CHALMERS

Evaluation of PV Systems in Gårdsten

Master's Thesis within the Sustainable Energy Systems programme

HELEN ELIZABETH HERRERA HUMPHRIES

Department of Energy and Environment
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2013

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HELEN ELIZABETH HERRERA HUMPHRIES

SUPERVISOR:

Maria Haegermark

EXAMINER

Jan-Olof Dalenbäck

Department of Energy and Environment
Division of Building Services Engineering
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden

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Department of Energy and Environment
Division of Building Services Engineering
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Installation of the PV system mounted in the balcony of a building in Gårdsten

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ABSTRACT

This thesis evaluates the performance of a balcony-mounted PV system and analyses the best tilt angle and size for installing roof-mounted PV systems on four other building blocks located in Gårdsten, Sweden.

A major aspect considered is the size of the PV systems in relation to the use of electricity in the building blocks where the PV systems are installed. The thesis investigates the electricity used from 2010 to 2012 for the Kastanjgården building blocks where the existing balcony-mounted system was installed and the Lönngården building block where the planned roof-mounted PV systems will be installed. The investigation shows that the hourly average electricity use in the summer months are of the order 15 kW early mornings and about 30 kW during daytime, i.e. when the PV system is at maximum.

The Kastanjgården PV system has a nominal power of close to 20 kW, i.e. well below the electricity demand during daytime. The PV system electric output was simulated in the software Polysun and compared with the measured electricity generated by the PV system. A first comparison indicates that the measured PV system yield is less than simulated by Polysun. The PV system has so far only been measured during a short period during the spring 2013 and it is too early to conclude if the simulations are being too optimistic or if the plant is not performing as expected.

Furthermore, a sensitivity analysis for different tilt angles was also conducted for three commercial PV modules available in Polysun. The best tilt angle found was used to simulate a 20 kWp PV system and to compare it with a PV system of equal capacity but with modules horizontally installed. A module with 40° tilted angle for the location studied gives 30% higher electric output per module area compared to modules tilted 0° and 90°. However, a horizontal installation (0°) may give a higher electric output per roof area. The choice should be based on the electric demand profile and the system cost.

Key words: Photovoltaic, energy yield, monocrystalline silicon, electricity use

CONTENT

PREFACE

This work is submitted as partial fulfilment for the master degree in Sustainable Energy Systems and it evaluates a PV plant which is part of the third phase of the Solhus project regarding the refurbishment of the Gårdsten area with solar systems. The project is carried out at the Department of Energy and Environment, division of Building Services Engineering, Chalmers University of Technology.

This work has been carried out with PhD student Maria Haegermark as supervisor and Professor Jan-Olof Dalenbäck as examiner. I would like to give special thanks to Jan-Olof for all the permanent technical support and commitment during the execution of the work, and to Maria Haegermark for her valuable comments. I would also like to thank staff from DirectEnergy Company, especially Petter Sjöström, for providing the information about the plant and its output data, and to PhD Johan Kensby for supply the information regarding the load demand measurements.

Finally, to my parents, sister and husband, all my gratitude and thankfulness for the support and encouragement during the whole process. This work is dedicated to you, without whom none of this would have been possible.

Göteborg June 2013

Helen Herrera

Notations

Roman upper case letters

BIPV	Building Integrated Photovoltaic
PV	Photovoltaic
STC	Standard Test Conditions
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
AC	Alternating Current
DC	Direct Current
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
SOC	State of Charge
Y_f	Final PV System Yield
P_o	Array Nominal Power
E_{out}	Annual Energy Output
PR	Performance ratio

Roman lower case letters

$a - Si$	Amorphous silicon
$m - Si$	Monocrystalline silicon
$p - Si$	Polycrystalline silicon

1 INTRODUCTION

Accurate and regular evaluations of the performance of photovoltaic (PV) systems are determinant to ensuring the continued development and expansion of the PV industry. The evaluation of the performance of PV systems provides benefits for all the PV market participants, from manufacturers of components to customers. The evaluation results can serve as benchmarking strategy for products and PV system company owners. They can also be used by R&D groups to identify future needs and source of improvements; and they can help guiding future decision of system-installers and customers as for example choosing the products with the best qualities. (Marion, et al., 2005)

1.1 Background

In a world constrained by fossil fuel resources and environmental problems such as climate change, the high share and rapid growth of the electricity demand imposes a challenge for the energy industry. In helping facing those challenges and achieving the EU targets for 2020 and 2050, not only improvements in the energy conversion efficiency of current systems are needed, but also alternative systems involving new sources such as renewables need to be developed.

With a worldwide total share in primary energy consumption of around 40% (IEA-news, 2012) and a trend expected to rise, the buildings constitute a target sector for many European countries which are driving efforts into a carbon-neutral energy system. Therefore, strong policies that backup the integration of renewable energy resources into current and new systems are being implemented. However, even with these policies, there are still fourth-fifths of the potential in the buildings sector for improving energy efficiency that remains unexploited (International Energy Agency, 2012).

The most common renewable technologies based on solar energy applied in buildings are solar thermal collectors and Photovoltaic (PV) modules. The former convert sunlight into heat and the latter directly into electricity. These two technologies also have the advantage that they can be integrated in a building envelope, thus performing two tasks at the same time: generating electricity/heat and replacing a structural component. Building integrated solar collectors are often used to supply hot water. Building Integrated PV (BIPV) systems are often connected to the electric grid.

Currently, the PV market in Sweden has a small share in the total electricity generated; however, it is consistently growing. Although off-grid connected systems have a stable market, the grid-connected systems are still dependent on capital subsidies. However, is due to the latter and to the ongoing reduction in the price of PV modules that the PV capacity in Sweden has been increased.

In the middle of May 2005 the government introduced the first capital subsidy for PV systems in Sweden. This subsidy scheme of 150 million SEK for PV systems on public buildings lasted until the end of 2008. It covered 70% of the cost of the PV installations with a maximum support of 5 million SEK per building (Palmblad, et al., 2007). After that, a second capital subsidy of 60 million SEKwas introduced in July 2009 to support grid-connected systems completed by the end of 2011. This subsidy was 10% less than the one of 2008 but it was opened for every type of system and owner, and not only restricted to public buildings as before. However, in November

2011, the subsidy was extended for installations completed by the end of January 2013, but only covering up 45% of the installation, system component and planning costs, and not exceeding 1.5 million SEK per system, a quantity 0.5 million less than the implemented in 2009.

Lately another 210 million SEK was allocated by the Swedish government for the period 2013-2016. From the 1th of February 2013, the subsidy was reduced and only covers 35% of the installation, system component and planning costs, and cannot exceed 1.2 million SEK per system, i.e. a further reduction in comparison to previous years due to lowering in system costs.

So far, the subsidies in Sweden have shown positive results in terms of both pursuing the goal of having 17 TWh of electricity generation coming from renewables from 2002 until 2016, and creating niche applications, which is crucial for increasing and spreading the knowledge and information about the PV systems. Besides, it has also shown an increased interest and has developed skills among the different stakeholders in the solar industry and the public in general, facts that facilitate the PV diffusion. However, the uncertainty regarding the PV diffusion for grid-connected systems still remains, because more subsidies than the given so far are still needed in the future to ensure the launch of this type of systems.

One of the PV niche projects in Sweden began in the year 1997 with the establishment of the company Gårdstensbostäder AB, which in turns is owned by the city of Gothenburg and was created with the purpose of managing, developing, and renovating the apartments of the district of Gårdsten, an area part of the “Million New Homes Programme” in the north-eastern part of Gothenburg.

Under the name of Solhus, Solar houses, Gårdstensbostäder in close collaboration with its tenants, starts a renovation project in 1998. The purpose was to decrease energy use in the residential buildings by implementing different measures such as: installation of heat recovery on ventilation; replacing existing inner part of the double-glazed windows with low emission glass; renovating the roofs by integrating solar collectors and adding more insulation; renovating the laundry room with equipments connected to the hot water system; installing sensors for the lighting of common areas and individual metering systems for heating, electricity and water. Besides, they add new common spaces such as greenhouses on the ground floor of the balcony access buildings. This project was also thought to serve as an example for other communities in how commitment can create better environments to live, and to inspire architects and building engineers with new aesthetic concepts. (Gårdstensbostäder, 2004)

The first part of the project, Solhus I, was finished after three years of preliminary work in the year 2001, and the second part, Solhus II, four years after, in 2005. Both phases comprise 3 blocks with 255 and 245 apartments respectively connected to a Solar Heat Collectors System installed in the roof. Solhus I was developed by a single contractor –Skanska-, and Solhus II through 31 different sub-contractors, both projects received financial supports for being included as EU projects. (Gårdstens-bostäder, 2004)

As the third stage of the Solhus project, the development of Solhus III started in 2009. Within it a variety of solar solutions has been proposed. For the first phase, different energy saving measures such as the installation of solar heat collectors for generating heat for the district heating network of the city have been arranged. On the second phase, PV modules in the facade (balconies) and in the roof of the buildings have been and will be integrated in 2013, so to convert solar radiation into electricity. Under the names of Solar PV-1 for the modules integrated in the balcony, and Solar PV-2 for the modules installed in the roof, both systems would be evaluated during the present master thesis work.

In order to evaluate the feasibility of PV systems and their potential for increased energy market penetration, the operational characteristics need to be considered in addition to the installation, technical characteristics, and economics.

1.2 Purpose

This work aim is to evaluate the performance of a Photovoltaic (PV) system installed in the balcony parapet of 24 residential apartments and one large office located in the first floor that are part of the Kastanjgården block of buildings. Moreover, suggestions will be given about the tilt angle and size for installing PV solar modules in the flat roof of four other building blocks in the Gårdsten area: Oxelgården, Lönngården, Askgården, and Poppelgården.

1.3 Objective

The objective of this master thesis is to generate the electricity profiles for the demand of the Kastanjgården and the Lönngården building blocks and for the electric output of the PV system installed in the balconies of the Kastanjgården building south facade. Data from simulations for the electric output of the PV system will be compared to gathered data, and these two in turn with the demand of the building. The sensitivity to the angle of inclination of three commercially available modules with different technologies will be assessed. Furthermore, an evaluation of the extent to which the PV plant meets the electricity demands of the buildings will be done.

1.4 Method

The performance of the building under this study was evaluated by using measurements data for both the demand of the building block and the current output of the PV plant installed in its balconies. In addition, data obtained from simulations with the software Polysun were also used.

Measurement data for the electricity demand for the Kastanjgården building block during the last three years was analyzed and compared to real and simulated electricity output data for the PV system with 20 kW_p capacity. A special emphasis was put on analyzing the electricity profiles during the months of lowest electrical demand (May, June and July) in order to study how large the PV system can be, and to compare that information with the actual size of the system. The comparison is done using daily values for months and hourly values for days.

The performance during working environmental conditions was evaluated by using the AC electrical output per collection area, per installed rated power, and per total building area as parameters. Due to lack of real data, information regarding the irradiation energy in the Gårdsten area where the PV system is located was obtained from the Polysun simulation software data base.

To complement the study, a sensitive analysis for different inclination angles ranging from 0° to 90° was conducted for three different PV module technologies: Polycrystalline silicon, Monocrystalline silicon, and Thin-Film (CIGS) modules with the same power output of 20 kW_p. This information is intended to serve as comparison for the PV system installed in the Kastanjgården building with modules tilted 90°, besides intends as a guide to decide on the best tilt angle to install solar panels on four other buildings blocks.

Literature review in relevant areas of the project has also been conducted.

1.5 Limitations

The PV system was put into operation in early January, but properly data collection began until February. Thus, the actual electric power output could only be measured for three months (February, March, and April), and important months like June and July could not be included for comparison with simulations data.

Concerning the simulations performed in Polysun, results are based on historic average data in a normal year registered in the data base for the locations selected, and thus they differ from real conditions in which the PV system operates. Based on this, a detailed comparison between calculated and measured daily patterns is not relevant and cannot be done.

2 THEORY

2.1 Solar Photovoltaics (PV)

Each year, the earth receives from the sun 10 000 times more energy than the amount we use from fossil fuels, hydro and nuclear power (Azar, 2009), and many nations worldwide are becoming more and more aware of its potential to meeting climate challenge.

Solar energy is able to cover the different energy needs of a building, from heating, lighting, domestic hot water, to electricity and space cooling. Besides the direct benefits sunlight can provide to buildings – light during the day, space heating due to the green house effect- it can also be indirectly use by two technologies: Solar thermal collectors and Photovoltaics modules. Those technologies rather than compete against each other constitute a complement for supplying all the energy demands of a building.

2.1.1 Fundamentals

Photovoltaic (PV) systems are devices which converts the sunlight into electricity in a virtually silent way. They are made of PV modules (also called PV panels), what allows the photovoltaic systems to be built in different sizes, i.e., by adding modules the total output can be easily increased. The photovoltaic systems are very reliable and have low maintenance requirements because they do not have any moving parts. Besides, they do not emit any green house gases during operation, and the amount emitted during the manufacturing is very low. It takes 1-2 years for a PV module to generate the equivalent energy that has been used during manufacturing, and it will continue working for about 20 years or more.

The PV module is the main building unit of a PV system, which in turns is made of a smaller parts called PV cell. A PV cell is constituted by two or more layers of semiconductor material, where the most common is silicon. When the photons of the sunlight strike the solar cell and are absorbed by the semiconductor material, the electrons are forced out from the atoms of the semiconductor material, creating electron-hole pairs. If both positive and negative sides of the solar cell are now connected through a load, a current will flow in the electric circuit formed, while the sunlight hits the cell. A typical electric circuit representing a solar cell is shown in Figure 2.1. This circuit can be used to represent from a PV system or array consisting of several modules, to a module consisting of a number of cells.

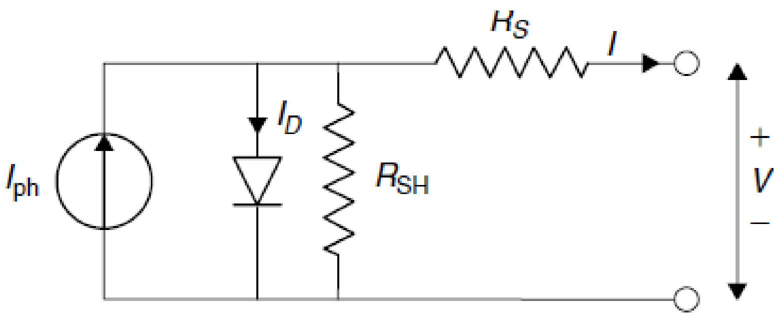

Figure 2.1 One diode-model of a single solar cell (Kalogirou, 2009)

2.1.2 Building Integrated PV (BIPV)

Building Integrated Photovoltaics (BIPV) is a PV application that almost delivers electricity at the cost of the grid electricity to end users in peak demand niche markets. Compared with PV systems one of the most important advantages of BIPV systems is that the PV modules can replace a particular building component, which in turn can diminish the purchase an installation of conventional materials, thus lowering the net costs of BIPV systems. The building envelope offers many possibilities for the inegrations such as slope roof, flat roof, façade applications and shading devices for windows (Brian Norton, et al., 2011 (Eke, et al., 2011)), as can be illustrated in Figure 2.2.

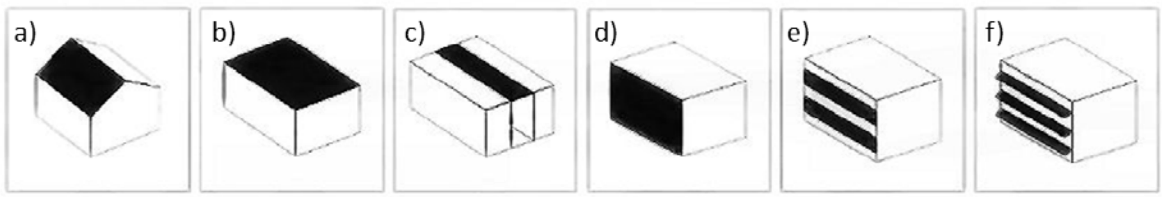

Figure 2.2 Integration typologies. a) tilted roof, b) flat roof, c) skylight, d) facade cladding, e) facade glazing, and f) external devices. (Farkas, et al., 2012)

The electric output of a BIPV system depends on different factor such as:

- The availability of and accessibility to solar radiation, which in turn is influenced by the climate, the inclination and orientation of the modules, and the urban setting;
- The PV technology which is related to facts such as the efficiency and its decline with time, and the cell temperature;
- The over shading in some areas of the modules.

2.1.3 Solar PV systems

When designing a BIPV system, one of the considerations that need to be addressed has to do with the intended application of the system. Two categories can be distinguished from this perspective: Grid connected systems and Stand-alone systems. On the one hand, the *grid connected systems* are the preferred option if an electric grid is available, which acts as a virtual storage system. The demand from the building is met by a combination of solar energy and grid electricity. These systems required an inverter to convert the DC (direct current) voltage into AC (alternating current) voltage. However, due to security reasons the inverters should be equipped with “anti-islanding” circuit that disconnects the solar system in case of blackout. This is in order to prevent the powering of the electrical grid and protect workers that might be working in the restoration of the electricity supply.

The electricity demand of a building varies depending on the activities and equipments that are switch on or off. In a similar way, the electricity generated by a solar system during a day varies with the change in weather conditions and the position of the sun in the sky. This may lead to periods where the demand of the building exceeds the solar electricity generated by the PV system or vice versa. In grid connected systems, when there is a surplus of electricity from the solar system, the excess is exported to the electric grid. When the PV system does not generate enough electricity to cover the consumption in the building, the lacking energy is provided by the electrical grid.

On the other hand, *stand-alone systems* are solar systems that work independently from the electricity grid in order to supply the load. They are used in sites were grid connection is not available or to which access is difficult, e.g. isolated houses, sparsely populated or poor regions. This type of PV systems needs to be coupled with storage equipment such as batteries, in order to be able to storage the surplus of electricity when it occurs. However, this additional component not only represents additional losses but also additional costs in comparison to grid-connected systems.

2.1.4 Solar PV technologies

Currently, different materials are being used in Photovoltaics such as silicon, arsenide, copper indium dieseline, indium phosphide, etc. The market is dominated by two main categories: crystalline silicon cells, and thin film cells. However, a more recently group is appearing in the market, the nanotechnology based solar cells. They all differ in terms of material, structure, manufacturing process, which at the end resulted also in different energy conversion efficiencies.

The crystalline silicon cells share a world market of about 85%. They are subdivided in two categories: monocrystalline (m-Si) and polycrystalline (p-Si) silicon cells. On the one hand, m-Si cells are made of one single crystal silicon, with a continuous lattice structure with few impurities. The main advantage of m-Si cells are their high efficiencies –the highest in the market- which are typically around 17-22%. However, the complex manufacturing process of cutting slices from silicon wafers make this type of cells slightly costly than other technologies. (Kalogirou, 2009). In Figure 2.3 it can be seen the dark blue/blackish colour appearance these cells have (Farkas, et al., 2012).

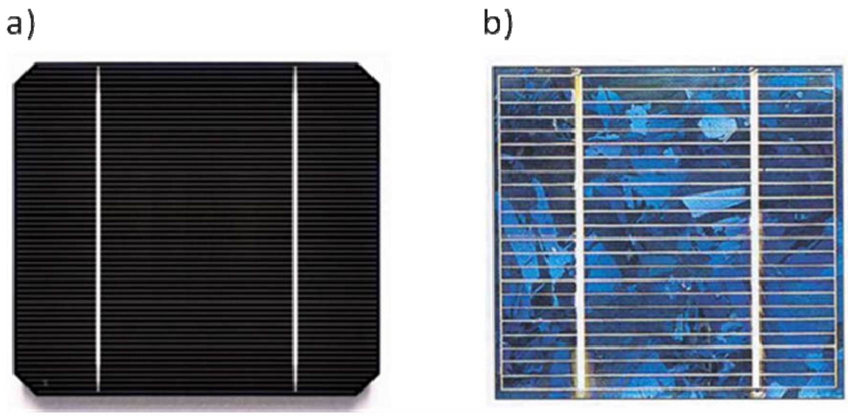

Figure 2.3 Crystalline silicon solar cells. a) Monocrystalline and b) Polycrystalline (Farkas, et al., 2012)

On the other hand, p-Si cells are produced using various grains of m-Si. The silicon is melted and cast into ingots where it solidifies into multiple crystals with different orientations, given the spotted and shiny appearance that can be seen in Figure 2.3. This manufacturing process is much simpler than the required by the m-Si cells, thus, they are cheaper than m-Si cells. However, since the casting process does not create uniform lattices, the overall efficiency is bringing down, with values around 11-17%.

The second technology type, the thin film cells, is made of different semiconductor materials. The semiconductor material is directly deposited together with their contact on a rigid or flexible substrate area that can be made of glass, stainless steel or polymers of different sizes. The main advantage of this type of cells is that they are potentially cheaper than wafer based crystalline technologies, since the manufacturing process only requires a small amount of material. Besides this, they can also be manufactured with a lower environmental impact, due to a production process that requires less energy than the one for crystalline technologies does. This is so because they can be deposited at quite low temperatures and do not require expensive purifications techniques, i.e., they can tolerate higher impurities than crystalline. (Farkas, et al., 2012)

According to the semiconductor material employed, this group can be subdivided into three main technology categories: amorphous silicon (a-Si), Copper Indium Gallium Selenide (CIS or CIGS) and Cadmium Telluride (CdTe), being the most developed the former, thus the most wide spread.

The a-Si solar cells differ from wafer based crystalline silicon cells in their atomic structure. They are composed of silicon atoms in a thin homogeneous layer instead of a crystalline structure. Furthermore, they absorb light more effectively than crystalline silicon, which allow thinner cells. However, and as for all the other thin film solar cells, the lower quality manufacturing process bring defects that lower the conversion efficiency compared to monocrystalline silicon cells. Historically, the a-Si cells have undergone the most development, however, the CdTe promises lowest production costs, and the CIGS cells has achieved the highest conversion efficiencies. The standard conversion efficiency of a-Si cells ranges from 5-7%, for a CdTe solar cells ranges from 7-8.5%, and for a CIGS solar cells ranges from 9-12%. The latter have reached efficiencies up to 18.7% at laboratory level. (Farkas, et al., 2012)

In general, this second generation of solar cells, i.e., the thin film cells have lighter weight, and can exist in opaque or semitransparent appearance, with colors ranging from brown/orange to purple and black, and parallel lines more or less marked as can be seen in Figure 2.4. The market share of these technologies is still behind the one for monocrystalline cells of 85%. Despite they have demonstrated operational lifetimes and dark stabilities under inert conditions during many hours. (Kalogirou, 2009)

A third generation of solar cells is emerging, and different stages of development can be distinguished. On the one hand, there are the emerging technologies, which are in the innovation phase, i.e., those solar cells technolgoies that have just started to be in regular production on the market. On the other hand, there are novel technologies, which are still in the invention phase, i.e. where it has been demonstrated the physical feasibility of the proposed technology, but where there is not hint on practically achievable conversion efficiencies or structure cost. (Farkas, et al., 2012)

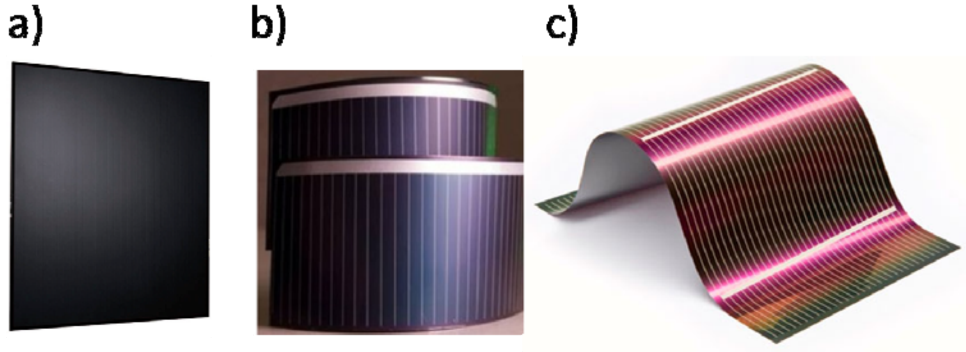

Figure 2.4. Thin film solar cells and modules. a) Amorphous silicon, b) CdTe, and c) CIGS (global solar, 2013)

Among the new PV technologies emerging, organic solar cells excel. They are attractive primarily due to the prospect of low cost substrates and active layer material, low energy input and easy up-scalling. This technology has an active layer consisting partially of organic dye, organic molecules or polymers which are appropriate for liquid processing. However, its main challenge is to improve their efficiency and stability. Two approaches can be clearly distinguished for this technology, the hybrid approach such as the Dye- sensitized solar cells which can be seen in Figure 2.5, and the full-organic hybrid approach. In the former, the organic cells holds an inorganic component, and the latter wich has organic cells and organic substrates.

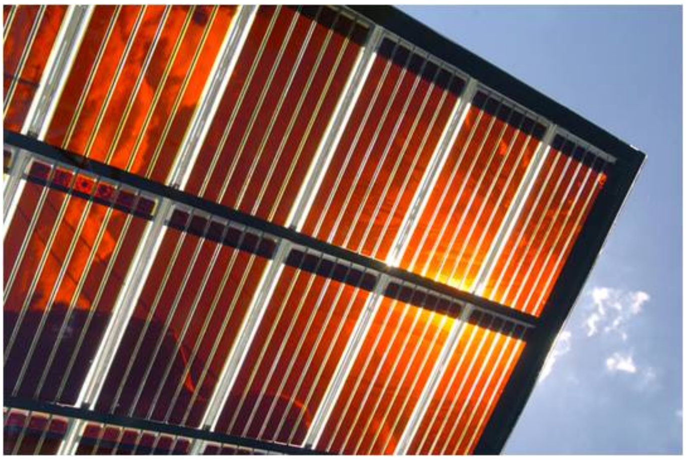

Figure 2.5 Dye-sensitized solar module. (©Dyesol)

2.2 Solar PV system components

Besides the photovoltaic modules, some other important equipment used in PV systems is batteries (in the case of stand-alone systems) and inverters. Next, the most important features of these components will be presented.

2.2.1 Modules

The modules constitute the main element of a PV system. They have life times of around 25 years, and are formed by group of cells, which are enclosed with various materials in order to protect them and the electrical connectors against the environment. A module contains N rows connected in parallel and each row containing M solar cells connected in series, as can be seen in the schematic shown in Figure 2.6.

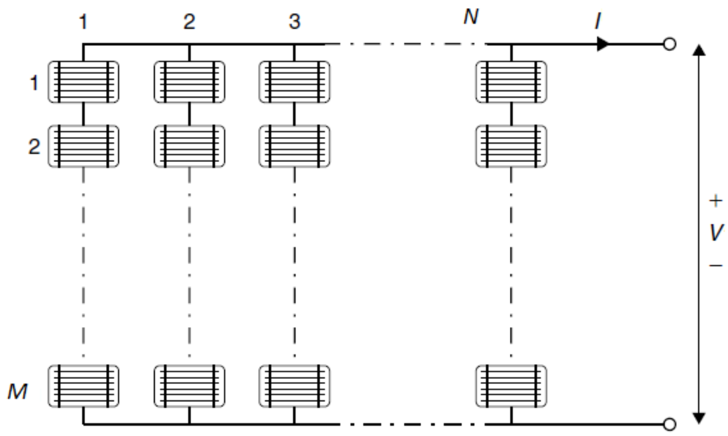

Figure 2.6 Schematic layout of a PV module with N parallel rows and M solar cells connected in series (Kalogirou, 2009)

The aggregation of solar cells in one module provides a higher voltage and power, i.e. a usable operating voltage, that cannot be obtain with one single cell that operates at 0.5 V. Usually the solar cells are connected in series to produce an operating voltage of around 14-16 V. These strings are then covered with a polymer, a front glass cover, a support material, and a junction box attached to the back of the module for allow electrical connections with other modules and electrical equipments, as can be seen in Figure 2.7. A Typical output power for a single module is around 180-250 W in bright sunshine days.

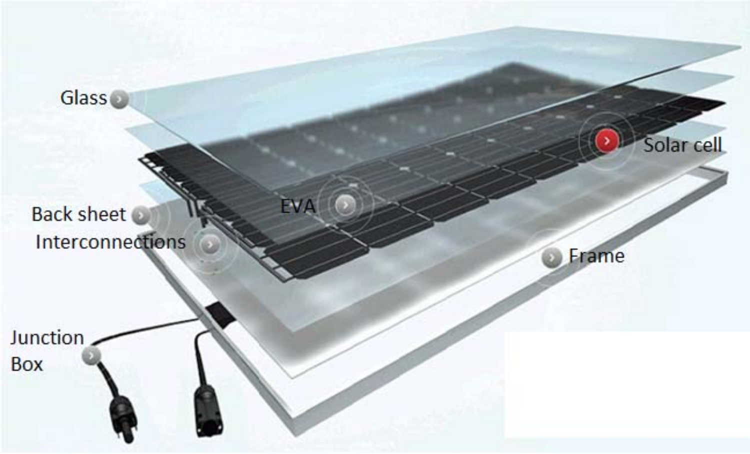

Figure 2.7 PV module structure for crystalline cells (©Robert Bosch GmbH)

2.2.2 Inverters

An inverter is an electric device which is used to convert the direct current electricity (DC) to alternating current (AC). Besides, they are also in charge of keeping a constant voltage on the AC side and to make the conversion at the highest possible efficiency. The inverter's efficiency depends on the portion of its rated power at which it operates. Its maximum efficiencies usually reaches above 90% for an input power level which is usually around 30% and 50% of its rated capacity. However, with values under 10% of its rated capacity, the efficiency of the inverter declines. (Brian Norton, et al., 2011)

The output of an inverter can be single or three phase. Sizing the inverter is extremely important for having a proper PV system performance. Inverter over sizing reduces annual efficiency substantially –due to stand-by losses-, and is more costly to buy and run. (Kalogirou, 2009). On the other hand, if it is undersized, it could shut off during operative conditions.

Inverters have been developed –particularly for BIPV applications- to improve the tracking of the maximum power point (MPP), and its reliability. An inverter with maximum power tracking (MPPT) system extracts maximum power from the PV array by varying the input voltage to keep the MPP voltage on thee I-V curve, since the PV output varies with solar radiation and module temperature. (Brian Norton, et al., 2011)

2.2.3 Batteries

Due to the intermittency nature of the solar radiation, batteries are required for many PV systems –mainly stand-alone systems- to store the electrical energy at times where the PV system covers and exceed the load, or when there in sunshine but no load required. Thus, they are used to supply power during times when the PV system cannot meet the demand or at night when no sunlight is available.

The selection of the battery type and size in mainly influenced by the load and availability requirements. They can be arranged in parallel to achieve higher storage capacity, and they need to be placed in spaces with good ventilation to avoid extreme temperatures. Unlike car batteries, batteries for PV systems need to be designed for sustaining repeated deep charging and discharging without damage.

The efficiency of a battery is defined as the ratio between the charge extracted during discharge and the amount of charge needed to restore the initial state of charge. Therefore, its efficiency depends on the state of charge (SOC), and the charging and discharging current. The state of charge oscillates between 0 (completely discharge) and 1 (completely charge) and is defined as the present capacity of the battery divided by its nominal capacity. (Kalogirou, 2009)

2.3 Evaluation of PV systems

The use of appropiate performance parameters makes easily the comparisson of PV systems that might differ regading design, technology, or geographic location. (Marion, et al., 2005). According to the different literatures reviewed, the most relevant parameters for evaluating the performance of PV systems are summarized in Table 2.1. (Senturk, et al., 2013)

The Final PV System Yield (Y_f) is a parameter that has been extensively used for its convenience when comparing the energy output among PV systems with different sizes, since it normalizes the energy generated with respect to the size of the system. It represents how many hours the PV systems needs to operate in order to give the same energy (Marion, et al., 2005). It is defined as the ratio between the total annual energy output (E_{out}) and the array nominal power (P_o), i.e. Installed PV power at Standard Test Conditions (STC), i.e., irradiance of 1000 W/m^2, module temperature of 25°C and air mass of 1.This relationship is expressed according to equation (2.1).

$$Y_f = \frac{E_{out}}{P_0}\left[\frac{kWh/a}{kWp}\right] \tag{2.1}$$

Table 2.1 Performance indicators

Parameter	Symbol
Useful Energy [kWh]	E_{out}
Nominal Power [W_p]	P_o
Final Yield [kWh/kW_p]	Y_f
Reference Yield [(kWh/m^2)/kW/m^2)] or [h]	Y_r
Performance Ratio	PR
Array efficiency	η_{array}
Overall system efficiency	$\eta_{average}$
PV module efficiency at STC	$\eta_{pv,STC}$
Module Temperature	T_m

The reference Yield (Y_r) is the total surface perpendicular irradiation (H_t) divided by the reference irradiation (G). If the reference irradiance is equal to 1 kW/m^2, Y_r represents the number of peak sun-hours in kWh/m^2. This parameter provides an indicator of the amount of solar radiation is available for the PV system, and it varies with the location, orientation of the PV modules, and weather variation. The relationship is expressed according to equation (2.2).

$$Y_r = \frac{H_t}{G}\left[\frac{kWh/m^2 \cdot a}{kW/m^2}\right] \tag{2.2}$$

The Overal system efficiency (η_{ave}) indicates into which extent the energy from the sun collected by the PV module area (A) is transformed into useful electric energy (E_{out}). The equation (2.3) shows how to calculate it.

$$\eta_{ave} = \frac{E_{out}}{H_t x A} [\%] \quad (2.3)$$

The performance ratio (PR) is a parameter that account for the overall effect of losses when comparing the PV system ouput during normal operation with its theoretical output, i.e., a PV system operating at STC. Some of the source of losses are inverter efficiency, wiring, mistmatch and other conversion losses; PV module temperature; limited use of irradiance by reflection of the module front surface; soiling or snow; system down-time; and component failures. (Marion, et al., 2005) It is defined as the ratio between the final yield and the reference yield and shown in equation (2.4).

$$PR = \frac{Y_f}{Y_r} \quad (2.4)$$

The PR is typically reported in monthly and yearly basis, and only measured in smaller intervals for identifying if a component is failing. Recorded PR values during winter are greater than in summer due to PV module temperature losses, and are typically around 0.6-0.8. A decreasing PR value is an indicator of a permanent performance loss. (Marion, et al., 2005)

2.4 Cost of solar PV systems

In despite of the individual characteristics of the different PV technology types, they all compete in the same market for having the lowest cost of generating electricity, i.e., the price per Watt peak (e.g. SEK/Wp). A consequence of this is that is possible to cover different areas for the same price by picking different technologies. Thus, if there is no limitation in area, it does no matter which technology type is chosen, while if there is a limitation, those technologies with the highest efficiencies will be more favourable, i.e., crystalline technologies.

A photovoltaic system total cost includes the PV modules price and the inverter, the cabling, the switches, the mounting system, and the installation cost. However, the modules share 40-60% of the total PV system cost. Depending on the type of product, if it is a standard module or custom made, and from which country it comes, the price of the PV module per Watt peak can varies greatly.

Currently the market expansion and the increments in production volume are causing a slowly but steadily drop for all the prices. According to the last National Survey Report of PV Power Applications in Sweden (Lindahl, 2013), not only the installation costs for typical turnkey PV systems in Sweden has been declining from 2010 to 2012 but the difference in prices among the systems of similar capacities and characteristics are declining as well.

In the case of grid-connected roof PV systems mounted in commercial buildings with an installed capacity higher than 10 kW, the prices range from 11 SEK/W to 22 SEK/W, with an average price of 16 SEK/W. For grid-connected roof PV systems in houses with an installed capacity between 1-5 kW, the prices range from 14 SEK/W to 30 SEK/W, with an average price of 22 SEK/W. Meanwhile, the off-grid-connected roof PV systems with an installed capacity up to 1 kW has prices ranging from 14 SEK/W to 36 SEK/W, with an average price of 26 SEK/W.

3 SYSTEM DESCRIPTION

The residential area of Gårdsten is located at the north-eastern part of Gothenburg, Sweden in the suburb of Angered, as can be seen in Figure 3.1. Gothenburg has an oceanic climate according to Köppen climate classification which is characterized by summers with extended periods of daylight (around 17 hours), and cold and windy winters with few hours of daylight (around 7 hours). Regardless of its northern latitude, the temperatures over the year are mild, oscillating around 10°C to 19°C during the summer and around -5°C to 3°C during the winter. Precipitation occurs regularly but moderate during the year, and snow mainly take place from December to March, and sometimes during October and May. (Wikipedia, 2013)

The 5-story building where the PV system is located is part of the "Million Programme" houses. It holds Gårdstensbostäder offices in the first two floors and residential apartments in the next three floors. It is located at the Kanelgatan 3 address which has the geographic coordinates 57° 48' 14.26''Latitude and 12° 1'31.17'' Longitude; with an elevation of 131° and a yearly sum of horizontal global irradiation of 939 kWh per square meter.

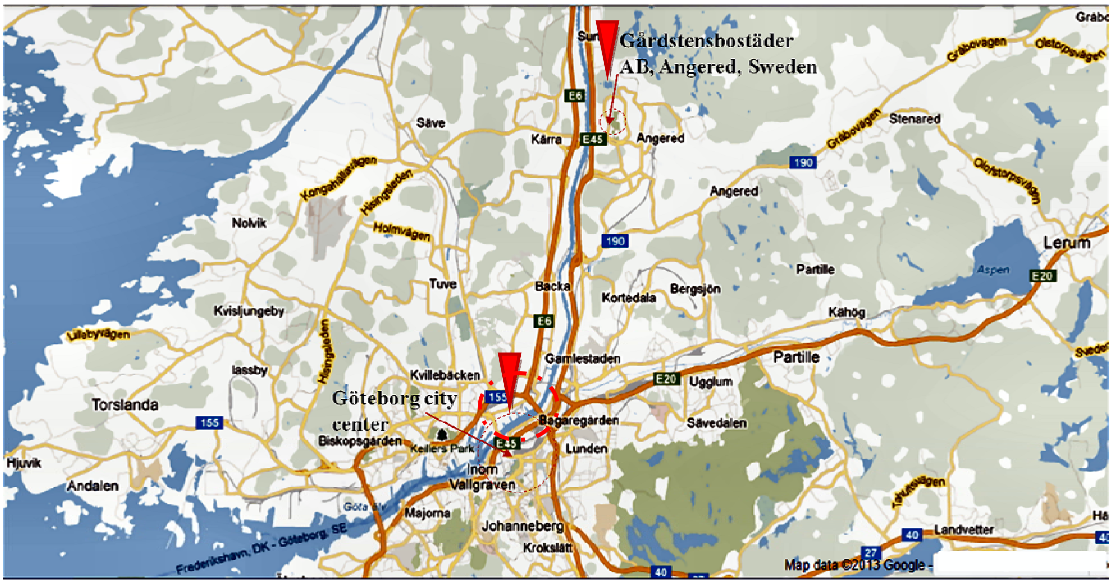

Figure 3.1 Geographic Location of the Gothenburg city and PV system in Gårdsten

As part of the refurbishing in the area, four additional buildings located in Peppargatan street -Oxelgården, Lönngården, Askgården, and Poppelgården- will have either roof integrated or roof-mounted PV systems. The top view of these buildings, as well as for the one with PV modules in the balconies is shown in Figure 3.2.

The PV system in Gårdsten is part of Solhus 3, the third stage of the Solhus project. It was developed with collaboration of CHALMERS, Gårdstensbostäder and Direct Energi. The plant was inspected and put into operation in early 2013 under the supervision of CHALMERS that is also in charge of evaluating the system during the year 2013. A detail view of the PV system can be seen in Figure 3.3.

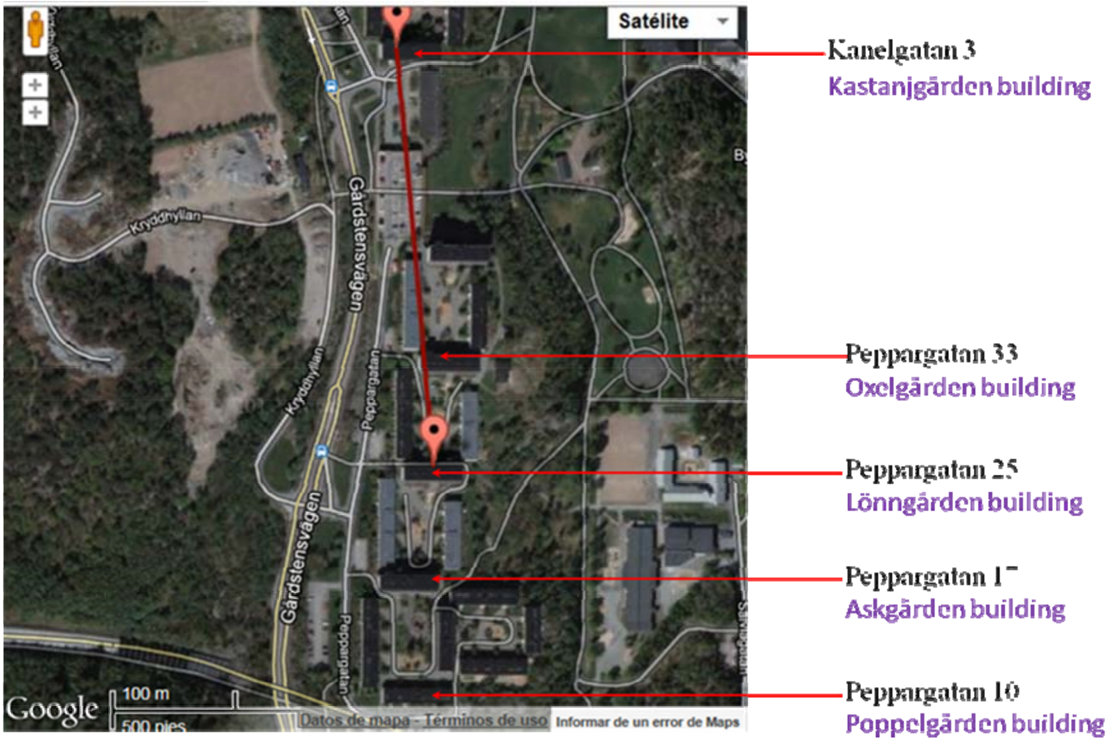

Figure 3.2 Top view of Solhus 3 area

Figure 3.3View of the PV plant integrated to the Kastanjgården building

3.1 Kastanjgården PV System

The facade of the Kastanjgården building was refurbished and PV modules were integrated into the front of the balconies during October-December 2012 and connected to the grid in January of 2013. The modules were mounted at a tilted angle of 90° (vertical) and the building is oriented facing south –orientation of 0°-. A layout of the PV system mounted in the building can be seen in Figure 3.3.

The PV system comprises a total of 270 solar modules which give a total gross area of 173.68m^2. The peak power under Standard Test Conditions (STC) for the whole system is 19.66kW$_p$. The PV system was specially customized to fit the dimension requirements of the balconies, thus they are not commercially available. The number of modules mounted per balcony varies from three to five and their width and height vary as well. Table 3.1 and Table 3.2.

present detailed information of the different sizes of the modules. As it can be seen, the modules type CV32 and CV48 have three different size variants, and modules type CV80 and CV120 have six different size variants.

In the plan 6 of the building where the flat roof is located, 33 modules type CV120 and 12 modules type CV48 are arranged. Similarly, in the five remaining plans where the residential and office apartments are located, 33 modules type CV80 and 12 modules type CV32 are arranged per plan for a total of 165 modules type CV80 and 60 modules type CV32. Detailed information about the layout and disposition of the modules in the building can be found in Figure 3.4.

Table 3.1 Sizes of the modules in the apartment-balconies and b) roof-balcony

Module-type variants	Width [mm]	Height [mm]	N° of pieces	N°cells
CV32A	434	753	25	8
CV32B	450	753	25	8
CV32C	454	753	10	8
CV80A	934	753	30	20
CV80B	893	753	50	20
CV80C	943	753	25	20
CV80D	925	753	25	20
CV80E	976	753	25	20
CV80F	983	753	10	20

Table 3.2 Sizes of the modules in the roof-balcony

Module-type variants	Width [mm]	Height [mm]	N° of pieces	N°cells
CV48A	450	1053	5	12
CV48B	434	1053	5	12
CV48C	454	1053	2	12
CV120A	925	1053	5	30
CV120B	976	1053	5	30
CV120C	893	1053	10	30
CV120D	943	1053	5	30
CV120E	934	1053	6	30
CV120F	983	1053	2	30

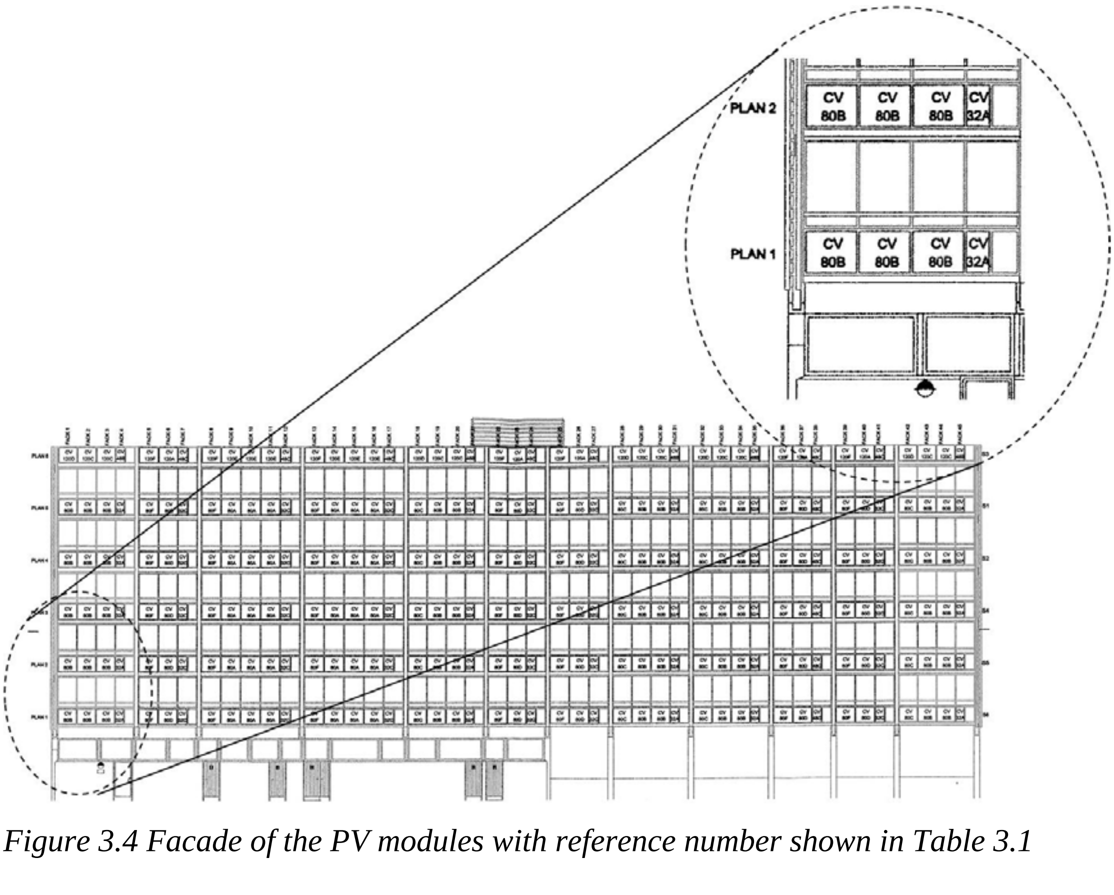

Figure 3.4 Facade of the PV modules with reference number shown in Table 3.1

The modules were manufactured by the Italian company Solbian Energie Alternative S.r.l. with the SolbianFlex technology. They are made of monocrystalline cells and laminated with a special thin light black polycabornate plastic polymer that has high chemical and mechanical resilience (Solbian Energie Alternative srl, 2012); which also offers weather protection. The type of PV modules employed are covered by the same testing certificate of the models CVXXL in compliance to the Kiwa Guideline DT ki-0409 for Solar Products and Components. Table 3.3 provides technical specifications of the four types of modules installed and Figure 3.5 provides a close view to the modules mounted. The modules were attached to the balcony parapet with stainless steel bolt with elastic lock nut and with double sided adhesive tape.

The PV system is grid-connected and will first of all reduce the amount of electricity bought from the grid. This is mainly because it is more profitable to replace the bought electricity than selling the generated one to the grid. No additional power storage systems such as a battery are been employed.

Table 3.3 Technical specifications of the PV Modules under STC (at 1000 W/m² irradiance, AM 1.5 and 25°C cell temperature)

Model	CV80	CV32	CV120	CV48
No of modules installed	165	60	33	12
Maximum Power (±3) [W_p]	80	32	120	48
Efficiency [%]	11.3	9.8	12.7	12.0
V_{oc} [V]	12.2	4.9	18.3	7.3
I_{sc} [A]	8.5	8.5	8.5	8.5
V_{mpp} [V]	9.7	3.9	14.5	5.8
I_{mpp} [A]	8.1	8.1	8.1	
Temperature coefficient (T_c) P_{max} [%/°C]	-0.45	-0.45	-0.45	-0.45
Temperature coefficient (T_c) V_{mp} [%/°C]	-0.3	-0.3	-0.3	-0.3
Temperature coefficient (T_c) I_{mp} [%/°C]	0.01	0.01	0.01	0.01
Height [mm]	753	753	1053	1053
Width [mm]	934	434	934	434
Weight [kg]	2.1	1.0	2.8	1.4
W_p/m^2	113.7	97.9	104.9	105.0

Figure 3.5 Overview of the installed modules (a) from the outside and (b) from the inside of the balconies; together with a closer view of each in (b) and (d) respectively

3.2 Inverter

The solar system has a total of two inverters sunny tripower STP 10000TL-10. The 270 solar modules were wired in 6 strings, with each string made of 45 modules in series, and 3 strings connected per inverter for two inverters in total. The inverters generate three-phase AC 230V/400V/50Hz and were manufactured by the company SMA Solar Technology AG and supplied by the company IBC Solar. *Table 3.4* provides technical data of the inverters used to convert the direct current (DC) energy generated into alternating current (AC). A diagram showing the multi-string array configuration can be seen in Figure 3.6. As can be seen, inverter 1 (V1) have strings 1 to 3 connected and inverter 2 (V2) have strings 4 to 6 connected. The first three levels of the building have strings 4 to 6 (S4 to S6), and the next two levels and roof-level have strings 1 to 3 (S1 to S3).

The AC voltage data is collected for each inverter and measured together in the ODIN meter supplied by ABB.

Table 3.4 Inverter Specifications

Inverter type	STP 10000TL-10
P_{out} [W]	10400
Max. V_{in} [V]	1000
Max I_{in} (Input A/Input B) [A]	22 A / 11 A
Max I_{out} [A]	16 A
Nominal V_{out} [V]	230 / 400V
AC connection	Three-phase

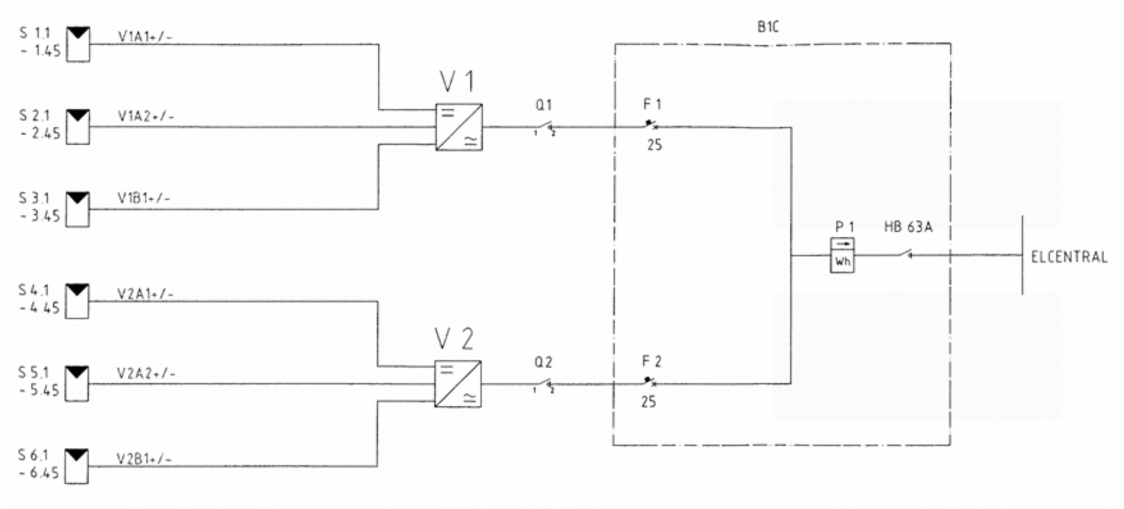

Figure 3.6 PV electric power string diagram

3.3 Data Acquisition System

The data of the solar power plant is monitored in the data logger Sunny WebBox. It continuously records and stores all the values measured for the two inverters. The recorded performance values of the solar system can be easily accessed through direct connection of the Sunny WebBox and a PC computer with internal browser and internet connection. Data is saved in conventional CSV or XML file formats and can be seen in the Sunny portal as well.

A display is also installed with the system showing to the public some electrical outputs of the PV plant (See Figure 3.7). The following parameters can be seen in the display:

- Actual power (W)
- Electric Energy Output (kWh)

- Distance Produced (mil)

The latter parameter indicates the distance that can be travelled with electric cars by using the electricity generated from the PV plant.

Figure 3.7 Display system installed in the basement of the building facade

3.4 System Costs

The system has a maximum electric output of 14 848 kWh/m^2,yr at Standard Test Conditions (STC), and its cost was calculated around 83 400 SEK/kW$_p$, whereof the modules themselves cost 43 080 SEK/m^2, i.e. 52% of the total system cost.

A 45% of the installation costs of the system were subsidized by the Swedish government thanks to the capital subsidy that was in place since the mid-2009 until 31th January 2013.

4 MEASUREMENTS AND ANALYSIS

During this chapter, measurements of the electric demand for the Kastanjgården and Lönngården building blocks will be presented. In addition, the electric output profile for the balcony-mounted PV system will also be displayed.

The Kastanjgården building block is comprised of two buildings (see Figure 4.1), one of which has installed the PV system in the facade. The block has 48 apartments with a total area of 3502 m^2, and one large office with an area of 777 m^2 that covers a floor and a half of the building at Kanelgatan 3 where the PV system is installed. On the other hand, the Lönngården is comprised of three buildings, which has 77 apartments with a total area of 5582 m^2. The buildings have different sizes.

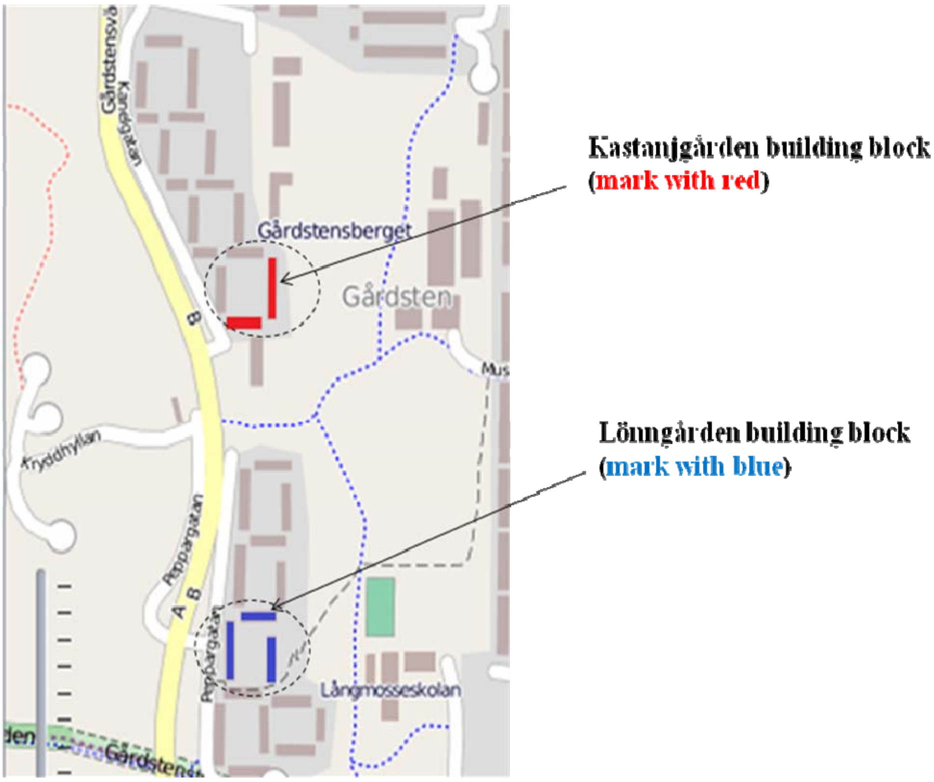

Figure 4.1 Map view of the location of the Kastanjgården and Lönngården building blocks

4.1 Electricity Demand

In the designing process of a PV system, besides the location and orientation, other aspects such as the building's electric use need to be considered for sizing the system. The electric load can vary significantly with occupancy and the characteristics of the building in both residential and non-residential buildings. In a grid-connected PV system, the optimal diurnal load profile to be satisfied do not match with the total load during night and winter (Norton, et al., 2011), mainly due to the mismatch between solar irradiance and daily building peak load. The above, from an economic point of view it is not optimal because the selling price for the electricity is less than the buying price. In Sweden, the retail price for household is about 1.72 SEK/kWh and the end-user energy price for industrial consumers is about 0.67 SEK/kWh approximately.

In order to evaluate how good the Kastanjgården PV system was sized, and to investigate a suitable size for the roof-mounted PV system in the Lönngården building, which avoid over generation all time and gives the best economics, the load characteristics of these two buildings will be investigated and results will be displayed in monthly and hourly basis. The hourly values results will be presented for one week in summer. This is mainly due to the risk of over generation during the summer months when the peak generation of the PV plant occurs at the same time as the off-peak load demand.

Comparing the demand profile of the two building blocks under this study from 2010 to 2012, the electric demand in the Lönngården building was always lower than for the Kastanjgården building, as can be seen in Figure 4.2. The peak demands that occur in winter time (January, February and December) are lowered each year for the two building blocks, however the trough demands that occurs during summer months (June, July and August) remain at the same level for the block with only residential apartments (Lönngården building) at a value of around 21000 kWh. However, from the year 2010 to 2011 in the block with residential apartments and offices (Kastanjgården building), the demand during summer months was reduced by 12%, and remain almost the same from 2011 to 2012 with only a small reduction of 3%.

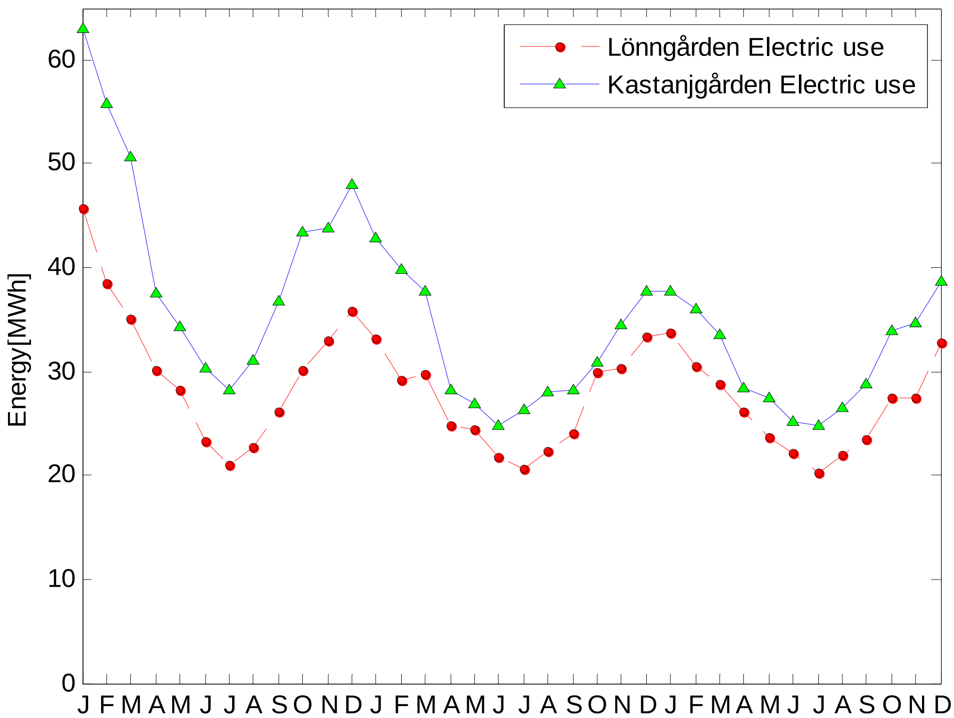

Figure 4.2 Monthly electric energy usage from 2010 to 2012

4.1.1 Kastanjgården building block

The monthly electric demand values of the Kastanjgården building block during the years 2010 to 2012 are presented in Figure 4.3. The two months with the lowest electricity demand are June and July, nonetheless, May and August also present low demand values. During July, the demand is around 63% lower than during January, which is the month with the highest load demand along with February and December.

The total electricity demand has been declining each year as can be seen in Table 4.1. The major reduction was from 2010 to 2011 with 23%, and 3% from 2011 to 2012. The lowest demand value among the three years studied occurs in June of 2011. Both years, 2011 and 2012 present very similar demand profiles.

During the year, the electric demand varies from 19 kW to 133 kW in 2010, from 16 kW to 96 kW in 2011, and from 16 kW to 92 kW in 2012.

Table 4.1 Overall demand data for the Kastanjgården building block

	2010	2011	2012
Lowest electricity demand [kWh]	28 214	24 853	24 869
	July	June	July
Annual demand [kWh]	502 745	385 900	375 859

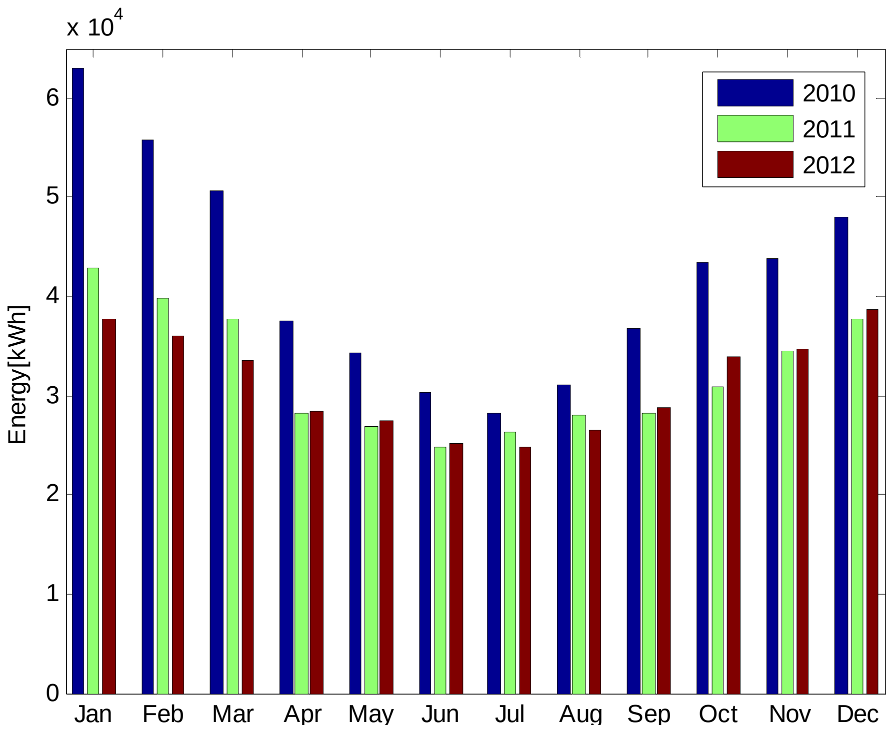

Figure 4.3 Monthly annual energy usage in the Kastanjgården building

Hourly electric usage profiles for a relevant week –a week with the lowest power demand values over a year - in summer are presented in Figure 4.4 for years 2010 to 2012. The lowest power used was 16 kW, and occurred during morning hours in 2011 and 2012. The minimum power for each weekday is sharp, being the lowest at 5:00 in the morning. The highest use of electricity during the day did not present a sharp peak; rather, it is distributed evenly between 10:00 and noon, with values up to 54 kW. No significance differences can be appreciated among the different weekdays; however, differences are appreciated along the day. In the evening and night, the electricity usage declined in comparison to afternoon hours, however, not to lower values than electricity usage during early hours in the morning. It is probably that the offices in the building block are the responsible for the increased usage of electricity in the afternoon versus in the evening and night.

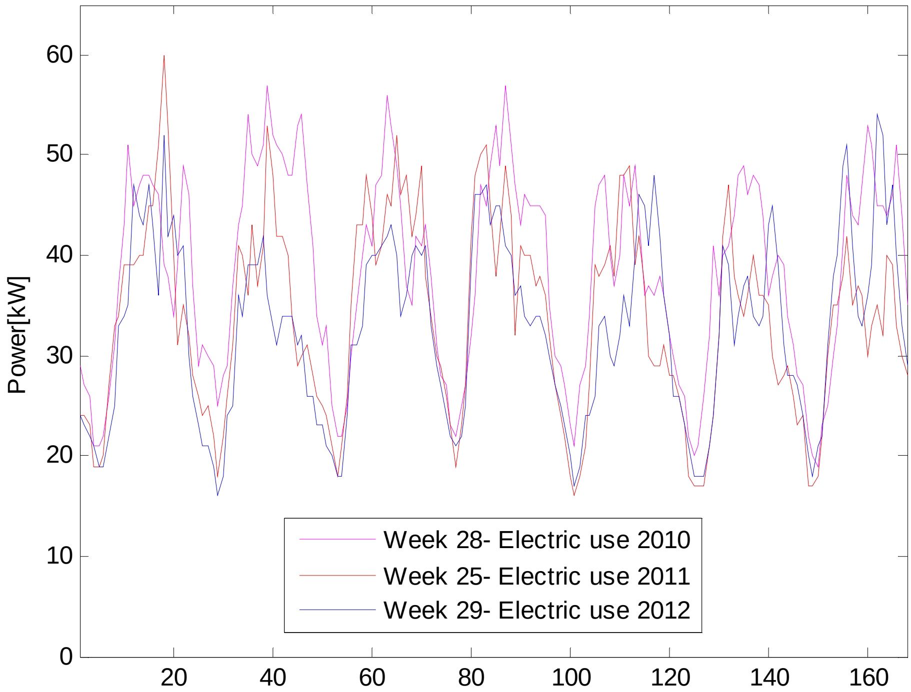

Figure 4.4 During this section, a relevant week is referred as a week with the lowest power demand values over a year.

4.1.2 Lönngården building block

The monthly electricity used in the Lönngården building block during the years 2010 to 2012 is presented in Figure 4.5. The month with the lowest electricity demand was July for the three years considered in this analysis as can be seen in Table 4.2. The demanded electricity during July is around 61% lower than the demanded during January, the month with the highest load demand along with February and December.

The summer months (June, July and August) demanded the lowest electricity, while winter months demanded the most. Though the electric used during spring and autumn was similar, the electricity used during autumn for both 2010 and 2012 was higher.

Table 4.2 Overall demand data for the Lönngården building block

	2010	2011	2012
Lowest electricity demand [kWh]	21 046	20 556	20 334
	July	July	July
Annual demand [kWh]	369 644	323 676	318 715

The electricity used was declining along the three years period studied. The major reduction was from 2010 to 2011 with 12%, and around 2% from 2011 to 2012. The electric demand reached in July is almost the same for the three years studied; only changing 2.3% from 2010 to 2011 and 1% from 2011 to 2012, being the lowest in July of 2012.

In a yearly basis, the electricity used varied from 15 kW to 268 kW during 2010, from 13 kW to 82 kW during 2011, and from 13 kW to 86 kW during 2012.

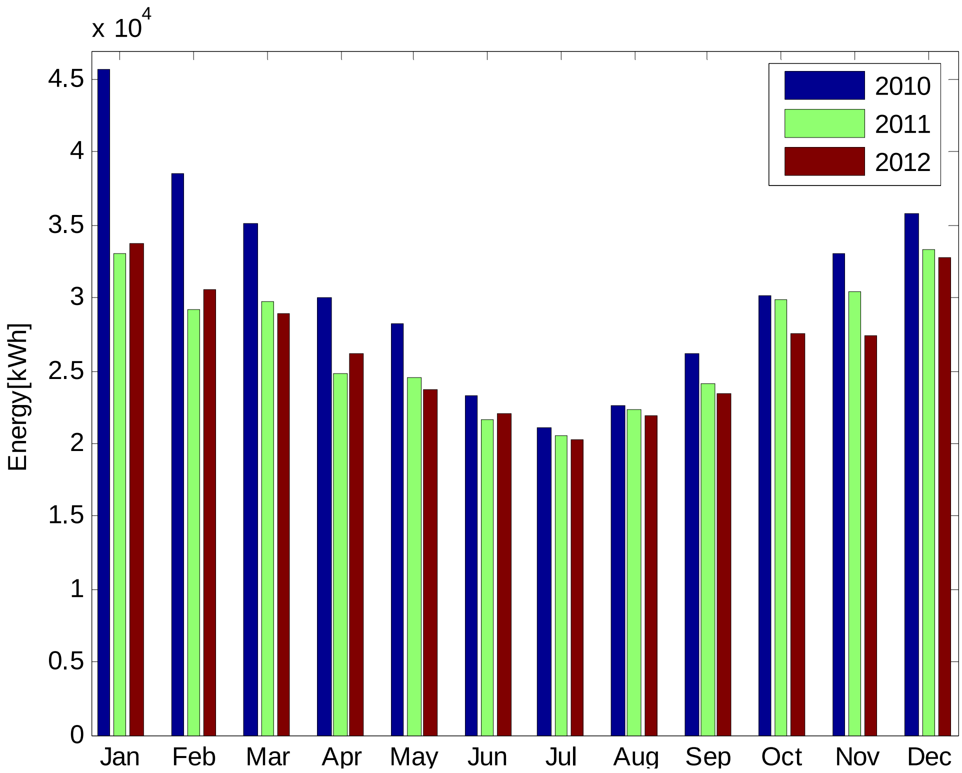

Figure 4.5 Monthly annual energy usage in the Lönngården building block

An hourly basis analysis for the electricity used during 2010 to 2012 is presented in Figure 4.6. This is so to take into account hourly variations in the demand for electricity, which becomes of importance when sizing a PV system to avoid overproduction at any time. For the Lönngården building block the same representative weeks as for the Kastanjgården building block were chosen, i.e. weeks

28, 25 and 29 for years 2010, 2011, and 2012 respectively. As with the Kastanjgården building block, no major differences are appreciated among the weekdays, however, the off-peaks values were lower for the Lönngården building block. In 2012 for example, the lowest power consumed during week 29 was 13 kW, and the highest was 48 kW. During a day, the Lönngården building block had its greatest electric consumption towards the evening, when people come back from work; while for the Kastanjgården, the major electric consumption occurred during the morning until noon with more distributed and less pronunictaed peaks. In general, it appears that for the electricity usage profile of a week, the troughs –hours when the electricity use was at its minimum- were smoother than the ones of the Kastanjgården building block. For the three time period studied the power electric used oscillates from 25 kW to up to 52 kW.

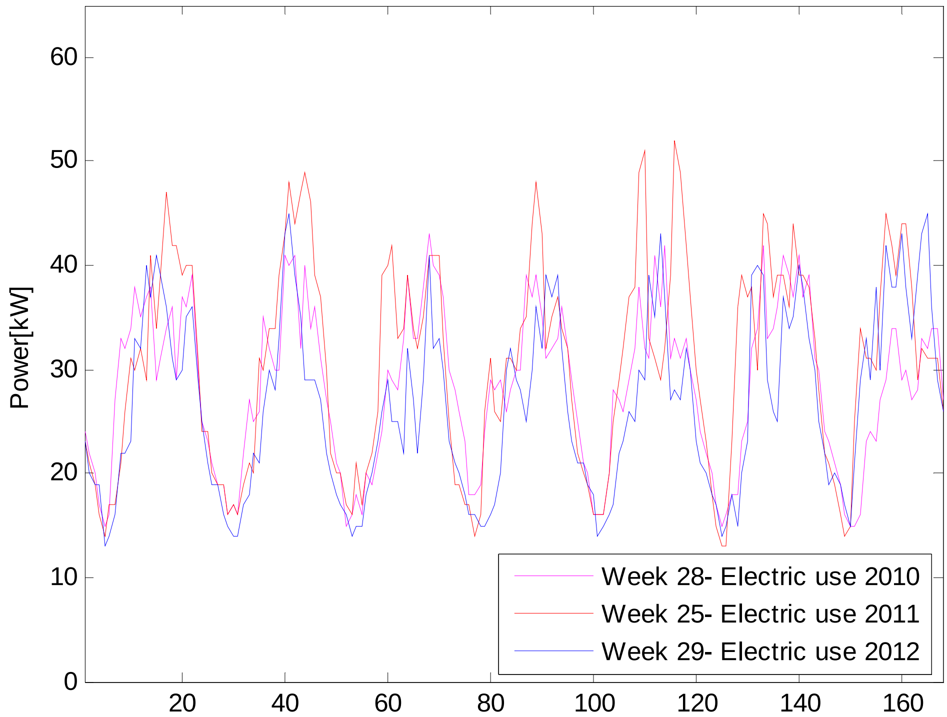

Figure 4.6 Electric load profile for the most representative week in Lönngården building

4.2 Electricity Output of the PV System

The electric output of the Kastanjgården PV system will be presented during this section. Only data from the 24th January to the 6th May 2013 will be presented, which is the period in which it was possible to access the data. In Figure 4.7 the monthly recorded electric PV output is presented along with the electric demand values for 2011.

The percentage of the electricity use in Kastanjgården building covered during this time by the PV system is presented in Table 4.3.

During winter months (January and February) where solar irradiation is low, the electric output of the PV is not even able to cover 1% of the electric used for the same time period in 2011. However, major percentages are covered by the plant during spring months (March, April, and May). Even though there are no data yet for the whole year 2013, the performance of the PV plant indicates clearly that the demand of the building block cannot be exceeded.

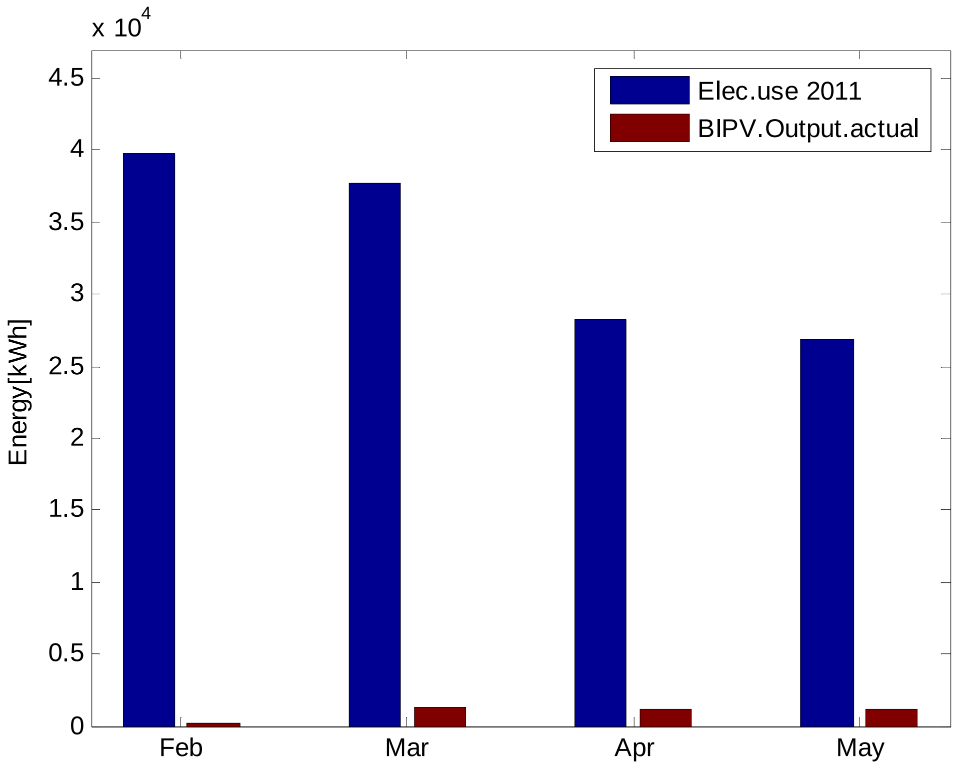

Figure 4.7 Monthly values for the electric use and PV output from February to May

Table 4.3 Monthly values for the electricity generated by the solar PV plant

	Electric Demand 2011 [kWh]	Electric Output from PV system [kWh]	Covered electric use by the PV system [%]
Jan 24 to Jan 31	10 755	29	0.27
February	39 756	265	0.67
March	37 669	1 276	3.39
April	28 242	1 101	3.90
May	26 892	1 149	4.27

It is to notice, that the PV electric output measured during January, February and the first four days of March correspond only for the electricity given by one of the inverters, i.e., inverter 21104XXXXX. This is so because the other inverter - 21102XXXXX V2- was broke down and replace since March 5, as stated by Petter Sjöström, CFO at Direct Energy Sweden AB.

In order to analyze the individual behaviour of each inverter, daily values for each month were analyzed from March 5, month in which both inverters began operating at the same time. In Figure 4.8, the daily electric output of the PV system is presented for April. As can be seen, inverter 21102XXXXX was given in average 11 kWh more than inverter 21104XXXXX for all the days until April 24; this was due to a faulty string in the latter inverter. Then, after this day and until the last day of April, the inverter 21104XXXXX started giving an average of 5 kWh more than inverter 21102XXXXX.

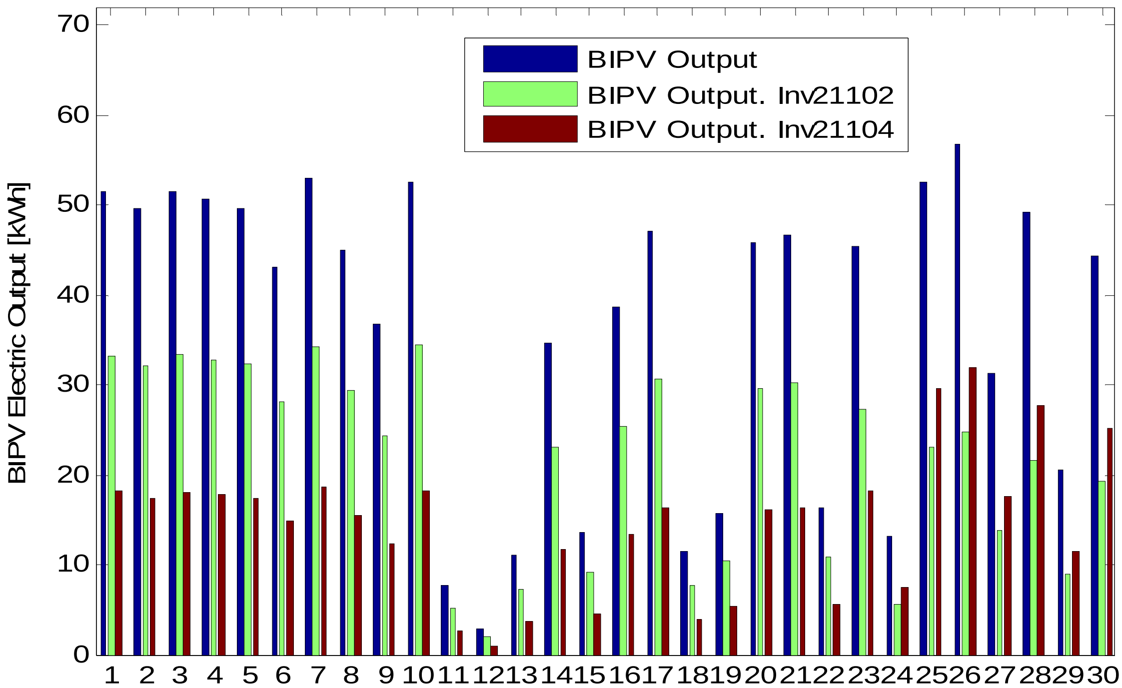

Figure 4.8 Daily PV Electric Output per inverter and in total for the solar plant during April

To analyze the profiles in more detail, hourly values for one week are plotted and shown in Figure 4.9 together with the electric use profile for 2011 and 2012 during the same dates. The week 18 was chosen for having the highest electric output values, which result of interest in order to study the relation between the PV output and the electricity demand. As can be seen in Figure 4.9, the hourly electric generation is far from the demand of the building. Furthermore, peak values for the electric PV output occur during peak demand values.

The week 18 in 2013 includes from 29th April to 5th May. The highest electric output generated by the Kastanjgården PV system over that week is 9.64 kW and occurred the 2nd May at 13:00. However, this value is roughly 50% of the maximum power of the PV system.

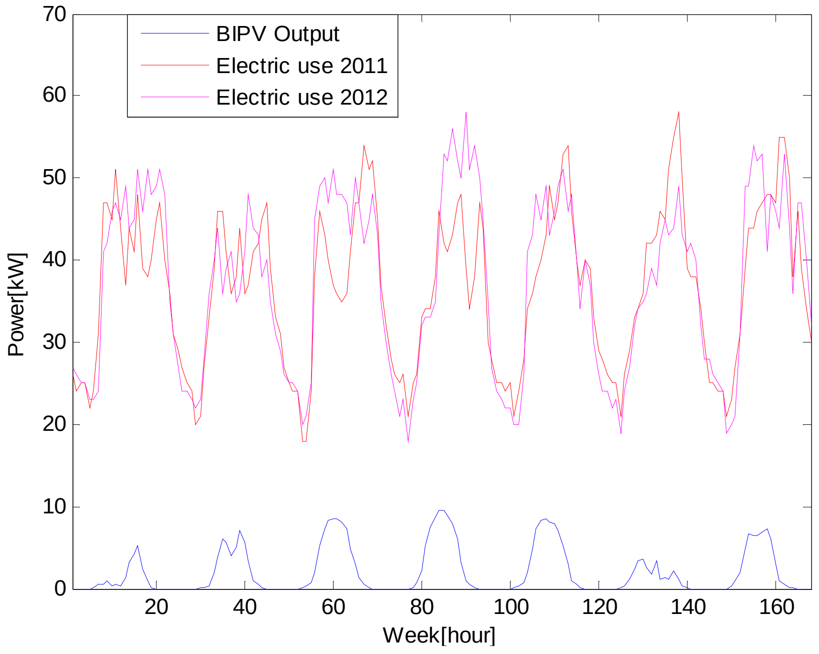

Figure 4.9 Hourly electric demand and PV system output from April 29 to May 5

In Figure 4.10, the profiles for the electric load of the building block and the electric output of the PV plant for the 2nd of May are shown. At13:00 the solar electricity generated attained to cover 23% and 18% of the demand in 2011 and 2012 respectively for the same time. In total for the whole day of May 2 of 2013, the PV system covers 7.7% and 8.4% of the demand during 2011 and 2012 respectively for the same day. From 00:00 to 5:00 and from 20:00 to 24:00, the PV system did not generate any electricity.

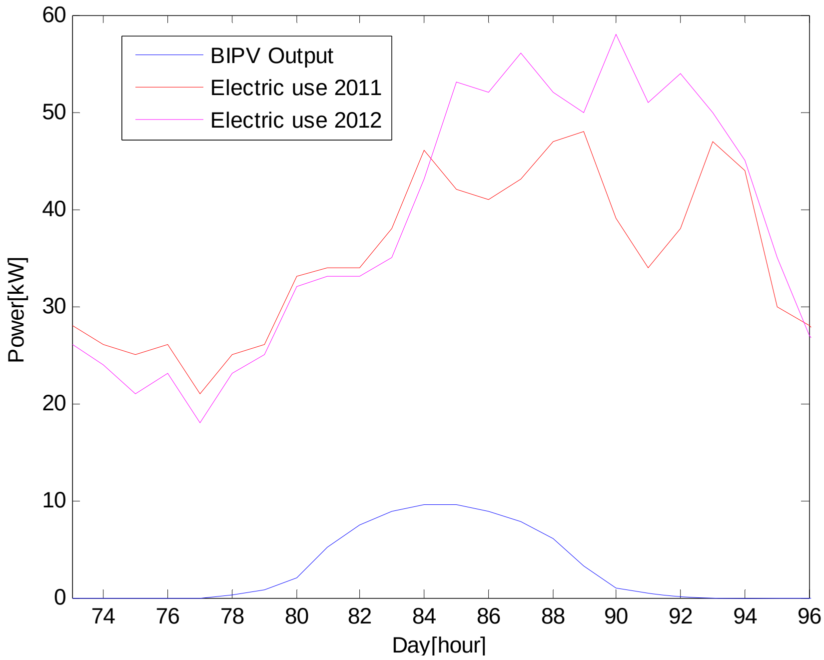

Figure 4.10 Hourly electric output of the Kastanjgården PV system during May 2, 2013

5 SIMULATIONS AND RESULTS

During this section, different simulations will be performed by using the software Polysun. First, a sensitivity analysis for determining best tilt angles at the location studied. Furthermore, the balcony-mounted PV system introduced in section 4.2 will be modelled and its performance simulated in the software Polysun. Finally, the performance of a flat roof-mounted PV of 20kWp will also be addressed. Results for all the simulations are presented after each sub-section.

5.1 Polysun

The simulation software Polysun® 6.0 *(Vela Solaris AG, 2013)* was used to simulate two Photovoltaic (PV) Systems located in the district of Gårdsten, which are property of the company Gårdstensbostäder AB.

The location of the system sites were found on "© OpenStreetMap contributors" *(Open Data, 2013)*, which is an open data base linked to the software through the internet. On it, the postal code of the building was used as search criteria to find the location.

The weather data was chosen by default after selecting the location. Results are display based on average data for a normal year. The data correspond to monthly and hourly values calculated through a stochastic model by Meteonorm, software developed by Meteotest. The solar radiation used by Polysun is shown in Figure 5.4 and Table 5.3.

During the simulation, the sun's position is updated each 4 minutes. Results are display in monthly and hourly basis for the whole system and each component, thus, the energy flows can be easily monitored.

To define the generator field, data such as number, orientation and tilt angle of the modules are given as input. Besides, the inverter layout and module type was chosen among the different manufacturers options available in the database of Polysun from commercially available devices or given as input.

5.2 Sensitivity Analysis

As an extension of this master thesis work, the most favourable tilt angle for integrating PV panels in the flat roof of four buildings in Gårdsten area will be analyzed. This evaluation is considered as one of the preliminary steps in the planning process when installing retrofitted roof-mounted PV systems and is intended to serve as a guideline for the decision-makers.

Due to the similar characteristics and proximity of the buildings, only simulations for the Lönngården building located in Peppargatan 25 will be carried out in Polysun. Results for the evaluation on the performance of three different PV module technologies for different mounted angles of inclination will be presented during this section. The parameters evaluated are the final electric output of the PV system per installed capacity and per module area. Additionally, the modules sensitivity when being installed at a non-optimal angle of inclination will also be presented.

5.2.1 Input data

The location chosen to perform the analysis was the one where the roof-integrated PV system will be placed, i.e., the Lönngården building roof. The exact location was selected directly from the map tool installed in Polysun as can be seen in Figure 5.1, at coordinates 57.801 Latitude and 12.026 Longitude.

For the simulation, a template for photovoltaic solar systems appropriate for residential installations with one generator field was chosen. Three commercial modules with different types of solar cell technologies were considered: polycrystalline silicon (p-crystalline), monocrystalline (m-crystalline) silicon and thin film (CIGS). The physical and electrical characteristics of the modules are shown in Table 5.1. The commercial modules were selected from the data base contained in Polysun. They are manufactured by well-known companies in the PV industry, and have similar power output and quite high efficiencies. They were chosen based on criteria of low weight and minimal thickness for the available options. Characteristics desirable for the easy integration of PV modules in the building envelope.

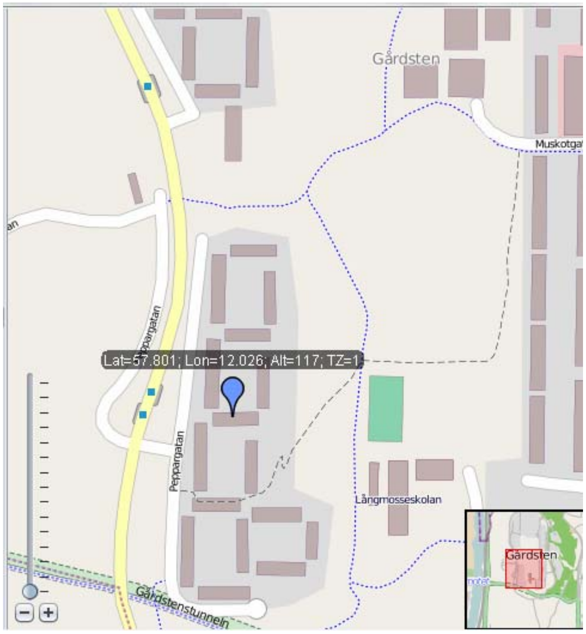

Figure 5.1Location of the Lönngården building

Table 5.1 Characteristics of the modules

Technology	Si monocrystalline	Si polycrystalline	CIGS
Manufacturer	Sunplugged GmbH	Saint Global Solar	Global Solar Energy
Model	85 Watt semi-flexible	Sunlap Tipo 4 Poli	PowerFLEX BIPV 90W
Power [W_p]	85	80	90
Efficiency [%]	12.88	12.05	9.05
V_{oc} [V]	22.2	14.74	23.6
I_{sc} [A]	5.3	7.82	6.3
V_{mpp} [V]	17.95	12.13	16.4
I_{mpp} [A]	4.75	6.62	5.5
Length [mm]	1 200	1 120	2 013
Width [mm]	550	664	494
Weight [kg]	2.7	12.5	3.5
Frame	frameless	Unknown	frameless
W_p/m^2	128.79	107.57	90.50

5.2.2 Results

The behaviour of the AC system electrical output with the tilt angle is shown in Figure 5.2. The tilt angle was varied from 0° to 90°, and the maximum productivity of the PV system was found at a tilt angle of 40°, a quantity little lower than the latitude position of the building. According to the results obtained in Polysun, the system with thin film (CIGS) modules yields the best results in kWh/a/kW. At 40° tilt angle the system with thin modules generates in a year 15% more electricity per installed kW than one with polycrystalline modules installed.

In terms of space requirements and electricity output, both the thin film and the polycrystalline silicon modules studied requires more area for generating the same electric output than monocrystalline silicon modules does. The latter generates a maximum of 122 kWh/m^2 at a tilt angle of 40°, which in turn is 1.3 times the electric output the thin film modules generates for the same area. This can be explained by the lower efficiency of the thin film modules, which is 42% lower.

In Figure 5.2.c the sensitivity of the modules in terms of their electricity generated when installed at a non favourable angle is shown. The electric output at the different angles was normalized by using the tilted angle of 90°. All the systems seem to be similarly affected when comparing with a system with modules vertically installed. However, the CIGS modules present the lowest variation. The annual generation of a system with modules tilted 40° is 32%, 34% and 29% higher than the one of a system with vertical modules for the monocrystalline, polycrystalline and thin film modules, respectively.

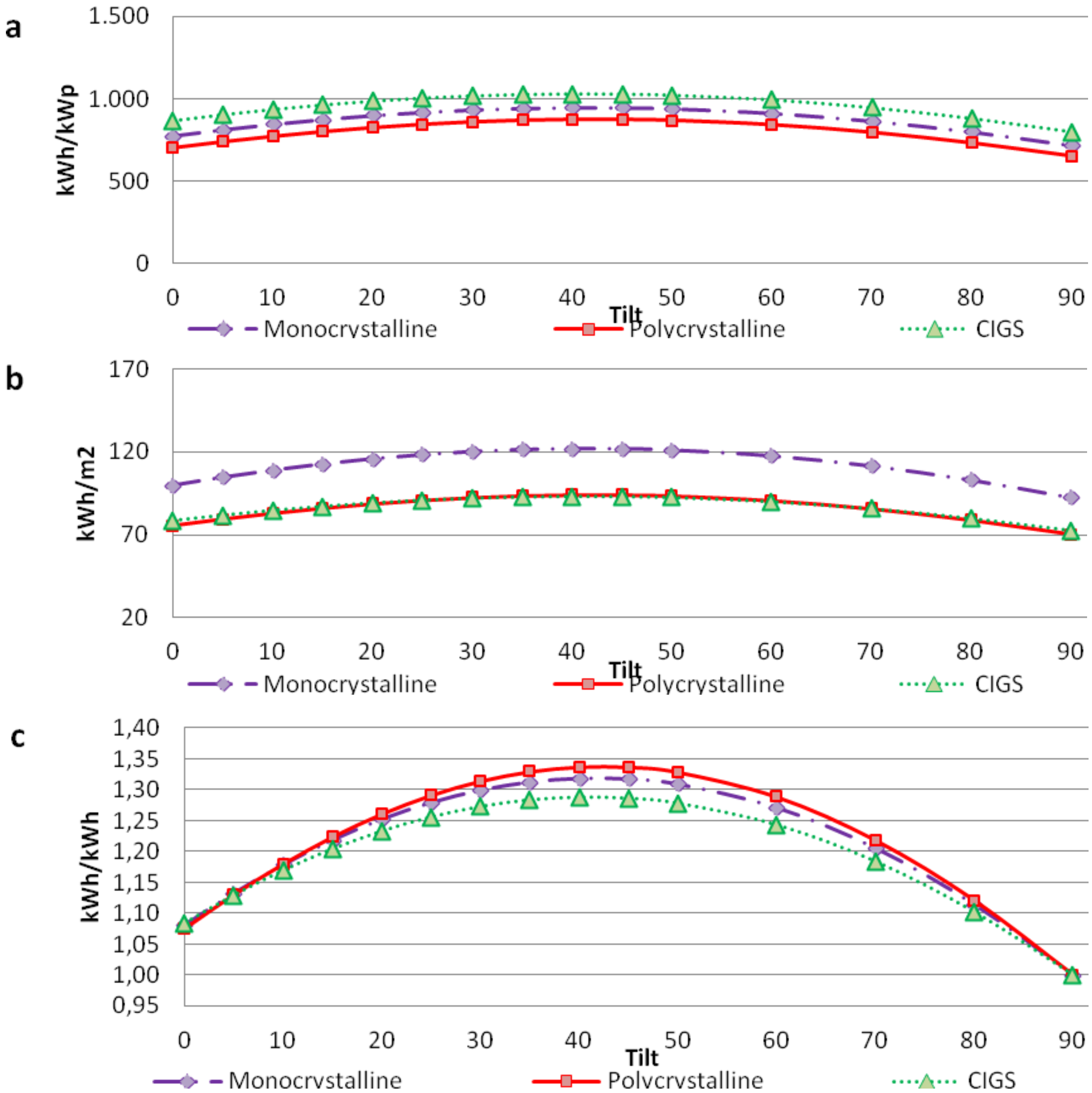

Figure 5.2 Variation of the annual AC system electricity output with the tilt angle (a) per installed capacity, (b) per collection area, and (c) per energy yield of the system with vertical modules

To sum up, for the parameters evaluated and the modules examined, a PV system with thin film CIGS generates more kWh/kW with a lower efficiency. If there is no restriction in area for installing the PV system, the criteria for selecting the PV technology needs to be based on its price per rated power (SEK/kWp) instead of in the modules efficiency. However, if there is a limitation in the area, it would be a better option to install crystalline silicon cells. Besides, regarding the optimum angle for installing at this location, a tilt of 40° gives the best results.

5.3 Kastanjgården PV System

In this section, input data and results from the simulation of the PV system mounted in the south-facade balconies of the Kastanjgården building will be presented. These results will be used to compare with monitoring data obtained during the months of operation corresponding to March, April and beginning of May, and thus assess the performance of the system so far.

5.3.1 Input data

The location chosen to perform the analysis was the one where the balcony-mounted PV system is placed, i.e., the Kastanjgården building site. The exact location has coordinates 57.804 Latitude and 12.026 Longitude and was selected directly from the map tool installed in Polysun as can be seen in Figure 5.3.

For the simulation, a template for photovoltaic solar systems appropriate for residential installations with one generator field was chosen. In the same way as for the real system, a total of 270 m-crystalline Silicon modules were chosen. A module type with the characteristics shown in Table 5.2 was used. As describe in Chapter 3, the system modules are many and not commercial available, thus, the characteristics of the module as shown in Table 5.2 were introduced manually based in some of the characteristics of the real modules.

Figure 5.3 Location of the Kastanjgården building

Knowing the nominal power, the total number of m-crystalline silicon modules, and the total gross area of the Kastanjgården PV system, the peak power and the area per module was calculated according to equation (5.1) and equation (5.2) respectively.

$$\frac{\text{Nominal Power}}{\#\text{of modules}} = \frac{19656\ \text{W}}{270\ \text{modules}} = 72.8\ \text{W/module} \quad (5.1)$$

$$\frac{\text{Total gross area}}{\#\text{of modules}} = \frac{173.68\ \text{m}^2}{270\ \text{modules}} = 0.643\ \text{m}^2/\text{module} \quad (5.2)$$

The efficiency chosen correspond to the average efficiency of the four module types installed in the Kastanjgården PV system. For the dimensions of the modules modelled, the chosen width was the same as the modules CV80 and CV32, which are the most frequently used modules in the real plant. When it comes to the length of the modules, this was chosen by default to fit the required module area previously calculated in equation (5.2).

Table 5.2 Characteristics of the CV73 module created for the simulation

Technology	Si monocrystalline
Peak Power [W_p]	72.8
Efficiency [%]	11.45
V_{oc} [V]	12.2
I_{sc} [A]	8.5
V_{mpp} [V]	9.7
I_{mpp} [A]	8.1
Temperature Coefficient (T_c) P_{max} [%/°C]	-0.45
Temperature Coefficient (T_c) V_{mpp} [%/°C]	-0.3
Temperature Coefficient (T_c) I_{mpp} [%/°C]	0.01
Length [mm]	753
Width [mm]	854
Thickness [mm]	2

On the other hand, electrical specifications such as current at P_{max} (I_{mpp}), short circuit current (I_{sc}), and temperature coefficients were chosen to be the same as for the four type modules employed in the real plant. Besides, the voltage at P_{max} (V_{mpp}) and open circuit voltage (V_{oc}) were set to the same value as for the module type CV80 due to their similar maximum power value.

Due to the south-façade position of the modules in the balcony, an orientation of 0° and a tilted angle of 90° were given to the software. The total gross area of the PV layout simulated was the same as for the real system, 173.6 m^2. Technical data of the module and inverter chosen to simulate the system is presented in Table 5.2.

In the same way as for the Kastanjgården PV plant, two inverters Sunny Tripower STP 10000TL-10 were chosen.

5.3.2 Results

Global horizontal radiation data used by Polysun (to perform the calculations), normal year data (1961-1990, SMHI) and actual data from 2013, are all displayed in Figure 5.4 and presented in Table 5.3. Polysun data correspond to a normal (average) year for the location selected and do not differ more than 2% from the average values obtained for Gothenburg between 1961 and 1990.

The global horizontal radiation in Gothenburg in 2013, on the other hand, so far has been higher per month in comparison with average historic years.

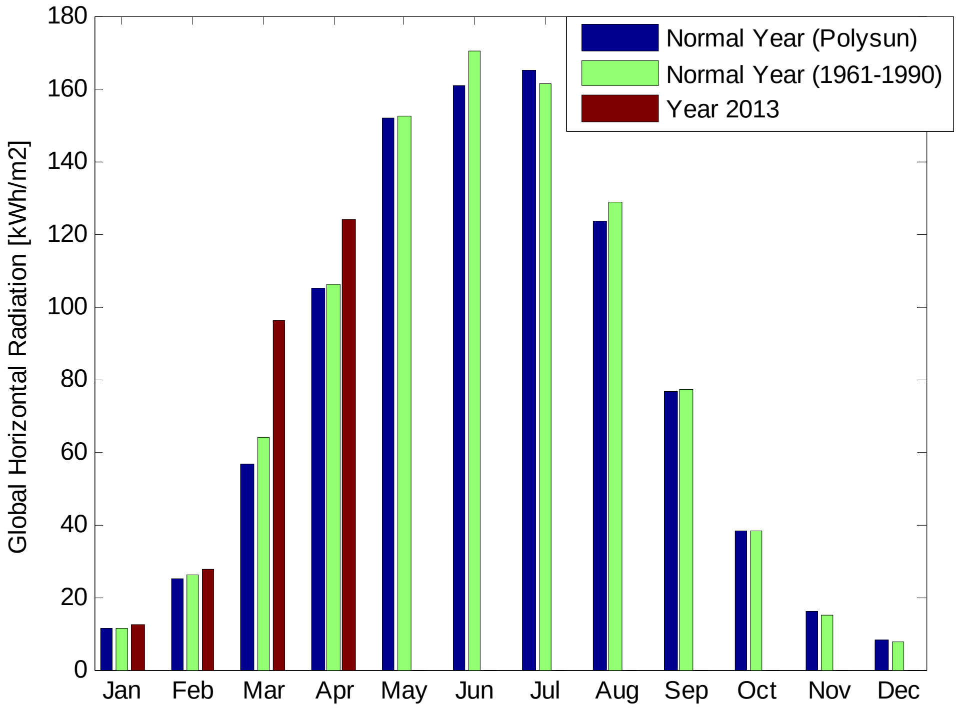

Figure 5.4 Global Horizontal radiation

Table 5.3 shows also the amount of diffuse solar radiation which is considerable. The sunniest month (July) has an average radiation of 165 kWh/m^2, and about 45% of that radiation is diffuse. In December, the radiation is 7.8 kWh/m^2, and about 73% of that radiation is diffuse. It is therefore less interesting to apply concentration technologies in Sweden in comparison to southern regions with less more solar radiation and less amount diffuse radiation.

Table 5.3 Solar radiation

Month	Average year (Polysun Results)		Average year (1961-1990)	Year 2013
	Global Horizontal radiation [kWh/m^2]	Diffuse horizontal irradiance [kWh/m^2]	Global Horizontal radiation [kWh/m^2]	
January	11.5	8.0	11.3	12.5
February	25.1	15.6	26.2	27.5
March	56.4	33.1	63.9	96.0
April	105,0	49.5	105.9	124.1
May	152.0	76.4	152.2	-
June	160.9	81.1	170.1	-
July	165.2	74.9	161.2	-
August	123.6	63.6	128.9	-
September	76.8	38.8	77.0	-
October	38,1	22.5	37.3	-
November	16.1	10.6	15.2	-
December	7.9	5.7	7.8	-
Annual	938.6	479.9	957.6	-

Figure 5.5 and Table 5.4 show the calculated monthly yield for PV system mounted on the balconies at Kastanjgården. Table 5.4 shows also the solar radiation on the modules, the power ratio and the maximum power output. While the global solar radiation shows a maximum in June-July (Table 5.3), the solar radiation on the modules is more or less the same from April to September (Table 5.4), as the modules are vertical. The vertical mounting also explains why the maximum power output of about 16 kW occurs in February, while the power output is 12-13 kW from April to September. The power ratio is also lower in the summer than in winter months, mainly as the module temperature becomes higher in the summer.

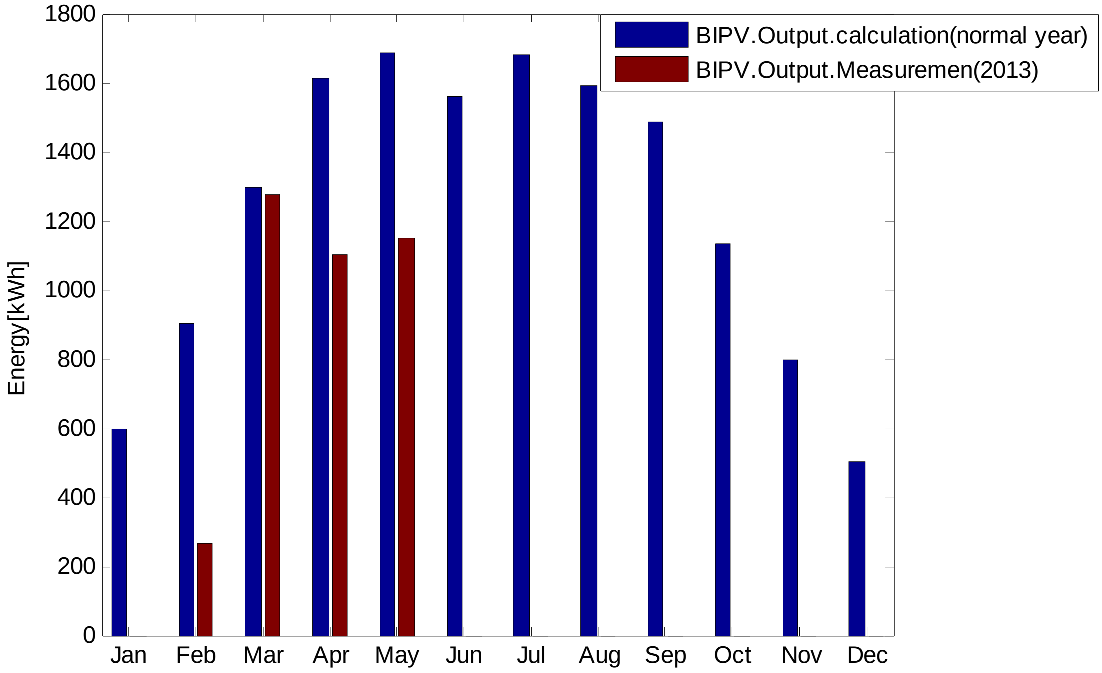

Figure 5.5 Monthly energy yield of the Kastanjgården PV system for a normal year calculated by Polysun and for actual outputs in year 2013

Table 5.4 Polysun simulation results for the Kastanjgården PV system

Month	Radiation onto module area [kWh]	DC Yield Photovoltaic [kWh]	AC Yield Photovoltaic [kWh]	Power Ratio [%]	Maximum Power Output [kW]
January	5 723	618	596	92.2	13
February	8 655	928	901	91.9	16
March	12 609	1 337	1 297	90.9	16
April	15 861	1 659	1 611	89.7	13
May	16 899	1 744	1 689	88.3	12
June	15 828	1 613	1 558	86.9	12
July	17 287	1 739	1 683	86	12
August	16 410	1 641	1 590	85.6	13
September	15 141	1 531	1 487	86.8	14
October	11 307	1 170	1 136	88.7	16
November	7 770	822	797	90.6	14
December	4 763	519	502	93.1	11
Annual	148 253	15 321	14 848	88.5	16

The actual recorded monthly yield for the PV system is compared to the calculated yield in Figure 5.5 and Table 5.5. The monthly electric output values of the PV plant calculated by Polysun differ from the actual values with an average of 46.5% from April to May, while in February differences are more than double. Although the global horizontal radiation assumed by Polysun is lower than what actually occurred in 2013 for the months under study, the energy yield given by Polysun was higher for all the months recorded so far, i.e., from February to March.

Table 5.5 Actual and calculated energy yield values for the PV system in Kastanjgården

	Actual PV Output [kWh]	Calculated PV Output [kWh]	Deviation [%]
February	265	901	240%
March	1 276	1 297	2%
April	1 101	1 611	46%
May	1 149	1 689	47%

A closer view to the monthly profile is given in Figure 5.6, where electricity output from the PV plant is presented in daily basis for simulations and actual data. The daily values are shown for April 25 to May 6, when both inverters should show correct values (with reference to chapter 4.2 and Figure 4.8). In general, it can be seen that the daily calculated output for April 25 to May 6 is higher than the recorded output for the period April 25 to May 6. A more detailed comparison such as hourly basis for the same period is not relevant, since the calculations were based on average data for a normal (typical) year. It would however be relevant to compare the profile for the day with the maximum power output in both measurements and calculations.

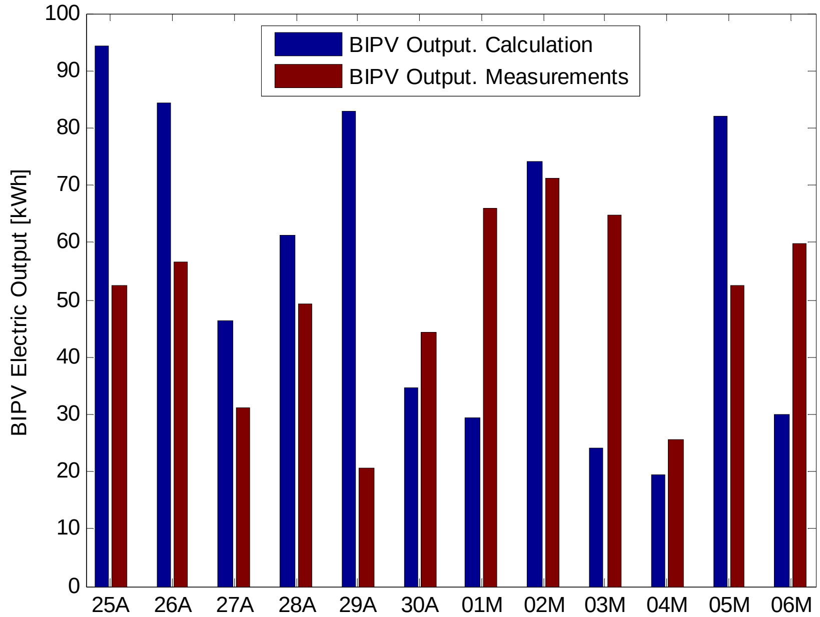

Figure 5.6 Daily PV electric output from 25 of April to 06 of May

In Figure 5.7 it is shown the hourly power output of the PV system during the day with the maximum calculated power output and the day with the maximum measured power output. The maximum power reached during the 25th of April according to calculations was 13 kW while for the 2nd of May according to data measured was 9.6 kW.

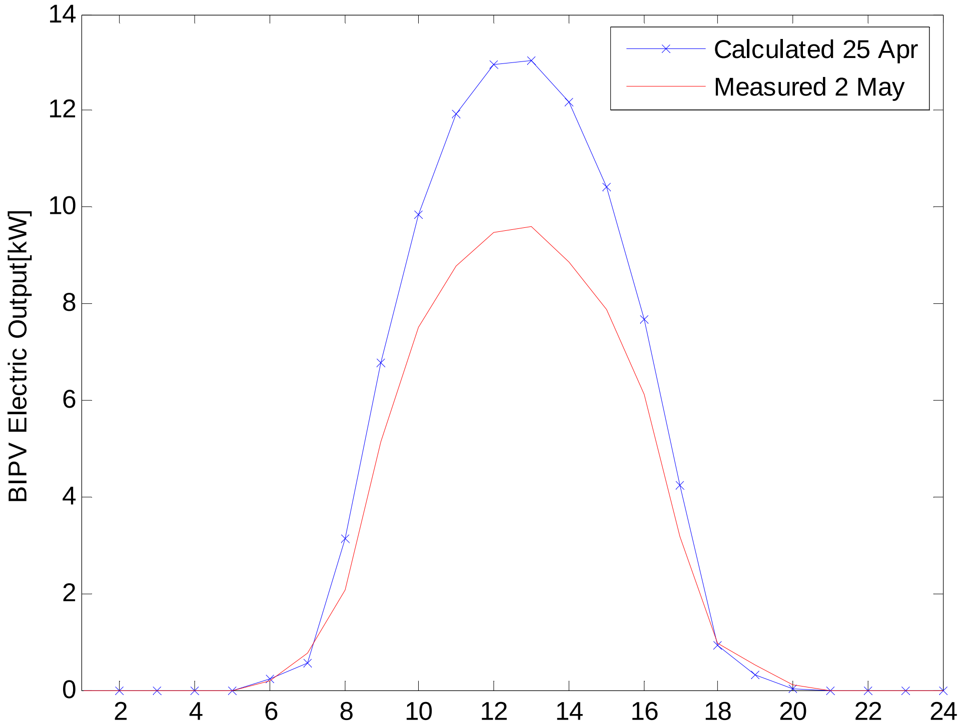

Figure 5.7 Hourly PV electric output for 25th April and 2nd May

5.4 Lönngården PV System

In this section, the integration of a PV system in the roof of the Lönngården building will be evaluated, and results from Polysun will be presented. Results obtained during this analysis are intended to serve as a guideline for decision-making regarding the best way for installing the PV modules in the roof of the Lönngården building, as well as for Oxelgården, Askgården, and Poppelgården buildings, i.e., 0° or tilt. The results will also be compared with the ones with 90° (vertical) mounted modules of the Kastanjgården PV system described in section 3.

5.4.1 Input data

The location chosen to perform this analysis was the one where the roof-mounted PV system will be placed, i.e., the Peppargatan 25 building site. The exact location can be found in section 5.2.1 together with the map view.

For this simulation, the same input values as for the Kastanjgården PV system were used (See section 5.3.1). However, two different tilted angles where chosen, 40° and 0° (horizontal). These angles were chosen from results obtained in Section 5.2.

5.4.2 Results

The annual data for systems tilted 0° (horizontal), 40° and 90° (vertical) are summarized in Table 5.6. The system with modules tilted at an angle of 40° generates 20% more electricity per module area than the system with modules horizontally installed and 31% more than the system with modules vertically installed.

The monthly energy yield of the systems with modules tilted 40° and 0° are presented in Figure 5.8 together with the results found in Section 5.3.2 regarding the modules tilted 90°. The horizontal system has a high yield in the summer months (when the sun is high) and a low yield in the winter months (when the sun is closer to the horizon). The vertical system (90°) has a high yield during the winter months (when the sun is closer to the horizon) and a low yield in the summer months (when the sun is high). The system tilted 40° has a high yield all the year.

Table 5.6 Overall annual systems performance

	Horizontal	**Tilted 40°**	**Vertical**
Annual Electric Production AC [kWh]	16 235	19 435	14 848
Specific annual yield [kWh/kW$_p$]	826	988.7	755.4
Effective solar radiation [kWh/m^2]	937.6	1129.5	853.9
Overall system efficiency [%]	9.97	9.91	10.02
PR [%]	88.1	87.5	88.5

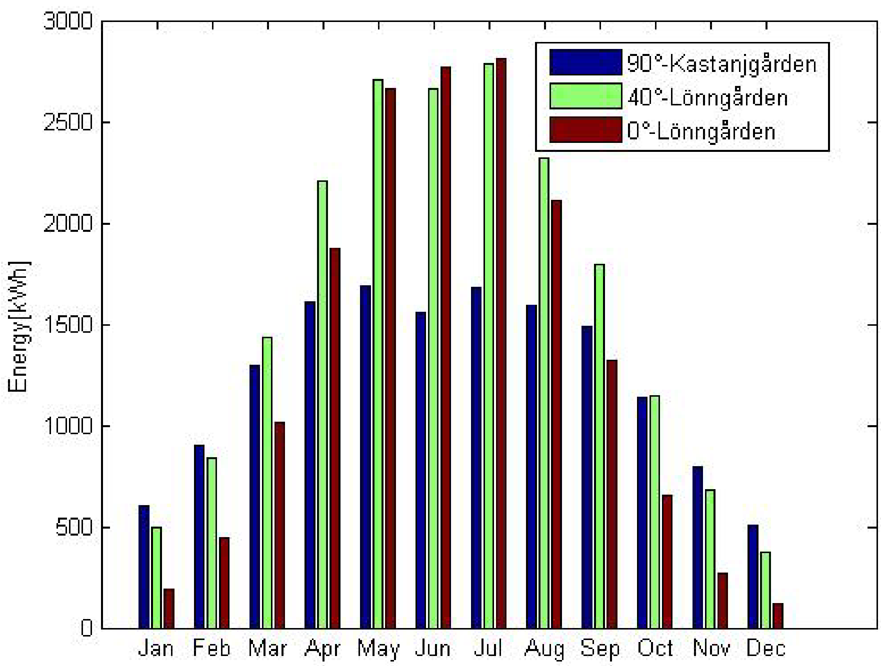

Figure 5.8 Monthly energy yield of the Lönngården PV system

In Figure 5.9, the output of the system tilted 40° and 0° is compared with the monthly demand during 2012 in the Lönngården building. The peak generation occurred for both systems in July at 2815 kWh and 2783 kWh for 0° and 40° tilted modules respectively. The off-peak demand also occurred during July 2012 at 20334 kWh, which is seven times the energy yield by the plant according to simulations.

Though both systems gives similar energy yield during the year, from an energy perspective point of view it seems more convenient to choose a system with a tilted angle of 40° because it gives the highest output not only for the total year but also during the months with the highest demand of electricity as seen in Figure 5.9.

For getting an idea in how large the system in Lönngården could be, hourly values during the day where the lowest electric demand was registered among the three year studied: 2010, 2011 and 2012 was chosen. This day fell in 2012, on Tuesday 17th of July. In Figure 5.10, the profile for this day is presented for the demand in 2011 and 2012, as well as for the solar PV electric output during the same equivalent period of time. As can be seen, the off-peak demand value mismatch with the peak electricity generation of the PV plant. The off-peak electricity use value was 13 kW in 2012 and occurred at 5:00, while the peak electricity generated by the roof-mounted PV plant according to calculations was approximately 11 kW and occurs around noon.

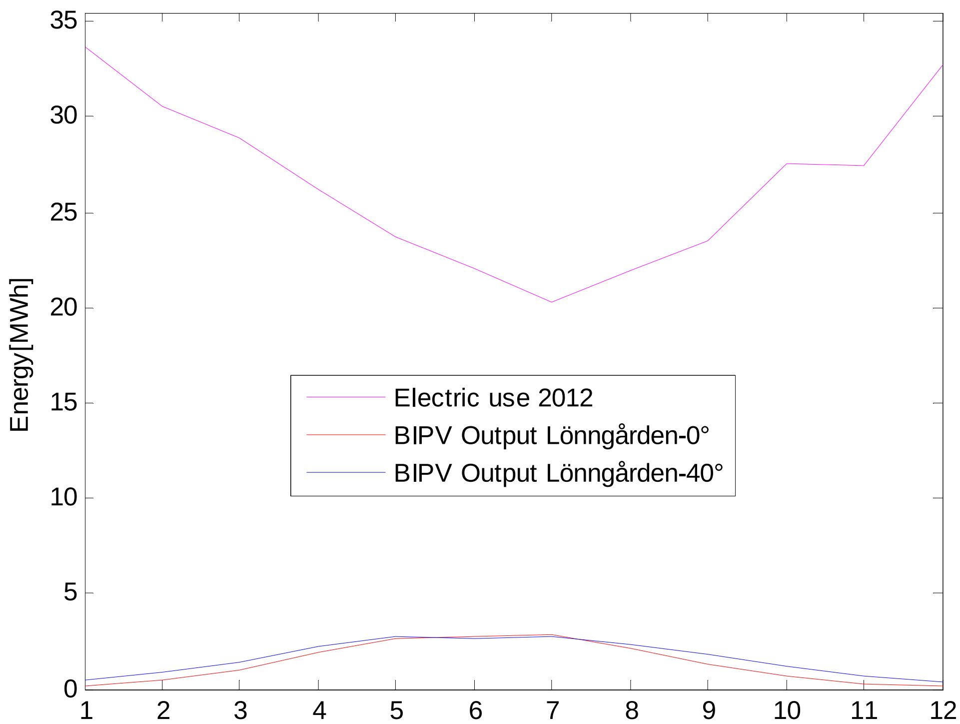

Figure 5.9 Monthly values for the electric use during 2012 in the Lönngården building calculated output from a horizontal and tilted 40° system.

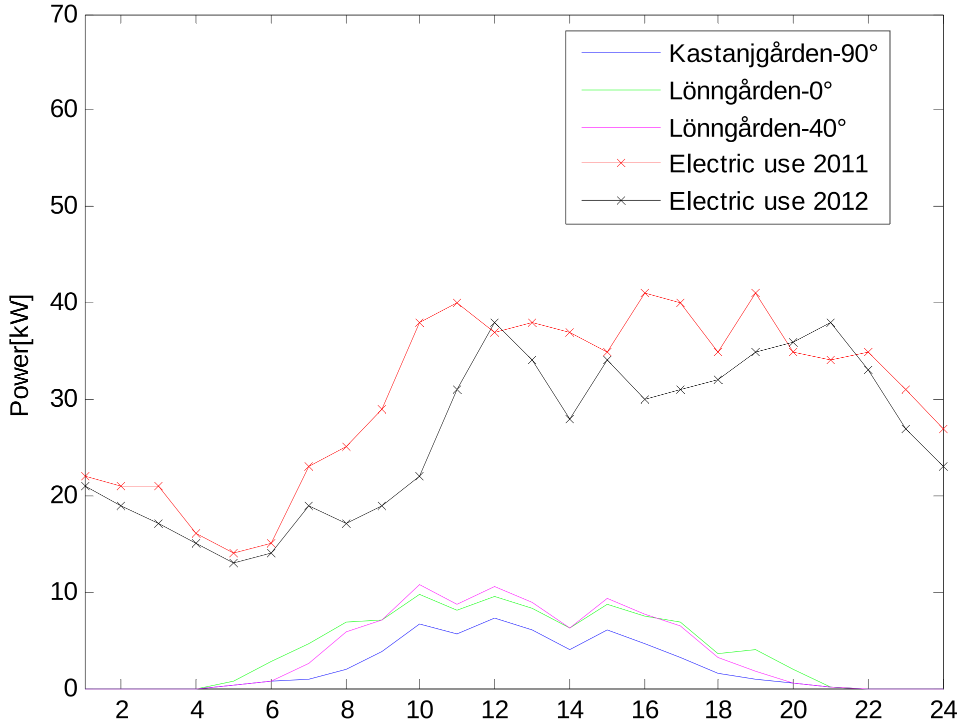

Figure 5.10 Hourly electric power values during July 17 for the roof-mounted PV systems of 20 kW capacity

In a similar way, the day were the maximum electric output of the roof-mounted PV photovoltaic was registered according to simulations, was also analyzed in more detail. This day fell in June 05 for both systems tilted 40° and tilted 0°. The profile of this day is presented in Figure 5.10. As can be seen, the lowest electricity used was 16 kW –at 4:00- and the maximum power delivered by the plant according to simulations was 17 kW and 15 kW for a system with modules tilted 40° and 0° respectively –both occurred at around noon-.

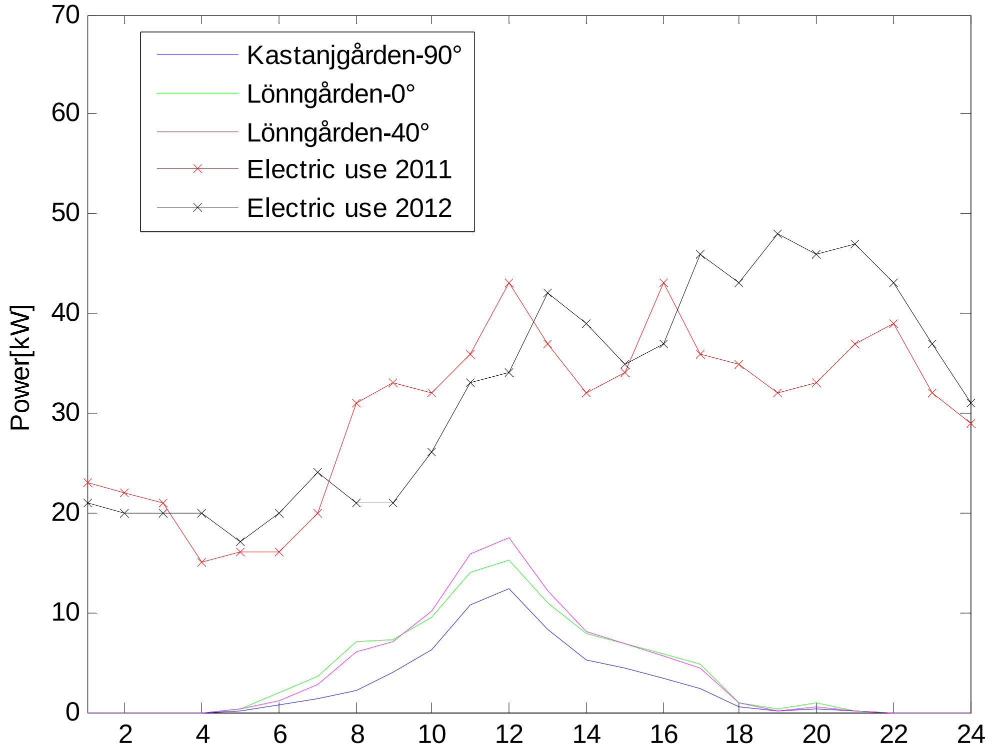

Figure 5.11 Hourly electric power values during June 05 for the roof-mounted PV systems of 20 kW capacity

Based on the comparisons shown in Figures 5.10 and 5.11 it would be possible to install a system with about twice the nominal power of the systems studied, i.e. a system with 40 kW nominal power, without the need to sell electricity.

6 DISCUSSION AND CONCLUSIONS

A major aspect to consider is the size of the PV systems in relation to the use of electricity in the building blocks where the PV systems are installed. The thesis investigates the electricity used from 2010 to 2012 for the Kastanjgården building blocks where the existing balcony-mounted was installed and the Lönngården building block where the planned roof-mounted PV systems will be installed.

Despite the fact that the Kastanjgården building block has a smaller total living area than the Lönngården building block, its electricity use was higher, being in 2012 of 88 kWh/m^2 compared to 57 kWh/m^2 -living area- for the Lönngården building block. The latter could be explained by the fact that the Kastanjgården building block not only has residential apartments but it also holds Gårdstensbostäder Company offices which occupied one and a half of the floors –a total area of 777 m^2- of one of the buildings of the Kastanjgården block, the one where the PV system was installed. It should further be noticed that the use of electricity has been reduced since 2010 and that it may be possible to reduce the use of electricity even further.

With current PV module technologies available today (yielding just more than 100 kWh electricity per m^2 module area), and for large building blocks such as the ones under this study (using 50-80 kWh electricity per m^2 living area), it is not possible to build a PV system that covers the entire electricity use of the building, since the area available for integrating a PV system in the building block is much smaller than the total living area demanding electricity. For this particular project, with PV modules on the façade of one out of two buildings in Kastanjgården, the area covered with the PV modules modules (174 m^2) is equivalent to 4% of the total living area (3 502 + 777 m^2) that demands electricity. Thus, the potential contribution from the PV system is rather small (here also about 4%) in comparison to the use of electricity.

The most feasible sizing of a PV system for the time being is to have a system where all generated electricity is used (e.g. in a building), i.e. that the PV will reduce the electricity bought from the grid. In order to have such a sizing it is necessary to study the hourly output of the PV system and the hourly use of electricity those days when PV yields at maximum and the use is at minimum. The investigation shows that the hourly average electricity use in the summer months are of the order 13-15 kW early mornings and varying between 30 and 40 kW during daytime, i.e. when the PV system is at maximum.

The Kastanjgården PV system has a nominal design power of close to 20 kW, i.e. well below the electricity demand during daytime. The PV system electric output was simulated in the software Polysun and compared with the measured electricity generated by the PV system. A first comparison indicates that the measured PV system yield is less than simulated by Polysun. The PV system has so far only been measured during a short period during the spring 2013 and it is too early to conclude if the simulations are being too optimistic or if the plant is not performing as expected.

Regarding the Lönngården building block, its minimum power demand was 13 kW (early morning) and varying between 20 kW and 30 kW during daytime –during some days in summer of 2011 and 2012-. However, according to the simulations performed for a roof-mounted PV system with 20 kW_p of maximum power capacity and located at the Peppargatan 25 address, the maximum power delivered was 17 kW for a system tilted 40°, and 15 kW for a system tilted 0° –in both cases some hours around noon in May and June-. Though both electric power output values exceed the minimum electricity use, they did not occur at the same time. However, a much larger system, i.e., more than 20 kW_p would not be recommended due to the risk of exceeding the electricity used during some hours in the summer months. For a total month the electricity used was never and far from being exceeded.

From the sensitivity analysis and regarding the commercially available PV modules analyzed, it can be concluded that the tilt angle of 40° gives the highest output per module area in all the cases, being in average 32% and 22% higher than for the systems with modules tilted 90° and horizontally installed (tilted 0°) respectively. In regards to the technology, the monocrystalline silicon modules seems to be the best option, since they yield more electricity for the same module area due to its higher efficiency; and in average their prices are lower than for CIGS PV modules. However, other things such as the installation costs and the maintenance requirements need to be considered when deciding between systems tilted 40° and 0° for a flat roof.

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