 gives a summary of the result for the optimum PV system sizes regarding highest NPV for the different office buildings studied. “A-huset Linköping” with district cooling (DC in table) with azimuth east/west resulted is negative NPV for all system sizes and has no optimum, but the result for a size of 220kW$_p$ with a slope of 15° is shown in the table. This size is the optimum size for “A-huset Linköping” with district cooling with azimuth south. The result is included to enable comparisons between a south and an east/west facing PV system. “Bengt Dahlgren Mölndal” had also negative NPV for all system sizes but had an optimum at 10kW$_p$ and therefore is this result included in the table.

Table 7-1 - Result for the economical optimum PV system for the different office buildings studied. The result for “A-huset Linköping” district cooling (DC) with azimuth to east/west is not optimum values, since there is no optimum for this configuration.

	Vasakronan Uppsala	**A-huset Linköping DC**	**A-huset Linköping DC**	**A-huset Linköping EC**	**Bengt Dahlgren Mölndal**
PV system					
Azimuth	South	South	East/West	South	South
Slope	45	45	15	45	45
Optimum size (kW$_p$)	80	220	No (220)	320	No (10)
Generated electricity per kW$_p$ (kWh$_{gen}$/kW$_p$)	919	887	707	887	854
Estimated used roof area (%)	188	39	9	57	68
Total electricity generation (kWh$_{gen}$/year)	73552	195092	155556	283770	8540
Building					
Tempered area (m2)	5721	34307	34307	34307	4113
Number of floors	4	3	3	3	6
Electricity load (kWh$_{dem}$/year)	338 886	846 599	846 599	1 241 508	57 287
Load match					
Coverage (%)	25.9	26.9	21.3	27.4	16,4
Overproduction (%)	5.4	8.0	4.5	7.3	5,5
Economic tools					
NPV (SEK)	155 000	461 000	-166000	728 000	-57000
PBP (years)	22.01	21.5	No PBP	21.2	No PBP
CSCE (SEK/kWh)	1.02	0.99	1.24	0.98	1.61

“A-huset Linköping” with electric cooling (EC in table) has the best economic result, with highest NPV, lowest PBP and CSCE. The second best is “A-huset Linköping” with district cooling (DC) and then “Vasakronan Uppsala”. The coverage for the systems with optimum is in the range from 25.9-27.4%, while the overproduction is varying between 5.4-8.0%. “A-huset Linköping”

7.6 Sensitivity analysis

The purpose of the sensitivity analysis is to investigate how large impact critical parameters have on the result. The critical parameters are variables that might influence the results significantly. The case if the electricity were to be sold was tested in the analysis, where the selling price was set to the spot price and the energy tax to 0.29SEK/kWh. This scenario is referred as selling electricity, where the electricity price was changed to a higher and lower price. The discount rate might be higher or lower depending on the investor’s required rate of return for solar PV investment and the impact was studied by changing it to ±1% of the originally set value. The system costs can vary depending on the solar PV system supplier and therefore a system cost of ± 10% was tested. The O&M costs are an uncertain cost, since it has not been well defined in the literature and calculated as a percentage of the initial investment cost (the system cost). Therefore ±0.25 percentage points were tested. There is uncertainty when estimating a price in the future, since it is hard to predict how the market will develop. Inverter price was estimated by studying different retail prices today and assuming a value within that span. Due to a large uncertainty, ±25% of the inverter price was used. Capital subsidy was chosen not to be included in the original result since it is not certain if the investment can get the subsidy or not when making the investment. In this analysis the impact of the capital subsidy on the investment is studied.

The sensitivity parameters were analyzed for a PV system for “Vasakronan Uppsala”. The evaluation was made for a system of 80kW$_p$, since this system resulted in an optimum regarding the NPV as showed in the previous chapter.

The results of NPV for the sensitivity analysis can be seen in Figure 7.11. Each parameter has four results, since there are four PV systems with different slopes which are differently colored in the diagram. The result for the original system is firstly presented in the diagram to act as a reference and enable to analyze the impact of the parameters. The x-axis states which parameter result that is presented and the y-axis the NPV in SEK.

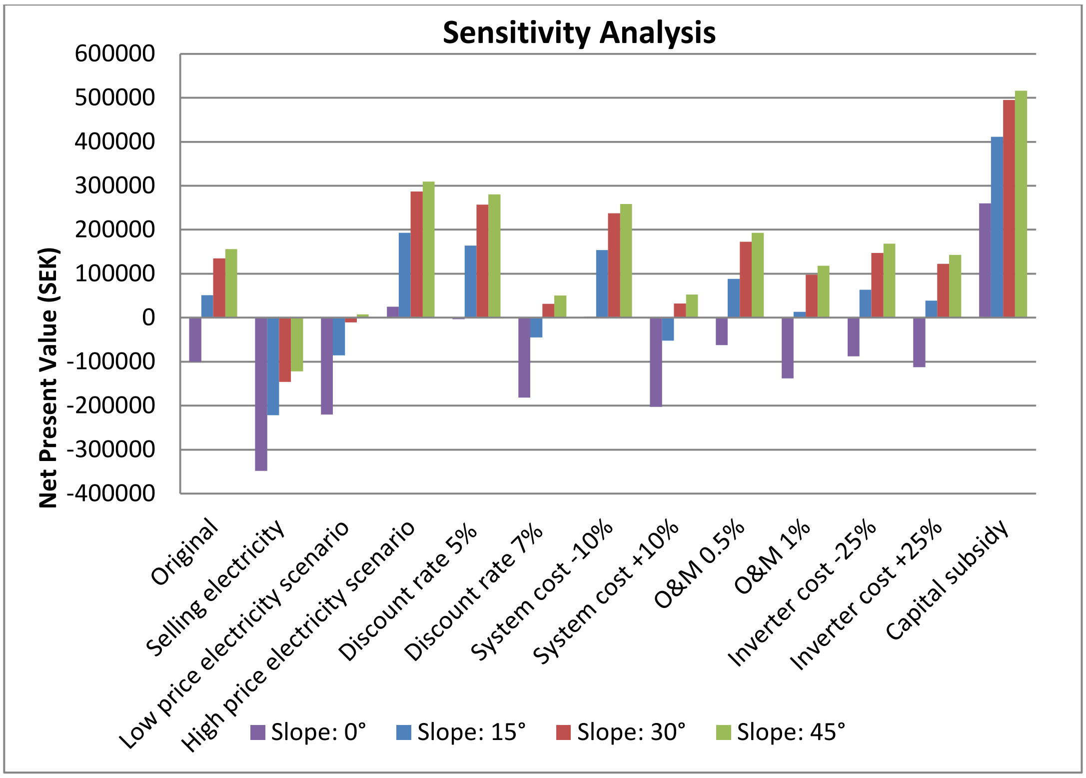


Figure 7.11 – Result of NPV from the sensitivity analysis, where the x-axis shows the original result for Vasakronan Uppsala with a PV system of 80kW$_p$ and the parameters that were studied and the y-axis shows the number in SEK.

The most negative impact on the NPV result is the scenario assuming that the electricity was sold. This scenario resulted in negative NPV values for all slopes. The low price scenario gives the second most negative result, where systems with a slope of 15° and 30° that previously have been profitable became unprofitable. The high price scenario results in a positive NPV for all slopes and is the parameter with the second largest positive impact. The most positive impact and the parameter which also has the greatest impact on the result is the capital subsidy. For all the slopes the NPV result is positive, where the result for each increased with about 360 000SEK, which corresponds to the size of the capital subsidy. The payback period for the system with a slope of 30° or 45° is less than 13years.

The discount rate of 5% resulted in positive NPV for all slopes and turned the result for the slope of 0° just above zero. The discount rate of 7% resulted in changing the NPV result for 15° to a negative value. A reduced system cost with 10% resulted in positive NPV for all slopes, while an increased system cost resulted in a change for the system with 15° slope. The change in O&M and inverter cost had compared to the other scenarios and parameters low sensitivity. There was no change in the outcome, since the system with 0° still was negative and for the other slopes still was positive.

Another sensitivity analysis that was performed was a case where the economic evaluation was made for “A-huset Linköping” with the east/west configuration using a discount rate of 4 %. The results in terms of NPV can be seen in figure 7.12. Comparing figure 7.12 with figure 7.6 where the economic evaluation was made for the same configuration but with a discount rate of 6 %. It can be seen that if using 4 % discount rate, this configuration has a positive NPV for several system options. For a slope angle of 45° system sizes over 40 kW_p will give a positive NPV. The optimum size corresponds to a NPV of 402 000 SEK which is compare to the optimum for the south facing system using a discount rate of 6% (460 000 SEK) not much lower.

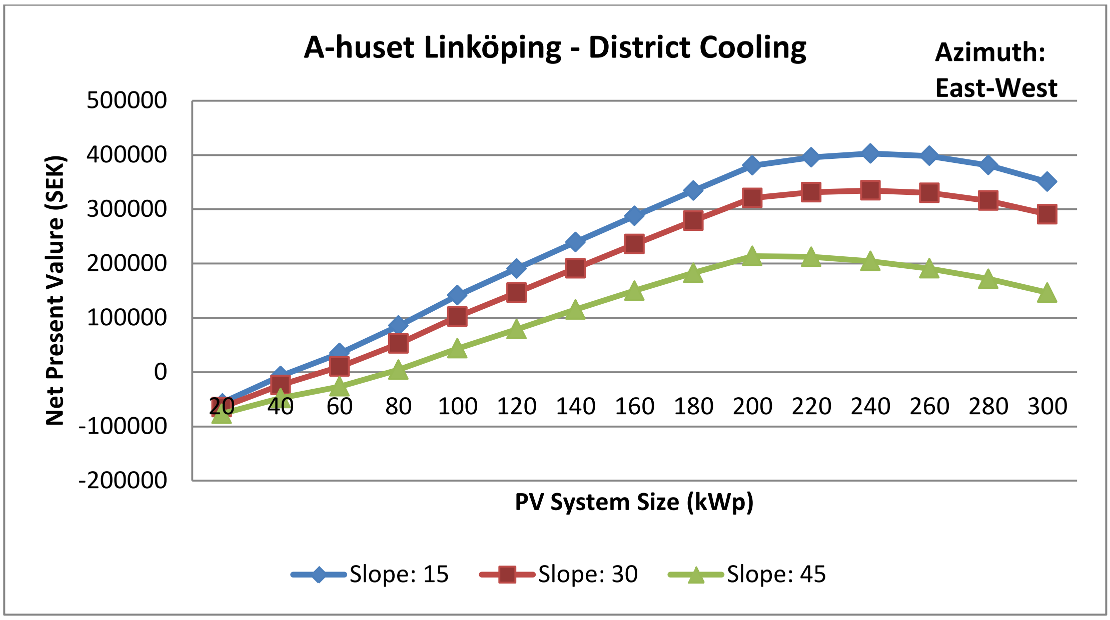


*Figure 7.12 - Net present value using a discount rate of 4% for different PV system sizes ranging from 20-300*kW_p *for "A-huset Linköping" with an east/west facing PV system.*

8 DISCUSSION

This discussion chapter is divided into the four parts, where the three first parts are divided into the three objectives of this thesis. The first section is a discussion about the electricity load profiles regarding their cooling systems for the five examined office buildings. It discusses whether it is possible to draw any conclusions from the buildings cooling systems and the electricity load profiles that were presented for a year. The second part discusses the existing solar PV installations and the load match of the office buildings existing PV systems to analyze how the installations have been made and what load match it corresponds to. The third part of the discussion is about the three office buildings which were further studied, where one of the buildings cooling system was changed and where PV systems were simulated to investigate how the size, orientation and slope of the PV system impact the economic viability of a PV investment for these cases. The fourth part in this discussion brings the technical, legal and economic potential for a PV investment into light, where information from the literature study and the result from the other parts of the thesis are used to describe the conditions needed.

8.1 Property Electricity Load Profiles

All the examined office buildings were different in terms of location, size, number of floors and shape. The buildings also differ in terms of energy performance. Considering the information from the literature survey, it can be said that the buildings studied has a property energy performance that differs from the average. Only one building has a value of the energy performance that is close to the average. Some buildings have a value significantly lower and some buildings had slightly higher value of the property energy performance. The studied buildings were also located at different geographical locations, which in turns could imply different heating and cooling demand and affect the load profiles. The dissimilarities of the buildings and the low number of buildings studied make comparisons with the aim to draw general conclusions regarding electricity load profiles for different cooling systems impossible.

The electric load profiles for the different examined buildings are complicated to compare because of the dissimilarity of the buildings. The data for “Akademiska Hus Solna” is for both property electricity and business electricity and it has been discussed if it could be relevant to use the load data for this building in the study. The conclusion that was made was that this building still could be relevant to study to investigate the load profile. The investigation is just about to get an approximately idea of the load profile for different cooling systems and it can be given from this data. “A-huset Linköping” is not solely used for office purposes, but is also used for labs and educational purposes. It is however clear that the examined building that used electric cooling has an increase in electricity use during the summer half-year when the cooling need potentially is higher. Correspondingly, for the examined building that uses district cooling it can clearly be seen that the electricity use is not increasing during the summer half-year. The original idea of this investigation was that the electricity use from an electric driven cooling machine potentially could be well matched with the electricity generation from a solar PV system. The analysis would then be about if it is possible to draw any conclusions about whether the type of cooling system itself could increase the suitability to use solar PV for an office building. Briefly, just by analyzing the load profiles no conclusion of this type can be made. This question is further examined in the economic evaluation where different PV system sizes are simulated for the buildings with different cooling systems.

In the study only one year was studied, due to the availability of data and it is not known if the year studied represented a typical year. Preferably an electricity load profile for a normal year would be used to make it possible to draw more general conclusions but this was not at hand. The load profiles for the buildings with a replaced cooling system from district cooling to electric cooling were calculated using a constant COP of 3 over the whole year. This is a simplification and this will in reality differ constantly when the cooling need is changing. The load profiles for the buildings with a replaced cooling system are despite this relevant to investigate how the cooling system affects the load profile. From the study of the load profile for an average day in July, the shape of the load for “A-huset Linköping” with electric cooling looked similar to the buildings with electric cooling systems.

8.2 Existing Solar PV Systems

By studying the existing PV installations on the five office buildings, it is noted that the roof conditions was important for the choice of slope and azimuth angles for the PV installation. For four of the five examined buildings, the PV system was installed directly on the roof which had different slopes and azimuth angles. Common for the azimuth was that the roof between southeast and southwest was used and if there were other roof orientations these roofs were not used. Only one building, which had a flat roof, used an installation to get another slope angles of 20° than the roof originally had. It has been speculated why the installation not was made with a larger slope, since it would generate more electricity. Possible reasons for that could be because of a too expensive mounting system and/or because of too heavy wind loads. One of the buildings had a roof with a small slope in different azimuth angles. The PV installation was only installed on the more south facing roof and left the east and west facing roofs without PV panels. It was seen in the simulation results, that east and west facing systems were not profitable to install, which might be the reason why these roofs were left without PV systems. The sizing of PV systems differed between the office buildings, due to varied conditions.

Both “A-huset Linköping” and “Bengt Dahlgren Mölndal” had the possibility to install larger PV system, but chose to install a smaller system. The reason for this could be that the dimensioning of the size was made so that there would be no or very small overproduction. A rule of thumb that seems to be commonly used in order to a avoid overproduction and to make a profitable investment is to choose a PV size slightly smaller than the electricity base load during daytime. “A-huset Linköping” chose to install 65 kW_p and the average base load during daytime for the summer-half year is 80 kW. “Bengt Dahlgren Mölndal” chose to install around 7.1 kW_p and the average base load during daytime for the summer-half year is around 3.3 kW. From this it can be said that “A-huset Linköping” have a PV system close to its base load during daytime but “Bengt Dahlgren Mölndal” have a small system even from this point of view. If the systems were sized from the mentioned rule of thumb, it could also be the case that an electricity load curve for another year was analyzed to size the system which could give a different base load.

The office buildings with large overproduction, “Akademiska Hus Solna” and “Välagård”, are interesting since the dimensioning is often made so that there would not be overproduction. ”Solna Akademiska hus” installed PV panels on the whole part of the roof that were orientated to a more southern direction. The sizing of this system was probably not made with a concern of the own electricity use of the building. ”Solna Akademiska hus” had an overproduction of 26 % for the year of investigation. “Akademiska hus Solna” is located on a campus area with an own electricity grid which makes it possible for most the overproduced electricity to be transferred to other buildings that consumes the electricity. “Väla Gård” on the other hand sells their overproduced electricity, whether this is economically feasible is not known. It is most likely that it for “Väla Gård” is more profitable to sell the overproduced electricity, since the overproduction is much larger than the self-consumption.

“Vasakronan Uppsala” filled the part of the roof with PV panels which had a slope towards southeast, but more close to south. Other parts of the roof had a slope towards east and west which were left without PV panels. The sizing of the PV system gave an overproduction of only 1% and coverage of 12% for the studied year. The PV system is 43 kW and the average base load during daytime for the summer-half year is 34 kW. How the PV system on “Vasakronan Uppsala” was chosen to size could possibly be just to fill the suitable roof space with PV panels. It could also be the case that the sizing was made with the intention to avoid overproduction.

“Bengt Dahlgren Mölndal” and “Väla Gård” are special office buildings in terms of energy performance, and for those could the investment motive be to market themselves as companies that are in the edge of energy performance and environmental thinking. These could of course be the reason for all of the examined PV system installations.

By studying the installations it can be concluded that these have been made the easiest way, since the slope and the azimuth angle is kept to the slope of the roof. But for the building with a flat roof another slope was chosen to generate more electricity. The matching of electricity load and electricity generation seems only be considered when selecting size of the PV system and not consider the load profile during the day, since the azimuth and slope is chosen for four of the five buildings by the roof conditions. Some were dimensioning for no or little overproduction, while others filled their whole available roofs, which had good orientation, with PV modules. It can be concluded that dimensioning of the PV system size varied for the examined buildings.

The matching of electricity load and electricity generation for existing PV systems were made using data from the same year on an hourly basis. Shorter time basis than hourly would increase the accuracy of the load match. The matching of generation and use are occurring on an instantaneous basis and to get a more precise result, the time steps that are to be matched should be as small as possible. Using an hourly basis would lead to estimating that more electricity is covered than it actually is. But only data on hourly basis was available for this study, which was concluded to be good enough since the result still gives an indication how much is covered and overproduced.

8.3 Simulation Result and Economic Evaluation

This section discusses the simulation results and economic evaluation results that were presented in Chapter 7. This section is starting with a discussion about the method that was used to investigate how the size, orientation and slope affect the economic results for buildings with different electricity load profiles and cooling systems. The results are then discussed considering the size, orientation and slope, as well as the electricity load profiles and cooling system of the building. Finally the impacts of sensitive parameters are discussed.

8.3.1 Method

The purpose of the method for the economic evaluation was to investigate how the size, orientation and slope affect the economic profitability for different electricity load profiles. From these results it was meant to study if there are any PV systems that are profitable for the given electricity load profile from a property owners perspective and by this investigate the economic potential of an investment, including existing technical and legal conditions. The study was built upon case studies of three buildings electricity load profiles during a year, where one of the buildings had an extra load profile with changed cooling system, from district cooling to electricity for cooling. This change was made to enable to study the impact of different cooling systems.

The method used are suitable to investigate the potential of PV systems in Swedish office buildings, since it is based on electricity load profiles for existing office buildings located in Sweden and the electricity generation are simulated for respective location of the buildings. It is also based on technical and economic input values that are reflecting today's conditions, where some costs are location specific. The location specific costs were chosen instead of average, since it then reflects the potential for the office buildings at the specific location. The initial investment cost for different PV system sizes was estimated by studying market prices from average PV system prices in Sweden and Germany, companies selling solar PV systems, the cost from installed systems in Sweden and average installation costs. It is in this thesis assumed that PV systems with different slopes had the same initial investment cost, which most likely is not true. The costs are depending probably on the roof conditions, if it is easy or difficult to install and what mounting system that is needed. A PV system with a higher slope would perhaps be more costly than one with no slope. The result should therefore not be used to draw conclusions whether which PV system is the most promising, but be used for indicating if there are any economic potential for having PV systems in Swedish office buildings. The curves of the different system prices for different system sizes are starting with a rather high value for small system and are quickly decreasing for bigger systems. It could be the case that the decrease in price not will be as large as the estimation used in this study, and that could affect the economic evaluation. The effect of this could be a lower profitability for smaller systems. The orientation was only studied for south for all cases and east/west for one case; it would be interesting to study other orientation between east and west. For example to study south-south west since the peak is in the afternoon, but limitations had to be made to limit the amount of result to process.

A drawback with the economic evaluation is that the PV systems are simulated for a typical meteorological year, while the electricity load data represent a specific year. The accuracy of this study could possibly be increased by using an average year from load data for a larger number of years for the studied buildings. This would primarily be of importance if the aim of the study would be to present a ground for an investment decision for each building. But considering the aim of this study, the examination of a potential, the conclusion is that the use of only one year of electricity load data is adequate. Another critic is the low number of buildings studied and that these may all not be representative. A-huset as mentioned in previous section is used for educational purposes also and is a very large building, while Bengt Dahlgren is a low energy building and is relatively small. It would have been preferable to have a larger amount of buildings included in the study, which purely was used for office purposes and corresponded to a typical office building size. On the other hand these buildings load profiles are quite similar, since the electricity load is highest during the day. It also showed for A-huset Linköping when changing the system to electricity for cooling that the shape turned more alike the other buildings which was solely used for office purposes and had electric cooling system. Due to the low amount of buildings and that the office buildings studied may not be typical buildings no general conclusions can be made. Another important notice is that the simulations were made with Polysun, which seems to underestimate the generated electricity output slightly. This was noted in the evaluation of simulation software’s. If this is true it means that the economic profitability in the study could be slightly underestimated.

The economic result from this study should not be used for making investment decisions, since the input parameters used are only for investigating the potential. But the method could be used to investigate a potential investment. This if input values for the specific building, the electricity load per hour for a normal year and the technical data of the PV system is and the costs of the PV systems is known, as well as the location specific costs which is given by the grid company.

8.3.2 Impact of PV System Parameters on the Economic Result

The result showed that the choice of size, slope and azimuth are important for making a profitable PV investment in terms of net present value (NPV), payback period (PBP) and the estimated electricity price of electricity from the solar PV system, cost of consumed electricity (COSE). In the result it was seen that there was an optimum PV system size in terms of NPV for some of the examined buildings. It also showed that the size of electricity load profile is important, since one of the buildings did not reach profitability, even though it had a similar shape.

Size

The result showed that there are several PV system sizes that are profitable for the buildings which had positive NPV. It showed that for small PV systems the result was negative, which can be explained by the higher investment cost per kW_p. In the result it was shown that it for the PV system that were profitable there was an optimum size for each slope, which allowed some overproduction. A plausible explanation of this phenomenon can be described by following reasoning. A bigger system size will lead to a bigger investment cost, but before the optimum, the increased savings from avoided purchased electricity together with the income from overproduced electricity generates a higher value in total during the lifetime than the additional investment cost when the system size is increasing. While the savings from avoided purchased electricity after the optimum is decreasing in relation to the increased investment cost. After the optimum the overproduction is fast increased with a bigger system and the coverage is decreasing slightly. At one point, the overproduction will be too large for a bigger PV system in relation to the increased investment cost and it will results in a negative NPV. The case studies showed that it is profitable to allow some overproduction.

During the work of this thesis, different opinions for how to size a solar PV system have been observed. One opinion has been that a PV system should be sized so that overproduction of electricity is avoided, and this opinion was current in the beginning of this thesis. The argument for that is that electricity that is fed into the grid is worth less than if the electricity is used in the own property. As mentioned previously the most profitable system size for the examined buildings having some percent of overproduction (5.4-8%) and there are PV system larger than the optimum that is profitable.

A rule of thumb in order to avoid overproduction and to make a profitable investment is to choose a PV size slightly smaller than the electricity base load during daytime. The average base load during daytime for the summer-half year was for “A-huset Linköping” 80 kW. For “A-huset Linköping” with district cooling is the economic optimal size 220 kW_p and the maximum load is 203 kW for the summer half-year (March-October). This means that this building had an optimal installed peak power bigger than the peak load. The fact that the most profitable system size is even bigger than the maximum electricity load may seem strange, and that the case is such is not explicit investigated. However, from the simulation result it was shown that a PV system did not generate at its peak power very often and the maximum load did not occur very often. Another plausible reason could be that a bigger system can make the value of self-consumed electricity higher in relation to the investment cost. “A-huset Linköping” with electric cooling has an economic optimal size of 320 kW_p and the average base load during day time for the summer-half year was 132 kW. The maximum load is 385 kW for the summer half-year. “Vasakronan Uppsala” with electric cooling has an economic optimal size of 80 kW_p and the average base load during day time for the summer-half year was 34 kW. The maximum load is 103 kW for the summer half-year. “A-huset Linköping” with district cooling with an east-west configuration and for “Bengt Dahlgren Mölndal”, no optimal size regarding profitability were found. Given those numbers, it can be said that the rule of thumb can be an unnecessarily cautious way to size a PV system.

Slope

The result showed that the evaluated buildings with PV system with a slope angle of 0° resulted in negative NPV, while the larger the slope was the NPV increased. This is because the systems with 0° slope will generate an insufficient amount of electricity in relation to the costs that are associated with the investment of the system. The results also showed that for south faced systems, the NPV value is higher for a slope of 45° than a smaller slope, which is explained similarly, by the increased generation in relation to the investment cost. Interesting to note from the result was that the NPV did not increase proportional to the slope. For example was the difference between 30° and 45° slope angle NPV not significantly large. This must mean that the electricity generation from these systems probably is not very different, since the slope is the only parameter varied. In the result it was seen that the choice of slope is important for an existing building with a flat roof, since the area is limited. For example is the needed area for 45° slope larger than for a PV system with a 30° slope, and if the roof space is a limiting factor for some buildings a wiser choice could be to use around 30° slope angle as shown in the result for Vasakronan Uppsala. The roof conditions, such as the area and dimensions must be considered since this affects which PV system will be the most profitable for the building.

Orientation

In the case study of “A-huset Linköping” with district cooling it was seen that the orientation to the south gave positive net present value while the orientation when half of the system was facing east and the other half west the result became negative. For the building “A-huset Linköping” that were economically evaluated for an east and west orientated system the NPV never became positive for any slope angle with the used economic input parameters. The reason why “A-huset Linköping” with the east-west configuration did not reach profitability is that the PV system is generating too little electricity in relation to the investment cost. Smaller slope angles gave better results than bigger slope angles. This is because an east-west orientated PV system with smaller slope will generate more electricity during the day when the insolation is bigger, than an east-west system with a bigger slope angle. The east-west system became profitable with a discount rate of 4% instead of 6%. This means with a lower required rate of return, the investment could be profitable, but it also means that the south faced system would be even more profitable. I.e. for the investigated buildings, a south faced system will always be more profitable than an east-west faced system.

Property Electricity Load Profile and Cooling System

The matching of electricity use and generation is dependent on the load profile for the building. “Vasakronan Uppsala” has a significantly higher electricity use during summer, when most of the electricity generation occurs, compared to the electricity use for the rest of the year for the same building. This could lead to the possibility to install a larger PV system for this building compared to a building with equally large yearly electricity load that has district cooling (if assuming it is true that district cooling has an even electricity load throughout the year). This since the matching is better during the year, resulting in more self-consumed electricity than overproduced for the electric cooling case than for the district cooling case. A better matching can therefore motivate a larger PV system and a larger PV system leads to higher NPV according to the results. From this point of view the electric cooling as cooling system would be to prefer.

The electricity demand for “A-huset Linköping” district cooling is not increasing during summer as for “Vasakronan Uppsala”. The load over the whole year is though high and this is the reason why a big system as 220 kW_p can be motivated as the optimal size regarding profitability for this building. The overall high electricity demand will lead to that a large amount of generated electricity can be self-consumed and this allows a big PV system to be installed, which leads to a high NPV. “A-huset Linköping” with electric cooling has a different load profile and electricity demand. This change in demand can allow installing a much larger system which resulted in an NPV almost 60% higher than the district cooling case. This value of 60 % is directly a consequence of the used COP of 3; a higher COP would lead to smaller increase of NPV. This result means that if the buildings cooling demand is going to be fulfilled, either with district cooling or electric cooling, the electric cooling system would be to prefer from a PV system investment point of view.

The results for “Bengt Dahlgren Mölndal” which had electric cooling system, shows that none of the investigated PV system sizes are profitable for the used input parameters. This can be explained by a significantly lower electricity load than the other investigated buildings. A low electricity demand will quickly lead to a high overproduction from the PV system in combination with that the investment cost is significantly higher for small system sizes. “Bengt Dahlgren Mölndal” also has a slightly smaller generated electricity per installed kW_p than the other buildings. Therefore is the size of the buildings electricity load profile, much more of importance since this rather than the cooling system influence whether a PV system investment will be profitable or not.

8.3.3 Economical Input Parameters

The results from the economic evaluation are highly dependent on the input parameters which can be seen in the sensitivity analysis (section 7.6). It was shown in the sensitivity analysis that the different electricity price development scenarios, the discount rate and the system cost had major impacts on the economic outcome, while the O&M and inverter cost had compared to the other less impact. The capital subsidy reduces the initial investment cost significantly and made the investment profitable for all the investigated slopes in the sensitivity analysis, where the lowest NPV is higher than the highest value in the original case. Other economical input values that were not studied in the sensitivity analysis are how the electricity certificate, feed in fee and the grid benefit compensation can vary. Feed in fee and grid benefit compensation is relatively small costs and incomes which probably will not affect the economic calculation significantly. A different value of electricity certificates could potentially lead to a change in the economic result. But in contrast to the electricity price, the price for electricity certificates seemed to have no steady trend in price development. Since the model is without inflation and that electric certificate only is paid for 15 years, it was decided to use one price for the certificates for those 15 years.

From the sensitivity analysis it was shown that high price development of the electricity price, a 10 % smaller investment cost or if the investor can get a 35 % capital subsidy for the investment, the 0° slope angle case can be profitable. Moreover, in this study, all investigated slope angles for all buildings was assumed to have the same installation costs as mentioned in the method. In reality this could differ for the different angles and the type of roofs the installation is made on. This means that it can be problematic to recommend a property owner to avoid installing a system with 0° slope angle. If the roof conditions are such that a small slope would lead to a cheaper installation it could be profitable to make such investment, while it for the opposite case installing a PV system of 45° would have a higher cost than presented in this thesis.

8.4 Prospects for Solar PV in Swedish Office Buildings

In this section the investment potential of a solar PV system in Swedish office building is described from a technical, legal and economic perspective. These conditions influence each other, for example influence the technical and legal conditions the economic conditions. The important technical conditions are firstly treated, followed by the legal aspects for a PV system installation and finally the conditions when it is economically feasible to make an investment are discussed.

8.4.1 Technical conditions

Roof specific conditions are important, since the system cost probably will increase rapidly if the PV system is difficult to install or a special mounting system is needed. As noted in the sensitivity analysis the system cost has a great impact on the result, which includes the installation and mounting equipment cost. The roof conditions also give the conditions whether it is possible to install a PV system that has a profitable azimuth and slope. Therefore are some buildings due to their specific roof conditions more suitable for having PV systems than others. The roof conditions is varying for office buildings and it is not likely to have the assumed conditions which was flat, unshaded and with an orientation to the south. The real roof conditions, such as the area, slope, azimuth and obstacles must be taken into account when optimizing the PV system from an economical point of view for existing office buildings. The potential of making a profitable PV system installation is larger for a planned building, since then the system can be considered in the construction phase of the building. There are many different mounting solutions adapted to different types of roofs, which also increases the technical potential of having PV system roofs.

The investment potential is not only technically influenced by the roof conditions, the electricity load profile also contributes to whether the PV system will be profitable or not. The result from the case studies shows that it can be profitable to install PV systems for office buildings with electricity for cooling and with district cooling. It also showed that if the electricity load profile is very low, the investment is not profitable. For this case it would be interesting to study the economy if the overproduced electricity would be sold. Due to the significance of electricity load profile when evaluating an investment it is important to make correct measurements, this at least should be on hourly basis. The shorter time steps the better, since the electricity transfer is instantaneous. It is also important to study the measured values of the electricity generation to identify whether the system is working as it should.

The location influences the electricity generation per installed kW_p. In the case study the three office buildings are located in the middle to southern part of Sweden. Uppsala had the highest generation per kW_p installed, followed by Linköping and lastly Mölndal. The lower electricity generation for Bengt Dahlgren also influences the result since there is less electricity for self-consumption per kW_p.

8.4.2 Legal conditions

Throughout the thesis it was encountered that the laws and regulations regarding generating electricity and selling electricity from a PV system are unclear and difficult to interpret, especially for systems with a fuse larger than 100A. Solar PV system as an energy source is still very small in Sweden, which can be one reason why the laws are not well developed yet. Electricity producers that are considered as commercial producers must pay energy tax if the overproduced electricity is sold, and most of the companies that produce electricity are counted as commercial producers. Even though the economic benefits only are given for “micro-producers”, the case studies showed that with today’s legal conditions influencing both the costs and the incomes gives positive economic result for some PV systems on a potential office building without using capital subsidy. The capital subsidy can make unprofitable investments profitable, but there is a long waiting time and not all investment will get subsidy.

Therefore should the capital subsidy only be seen as an extra income and not be used in the evaluation of the investment with today's conditions.

The legal conditions today makes it unprofitable to sell electricity for a company. This was studied in the sensitivity analysis where selling electricity resulted in large negative result. This result is explained by the energy tax that is added on the self-consumed electricity, which causes a larger cost than income since the amount self-consumed electricity is larger than the amount overproduced electricity and sold for the office building studied. The energy tax is 0.29SEK/kWh while the spot price is ranging from 0.34-0.73SEK/kWh. In the past and also today it is common to dimension the PV system so that there is no overproduction. The result in the analysis shows clearly why this is common and recommended for non-micro producers. A special case are if there are several buildings connected in an own electricity grid. Then the dimensioning should take the whole area´s electricity load profile into account. This means that a building with a solar PV system in such area can have large overproduction when studying the load match between the system and the buildings electricity load profile. This is only valid if the owner is the same for all the buildings in the area.

A legal aspect that is increasing the potential for solar PV in buildings in general is the requirements for the specific energy use, which are being lowered. This is because the electricity used from a solar PV system connected to the building can be subtracted from the specific energy use. Therefore are there motives from this perspective to implement solar PV when the target is hard to reach or when the aim is to have low specific energy use.

The uncertainties in legal conditions can in the worst case prohibit investment by making it too complicated to evaluate a PV system installation. The larger the solar PV electricity generation in Sweden becomes the importance of making clarities in the laws probably will increase and put more pressure on the politicians. Seen from a long term perspective the laws and regulations probably will change during the 30 years the PV system investment is active, which also must be considered when making the investment decision. The potential for solar PV is increasing when the regulations lower the specific energy use.

8.4.3 Economic conditions

The case studies showed that it is profitable to install PV systems on office buildings with the economic assumptions made, with no capital subsidy and where the discount rate was chosen to represent the same rate of return as any other investments for the property owner this study was aimed for. This means that the economic analysis in this study is made from a perspective that the investment should generate a direct profit.

Payback time is an investment evaluation measure that seems to be frequently asked about. However, a PV system investment often has a long payback period. This could for other investments be unacceptable high, but depending on how the investment is viewed, for example to secure the future electricity price, this long payback time could be of less importance. A common criticism to use PBP is that it does not take into account the cash flow after the time when the investment cost is paid back, and therefore not reflect the profitability of the investment. The payback time could therefore be more relevant to use to compare different similar investment alternatives.

Investment must be seen as something else than only a contributor to an income. For example could the intention be to build a trademark to the company as environmental friendly. The investments of existing PV installations on the studied office buildings were discussed in a previous section. The conclusion was that these investments must have been motivated other than economically. Therefore is it possible that property owners are willing to make investments with lower demands for PV systems compared to other investments.

The sensitivity analysis showed that there are some economical parameters that can change the result from being profitable to becoming unprofitable, and the other way around, hence resulting in a change of the investment decision. It is therefore important to choose the input parameters carefully and to make reasonable estimations of future prices. The only parameter the investor can influence is the discount rate. If the investor could allow a lower discount rate it will result in a larger range of PV system that is profitable and the NPV would increase for the already profitable systems. The other economic parameters are set by market conditions as well as technical and legal conditions. The initial investment will be known when the investment decision is being made, since the cost is paid in the beginning of the investment. In reality a loan is probably taken for making the investment and smaller amounts are paid every year including an extra cost of interest. However, this is not studied in this report and the impact of a loan cannot be described. The future electricity prices are not known and are therefore the most uncertain parameter. With a low price scenario there is a risk that the investment becomes unprofitable. The investor can instead study the CSCE of the PV investment which is the average price of the generated electricity during the investments lifetime. By making an investment of a PV system the investor can secure their future electricity price for some part of the electricity use. This reduces the uncertainties in future electricity costs, which can be preferable.

9 Conclusions

The case studies showed that it can be economic feasible to install a solar PV system on a Swedish office building from a property owners point of view taking the technical, economical and legal conditions of today into account. This economic feasibility is dependent on several conditions that can increase the profitability of the investment and in turn decrease the payback period. The following conclusions were drawn in this thesis regarding the conditions that are important to make the investment in a solar PV system for a Swedish office building economical feasible:

Office building with good geographical location with roof that has enough available area with conditions that are allowing easily installation is more profitable. The PV system should be faced towards south or close to south with a slope of 15°-45°, the bigger of these slopes might be more profitable. In this study PV system with a slope of 0° was not shown to be profitable. However, such systems could potentially be profitable since it can be cheaper to install horizontal systems. Different buildings will have different roof conditions with different slopes and azimuth angles. New buildings in the planning phase have the potential to make the conditions for more profitable PV, if the PV systems are considered during the construction phase.

The existing PV installations studied seem to be made the easiest way, where the slope and orientation is given by the roof. Roofs in the direction close to south have been used for PV installation, while roofs with other directions have been rejected. The dimensioning regarding PV system size differs among the buildings, since some buildings have high overproduction while others almost have none. The motives must therefore been different when making these investments decision.

A suitable electricity load profile for the building that can match well with the electricity generation will lead to better profitability. The case studies of the economic evaluation showed that there are office buildings with district cooling and electric cooling that both can have profitable PV system investments, the building with electric cooling was more profitable. From the study it is not possible to draw any conclusions if the cooling system increases the profitability for the investment or if this result solely is because of an increase in electricity load. Instead the size of electricity load seem to be of more importance than the cooling system, since a higher electricity load results in a potentially larger PV system, decreasing the initial investment cost per kW_p.

The economic evaluations of the different case studies showed that there can be an optimum size for a PV system regarding net present value for different slope angles. This because of the relation between the value of the self-consumed electricity and the system investment cost. For the optimum PV size and several other profitable PV systems some percent of the generated electricity was fed into the grid. This means that some overproduction is acceptable. The sensitivity analysis showed that the discount rate and the electricity price scenario are important parameters that must be selected carefully since these have a large influence if the investment will be profitable or not. It was also shown that, with today's legal conditions, it is not profitable to sell the overproduced electricity when the self-consumption is much larger than the overproduction. Selling the electricity might be a better option if the self-consumption is low or much lower than the overproduction, but this must be further studied.

The economic evaluation of the PV systems showed a long payback period and there are uncertainties regarding costs and future legal conditions. There may be argument to not view a solar PV investment as any other investment with a high required rate of return, because of those reasons. The investment could instead be motivated with something else, for example an improved environmental profile or to secure the future electricity price, and in turn, be allowed to use a lower discount rate. Clarifying and reducing the uncertainties of the legal conditions for a PV investment would probably increase the economic feasibility, since the technical, legal and economic conditions today as shown in the case studies is good enough to make a PV investment profitable.

10 Future studies

It is recommended for future studies of the economic feasibility for solar PV in Swedish office buildings to study a larger number of office buildings that represents typical Swedish office buildings to be able to draw general conclusions. It is also recommended in these studies to consider additional costs from having a loan and to use hourly estimated electricity prices instead of yearly average, since the property owner probably takes a loan and since the electricity prices showed great importance for the profitability. Another study could include the reasoning of property owners regarding investments of green technology, such as PV systems to investigate how low discount rate that would be acceptable. In this thesis building attached PV (BAPV) system has been studied, but for new buildings or refurbishment of existing buildings the building integrated PV systems (BIPV) where other costs can be reduced might be more interesting. It would also be interesting to study if it is economically viable for building with low self-consumption of the generated electricity and high overproduction to sell the overproduced electricity and to investigate options for the property owner of office buildings to be considered as a micro-producer, since these have more benefits. For example if it would be possible to install the PV system so that the fuse of the system would determine if the system would be considered as micro-production, and not the main fuse of the building.

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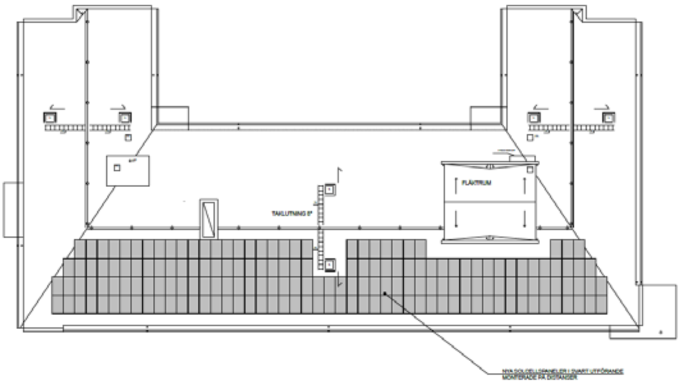
Appendix A – Information of the Studied Buildings

Vasakronan Uppsala

Location:

Address:	Dag Hammarskjölds väg 50, 752 37 Uppsala
Longitude:	17.64
Latitude:	59.84



Building details:

Building year:	2004
Renovation year:	-
Area (tempered):	5721 m^2
Levels:	4
Specific energy performance:	150 kWh/m^2/year
Property electricity:	60 kWh/m^2/year
Roof type:	Double-pitched
Roof area:	1175 m^2
Description:	The long side of the building is facing southeast and the roof is double-pitched with a slope of 8°. 97% of the building is used as office, the rest is used as storage.

Energy systems:

Cooling system:	Electrical driven cooling machine.
Heating system:	District heating.

Solar PV system:

Installation date: 2014-02-19

Peak power: 43 kW$_p$

Estimated annual production: 40 000 kWh

Modules:	177 solar polycrystalline modules of ET solar 255Wp with an area of 281 m^2.
Inverters:	2 inverters from SMA, one of 17 kW and one of 20 kW maximum AC power. (Sunny Tripower 17000TL-10 and Sunny Tripower 20000TLEE-10)
Mounting:	The panels are installed directly on the roof with same slope as the roof. Azimuth: 11° towards east Slope: 8°

A-huset Linköping

Location:

Address: A-huset
Linköping University
581 83 Linköping
Longitude: 15.58
Latitude: 58.40

Building details:

Building year: 1972
Renovation year: 2007
Area (tempered): 34 307 m^2
Levels: 3
Specific energy performance: 184 kWh/m^2/year
Property electricity: 33kWh/m^2/year
Roof type: Sawtoothed
Roof area: 15 301m^2
Description: The building has been renovated several times and the latest renovation was in 2007 which included renovation of ventilation system, lightning, district cooling and implementation of a solar PV system. The building consists of 60% classrooms, 25% laboratory rooms and 15% of office rooms.

Energy systems:

Cooling system: District cooling
Heating system: District heating

Solar PV system:

Installation date: 2007
Peak power: 65 kW_p
Estimated annual production: Unknown
Modules: 421 modules GPV-150 polycrystalline and 18 Gaia solar semitransparent modules, whereof 12 of them 67W and 6 of them 155W.
Inverters: 11 inverters from Powerlynx, all of them Powerlynx PGI 4.5 with 4.6kW maximum AC power.
Mounting: Special designed mounting system for the modules made of aluminium.
Azimuth: 0° Slope: 30°

Akademiska hus Solna

Location:

Address:	Campus Solna Berzelius väg 8 171 77 Solna
Longitude:	59.35
Latitude:	18.03

Building details:

Building year:	1960
Renovation year:	2011
Area (tempered):	1829 m^2
Levels:	5
Energy performance:	201 kWh/m^2
Property electricity:	37 kWh/m^2
Roof:	Pitched
Roof area:	Unknown
Description:	The whole building is used for office purposes.

Energy systems:

Cooling system:	District cooling.
Heating system:	District heating.

Solar PV system:

Installation date: 2013-05-23
Peak power: 26 kW$_p$
Estimated annual production: 22 000 kWh

Modules:	106 polycrystalline modules of type Suntech Power STP245-20/Wd with a conversion efficiency of 15.1 % on an area of 177 m^2.
Inverters:	Two inverters from SMA are used, one of 15 kW and one of 7 kW maximum AC power.
Mounting:	The solar PV panels are installed directly on the roof with same slope. Azimuth: south - southwest Slope: 9°

Väla Gård Helsingborg

Location:

Address: Kanongatan 100A,
250 13 Helsingborg
Longitude: 12.74
Latitude: 56.08

Väla Gård 2012. Photo: Skanska Sverige, Klas Andersson.

Building details:

Building year: 2012
Area (tempered): 1750m^2
Levels: 1-3
Specific Energy performance: 8kWh/m^2/year taking solar electricity into account.
Property electricity: 7 kWh/m^2/year
Roof: Pitched, flat
Description: The whole building is used as office. The building consists of two main building blocks with double pitched roof and three floors, whereof two floors are used for office. These buildings blocks are connected by a one floor building block with a flat roof.

Energy systems:

Cooling system: By increasing the airflow with cooled air into the room the cooling demand is met. The cooling coil uses free cooling from the bore holes in the ground source heat pump systems when the supply air temperature is too high.

Heating system: A ground source heat pump system produces both heating and domestic hot water with four variable heat pumps. This system is dimensioned to produce more than estimated peak load for the four building it supplies, whereof Välagård is the first building. The two main buildings both have their own radiator system which is controlled from master air supply devices.

Solar PV system:

Peak power: 70kW$_p$
Estimated annual production: 65 000kWh
Installation date: Autumn 2012
Modules: 288 monocrystalline solar modules of 245W from Naps Saana with a module efficiency of 15.6% on an area of 455m^2.
Inverters: 5 SMA Sunny Tripower 17000TL inverters.
Mounting: Building-applied photovoltaics with same slope as the roof.
Azimuth: Southwest (45°) Slope: 45°

Bengt Dahlgren Mölndal

Bengt Dahlgren´s Office building in Mölndal (Jönsson & Olsson, 2013).

Location:

Address:	Krokslättsfabriker 52, 431 37 Mölndal
Longitude:	57.67
Latitude:	12.01

Building details:

Building year:	2010
Area (tempered):	4113
Levels:	6
Energy performance:	75 kWh/m^2/year
Property electricity:	46 kWh/m^2/year
Roof type:	Flat
Roof area:	390m^2
Description:	The building serves as an office but has also a canteen for the staff, two conference rooms, a server room and a changing- and relaxing room. It has a mechanical solar shading system, with lamella angles adjusted by season. The lighting is mainly controlled by the demand and incoming sunlight.

Energy systems:

Cooling system:	Air is used as energy carrier for cooling. The room temperature is allowed to vary and is not controlled to a fixed value. In absence of people the temperature are allowed to vary more. An electrical driven cooling machine cools the server room and the KK-room has a cooling demand all year around.
Combined cooling and heating system:	Reversible outdoor heat pumps are used for cooling or heating the air depending on the need.
Heating system:	District heating is used when the demand is higher than what the internal load, heat recovery and solar insolation contribute to. The heating is done by radiators. Heat recovery from the cooling machine for the server is used for heating hot water and partly for the radiators.

Solar PV system:

Installation date: 2010

Peak power: 7.05kW$_p$

Estimated annual production: 5000 kWh

Modules:	30 modules of 235W from PV Enterprise on an area of 50m^2.
Inverters:	Fab StecGrid 9000 3ph with a maximum power of 10.5kW.
Mounting:	The modules are mounted on racks with a distance of 1.9m. Azimuth: south Slope: 20°

Appendix B - Evaluation and Selection of Simulation Software's

The software's IDA ICE, Polysun and PVsyst have been evaluated to analyze how well these programs perform compared to measured electricity generation data. The purpose of the evaluations was that the company wanted to invest in software for simulation software of solar PV system. IDA was included since the company already had this program available and it would be the easiest to use with no additional costs. A Polysun license was given by the University. PVsyst was suggested by many people from the field of solar PV in Sweden. The solar photovoltaic system located at the office building Solna has been used to perform the evaluation.

Method

To evaluate the simulation software's it would be preferred to import weather data (temperature, global and diffuse irradiance) for the studied year into the programs to generate results for the comparisons. This weather data must be measured at the exact location if one wants to evaluate the PV system by hour. Since there is no such data, an attempt of using data from STRÅNG together with data from SMHI from nearby weather stations was made. The data from STRÅNG had a lot of errors ranging from 30% up to 60% compared to measured values, which also showed in form of calculating negative values for the diffusive irradiance. Due to this and the fact that importation of weather data into IDA seemed to be limited it was chosen to use the following method:

Simulations were made for each program with their existing climate files for a normal year of the certain location. The values for global irradiance were then collected from Polysun and PVsyst, while for IDA the direct and diffuse irradiance was extracted since the global irradiance was not given. The global irradiance for IDA was calculated from equation X, where G is the global irradiance, D is the diffuse irradiance, I_n is the direct normal irradiance and z is the zenith angle[1] (NREL 1, 2014). The solar altitude is the angle between the sun and the ground and was calculated with help of an online calculator by NREL[2] (NREL 2, 2014).

$$G = D + I_n \cos z$$

The global irradiance for the normal years was then together with measured value for the real period used to calculate scaling factors. These scaling factors were then used to correct the simulation results on a monthly basis. The measured global irradiance data was collected from SMHI from a station close to the solar PV system. This data had not been checked by SMHI and had therefore some faults in form of negative and low values measured irradiance during the nights. Values below 2.3 W/m^2 were set to zero to eliminate this fault, since this was about the highest value that occurred during the night. The drawback of the method is that it is not taking into account the temperature, which influences the efficiency of the solar cells.

Input data

In IDA it is only possible to fill in the efficiency, the tilt, the azimuth and the area. The nearest climate file was for Bromma. The area was calculated from specifications

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[1] http://rredc.nrel.gov/solar/glossary/gloss_g.html, 2014-11-11

[2] http://www.nrel.gov/midc/solpos/spa.html, 2014-11-14

of the module[3]. The result of electricity generation was obtained per hour. Student version used.

In Polysun the same type of module (Suntech Power STP245-20/Wd) was used, but the same type of inverter was not found in the software (15kW and 7kW). Therefore 17kW and 5kW inverters were chosen from the same brand SMA, since the configuration will give the same possible power output. All other setting was kept to default values. The climate data was taken for the locations longitude and latitude. The result of electricity generation was obtained per hour.

In PVsyst the same type of module and inverters were used. The climate data was taken for the locations longitude and latitude. The result of electricity generation was obtained per month.

Result and discussion

The result from the evaluation can be seen in Figure A. According to the result, PVsyst matches the existing plants measured values best, followed by Polysun and lastly IDA. Both PVsyst and Polysun have good estimations during the spring and summer months, while the result for the winter months differs especially for January when it is a lot higher. An explanation to this lies in the method used. By scaling the generation by the global irradiance it probably leads to an overestimation when there are conditions of low global irradiance under which the solar PVs cannot generate electricity. These conditions most likely occur during the winter, when the irradiance is lower in general. The difference in result between PVsyst and Polysun might be explained by the different input values in terms of inverters, since they use the same weather database MeteoNorm. The low performance of IDA can be explained by two factors. Firstly an additional calculation was made for IDA, which increases the uncertainties. Secondly the program as stated before is very limited and does not take into account parameters that affect the electricity production such as technology and temperature, therefore could IDA be used as an initial guess to see the potential.

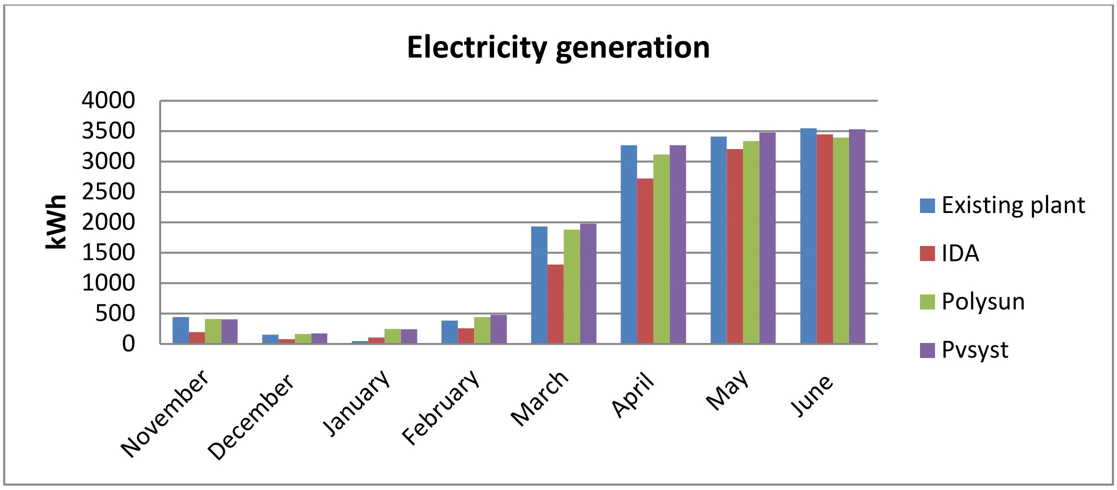

Figure A. Shows the measured and simulated electricity generated.

It is hard to tell which software of Polysun and PVsyst is the best since the result cannot completely be compared due to difference in the generation of result. On the other hand PVsyst seem to have a larger component database compared to Polysun

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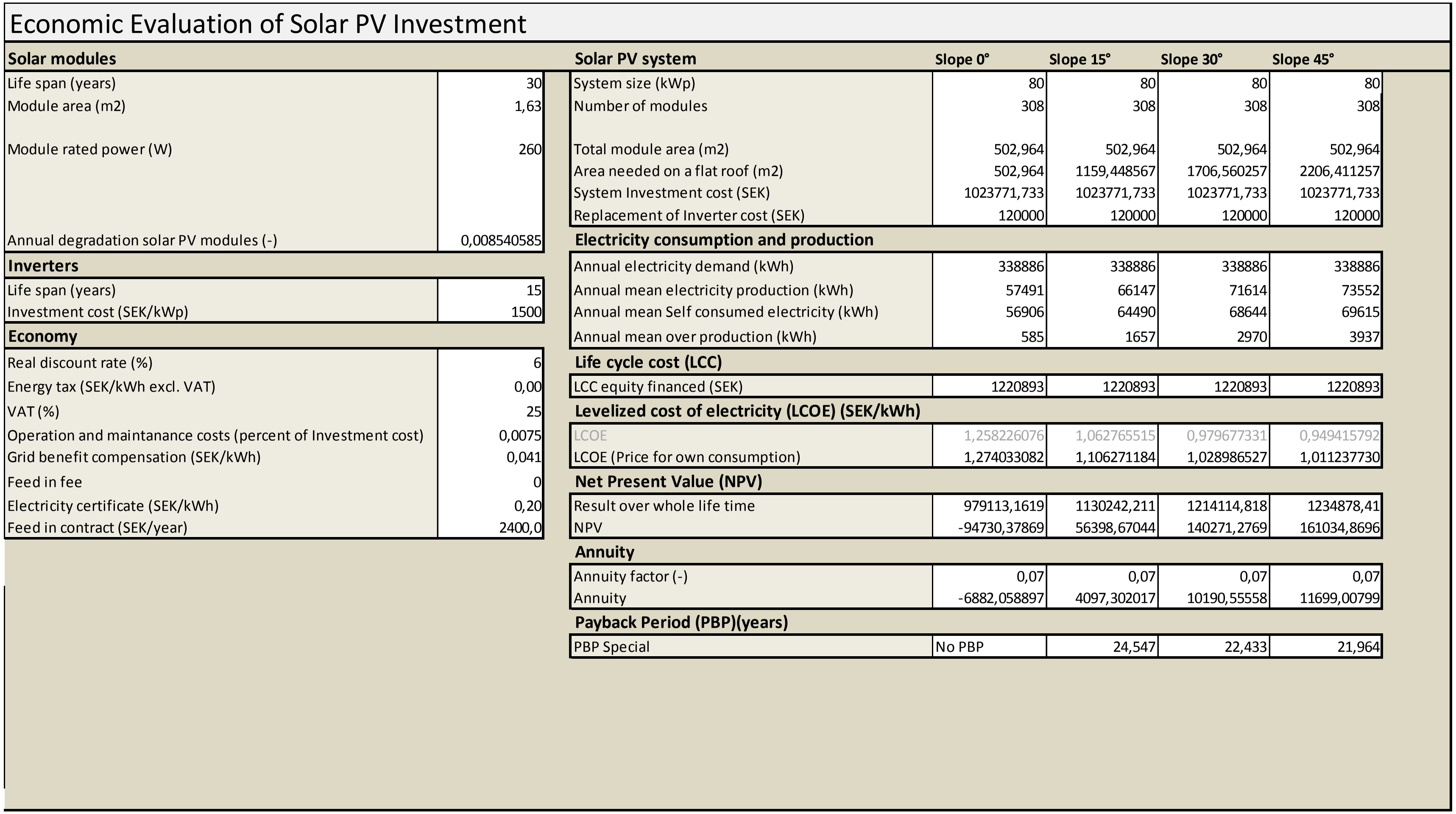
[3] http://www.elektropartners.nl/local_resources/file/zonnepanelen/STP250.pdf , 2014-11-11

and more details regarding the system design can be chosen by the user. PVsyst requires more knowledge about PV systems design, while Polysun is easy to use for a complete beginner. For example in PVsyst the PV arrays must be selected by the user, but in Polysun this is already defined when selecting an inverter. The economic evaluation seems to be more advanced for PVsyst as well. PVsyst has been recommended by several people working in the field. Although PVsyst seems to be the better program for simulations of PV systems, Polysun was chosen. The reasons is that the program is easy to use, with pre-defined inverter configurations and has less parameters to define which means that it will be easier to make comparable PV systems. Polysun has commonly used solar modules and inverters representing today’s technology, which is enough since it is not interesting to use different types of solar modules and inverters.

Appendix C – Interface of Economic Evaluation in Excel Tool



Economic Evaluation of Solar PV Investment

Solar modules	
Life span (years)	30
Module area (m2)	1,63
Module rated power (W)	260
Annual degradation solar PV modules (-)	0,008540585
Inverters	
Life span (years)	15
Investment cost (SEK/kWp)	1500
Economy	
Real discount rate (%)	6
Energy tax (SEK/kWh excl. VAT)	0,00
VAT (%)	25
Operation and maintanance costs (percent of Investment cost)	0,0075
Grid benefit compensation (SEK/kWh)	0,041
Feed in fee	0
Electricity certificate (SEK/kWh)	0,20
Feed in contract (SEK/year)	2400,0

Solar PV system	Slope 0°	Slope 15°	Slope 30°	Slope 45°
System size (kWp)	80	80	80	80
Number of modules	308	308	308	308
Total module area (m2)	502,964	502,964	502,964	502,964
Area needed on a flat roof (m2)	502,964	1159,448567	1706,560257	2206,411257
System Investment cost (SEK)	1023771,733	1023771,733	1023771,733	1023771,733
Replacement of Inverter cost (SEK)	120000	120000	120000	120000
Electricity consumption and production				
Annual electricity demand (kWh)	338886	338886	338886	338886
Annual mean electricity production (kWh)	57491	66147	71614	73552
Annual mean Self consumed electricity (kWh)	56906	64490	68644	69615
Annual mean over production (kWh)	585	1657	2970	3937
Life cycle cost (LCC)				
LCC equity financed (SEK)	1220893	1220893	1220893	1220893
Levelized cost of electricity (LCOE) (SEK/kWh)				
LCOE	1,258226076	1,062765515	0,979677331	0,949415792
LCOE (Price for own consumption)	1,274033082	1,106271184	1,028986527	1,011237730
Net Present Value (NPV)				
Result over whole life time	979113,1619	1130242,211	1214114,818	1234878,41
NPV	-94730,37869	56398,67044	140271,2769	161034,8696
Annuity				
Annuity factor (-)	0,07	0,07	0,07	0,07
Annuity	-6882,058897	4097,302017	10190,55558	11699,00799
Payback Period (PBP)(years)				
PBP Special	No PBP	24,547	22,433	21,964