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Theoretical optimization of solar electricity using a DC-microgrid

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Abstract

This master thesis contributed to a project financed by the Swedish Energy Agency and managed by the housing company Eksta AB in collaboration with the consulting company WSP. The main aim of this master thesis was to perform a theoretical optimization on the usage of own used solar electricity by transferring the surplus PV between buildings in a demonstration area in a DC-microgrid. To achieve this objective, the Swedish regulatory framework for concession was analyzed in order to find exceptions that allow the transfer of solar electricity surplus between buildings in the same real state. A demonstration area belonging to Eksta and located in Fjärås, Kungsbacka, was used in order to simulate the transfer of solar electricity surplus. The area consisted of four new residential buildings, one substation, a preschool, a community living, a retirement home and Eksta's expedition building.

The regulation 2007:215 presents the exceptions for the Swedish electricity law (1997:857). The exceptions 22A and 30 from the regulatory framework for concession stated that an internal power line, allowing the transmission of electricity between facilities, could be built when connecting to electrical production facilities. These exceptions were interpreted as valid for the demonstration area although not all buildings generated solar electricity.

The electricity usage and solar electricity generation for each building varied dependent on the building's purpose and PV system design. When combining all buildings in a DC-microgrid the electricity usage and PV generation were summarized leading to a more homogeneously distributed consumption and higher solar electricity generation. As a consequence, the own usage rate and self-sufficiency rate were increased by 32 and 6 percentage points compared to the current individual system. In a DC-microgrid the solar electricity surplus accounted for 9% of the total PV generation compared to 41% if not interconnected. The difference was calculated to an optimization of 27 000 kWh/year which represented the demonstration area's total electricity usage that could come from solar electricity instead of delivered from the grid.

Further optimization of the own-used solar electricity could be achieved by maximizing profitable PV roof areas, increasing the electricity efficiency and connecting the solar electricity surplus to a common energy storage system.

Contents

Acknowledgement

I would firstly like to thank my supervisor Charlotta Winkler for giving me the unique opportunity to write my master thesis in collaboration with WSP and Eksta AB. It has been highly inspiring to write about such a relevant issue which in my opinion is crucial for the current global energy transition. Thank you for the endless support and inspiration during the whole project. I would also like to give a special thank you to Jens Penttilä from WSP, for all the Friday Skype meetings and always being available for discussion. Thank you Niklas Christensson and Christer Kilersjö from Eksta AB, for providing me with all the data necessary to perform all the calculations. I could not forget to thank Mats Karlström from Ferroamp, for showing so much interest in the project and helping me understand the Swedish regulatory framework and Ferroamps technology. I would also like to thank my LTH supervisor Elisabeth Kjellsson for helping me with the thesis writing and always being available for discussion. Finally, nothing would have been possible without the endless love and support from my family, thank you for believing in me and always being by my side despite the distance.

1 Background

1.1 Introduction

1.1.1 PV in Sweden

The UN Sustainable Development Goal 7, Affordable and clean energy, focuses on ensuring access to affordable, sustainable and modern energy for all (UN 2016). Solar energy plays an important role in achieving this goal. Its global potential has been estimated by the International Energy Agency (IEA) to 303 GW in 2016 which was an increase of 75 GW compared to 2015 (IEA 2016).

The Swedish Energy Agency has presented a strategy aiming to increase the solar energy usage in Sweden which will contribute to the Swedish long-term goal on having 100 % renewable energy. The strategy is divided in three phases based on the already existing PV-market: establishment, expansion and continued commercial development. The goal is that by 2040 solar electricity will represent 5-10% (7-14 TWh) of the Swedish electricity mix. Today solar electricity represents approximately 0.13% of Sweden's total electricity consumption (Lindahl 2016).

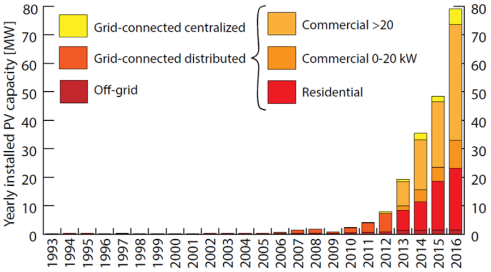


Figure 1: *Annual installed PV capacity in Sweden (Lindahl 2016).*

The PV-market in Sweden has increased in recent years, as seen in figure 1. In 2016, the PV market grew 63% compared to 2015 which was an increase of 79.2 MW. In total, in 2016 there were 205.5 MW solar electricity installed in Sweden with both systems connected and disconnected from the grid. The strong growth in the PV-market is due to falling prices, new subsidies and an increased popularity of the PV technology (Lindahl 2016).

Thanks to the Swedish national initiative to stimulate the solar electricity market several economic incentives have appeared in recent years. Sweden has a solar subsidy scheme for 2018, which entitles companies 30% and private persons 30% of the total investment costs of a PV system. There is the possibility for private persons to receive 30% deduction for the labor cost when installing a PV-system. However, it is not possible to apply for both the subsidy on investment costs and the reduction. Since January 2015, a tax reduction of 0.60 SEK/kWh is given for the solar electricity surplus delivered to the grid. Additionally, the owners who submit solar electricity surplus to the grid have the possibility to sell it to the electricity companies. As a producer of renewable electricity there is also the possibility to apply for electricity certificates, which can be received for the entire amount of produced electricity which is metered and connected to a specific system (Swedish energy agency 2016).

1.1.2 Project description

The Swedish Energy Agency has granted financial support to Kungsbacka municipality's housing company Eksta Bostads AB, during the time period 2016.10.01 - 2019.10.31, to perform a study on the development of an overall solution for solar electricity in buildings. The study is performed in collaboration with the consulting company WSP. This master thesis is one part of the project, which will continue with evaluation and analyses until 2019. The main purpose is to evaluate the possibility to transfer solar electricity between buildings in a DC-microgrid and maximize the self-usage of solar electricity. From a real estate owner's perspective, such as Eksta AB, maximize the usage of the own produced solar electricity is important in order to increase both the electrical and economical efficiencies of the PV system and reduced the electricity bought from the grid. By directly using the produced solar electricity, variable cost e.g. energy tax, network charge or VAT are avoided. If the surplus PV is instead delivered into the grid, it can usually only be sold by the market price.

The Swedish electrical regulation states that an electrical grid could not be built or used without permission from the national Swedish Energy Markets Inspectorate (Notisum 2017). According to this law if an apartment building has a solar electricity surplus, the electricity has to be delivered into the grid. Therefore, one of the main purposes of this master thesis was to use an exception from this law enabling solar electricity to be transfered between buildings in the same property using a DC-microgrid, aiming to increase the electrical and economical efficiencies of the PV-system. (Regeringskansliet 2013) .

Figure 2: *The left picture presents the location of Fjärås in Google Maps and the right picture describes the demonstration area.*

A demonstration area belonging to Eksta AB and located in Fjärås, Kungsbacka, was used in order to simulate how the solar electricity could be transferred between buildings with different electricity usage profile aiming to optimize the balance between solar electricity supply and demand. As seen in figure 2, the area consisted of four new residential buildings with a total of 16 apartments, a preschool, a community living, a retirement home and Ekstas AB expedition. The move-in-date for the 16 new apartments was November 2017.

The new apartments were equipped with the Energy Hub system from the company Ferroamp (Ferroamp 2017a) as well as PV-systems and energy storage battery system in 12 of the apartments. The preschool, community living and retirement home also had installed PV-systems.

1.2 Aim

The overall aim of this master thesis is to perform a theoretical optimization on the usage of own-used solar electricity by transferring the surplus PV between buildings in a demonstration area in a DC-microgrid. The calculations were based on the buildings electricity usage and solar electricity generation, no storage system was taken into account.

1.3 Objectives

The aim will be achieved by the following objectives:

- Assess the current Swedish regulatory framework for concession and its exceptions in order to facilitate solar electricity transfer between buildings in the same property.
- Describe and analyze existing buildings electricity usage and solar electricity generation (preschool, community living, retirement home and Eksta expedition).
- Describe and analyze the new residential buildings calculated electricity usage and solar electricity generation by using the PV simulation program SAM (NREL 2017b).
- Create a theoretical scenario where the surplus solar electricity is transferred between the buildings in a DC-microgrid instead of delivered into the grid.
- Compare how the own used solar electricity varies if the buildings are connected in a DC-microgrid vs individually.

1.4 Limitations

One of the main limitations of this master thesis was the time constraints as it was limited to 20 weeks. As a consequence only the energy efficiency was calculated and the cost-efficiency was taken out of the scope. Furthermore, as the moving-in-date for the new apartments was November 2017 the energy usage and solar electricity for the apartments were calculated based on theoretical models and calculations instead of measured data.

2 Theory

The following theory, firstly, presents the parameters used when describing the buildings energy usage and solar electricity generation. Secondly, the theory explains the advantages with DC-electricity and DC-microgrid technology. Thirdly, it describes the Swedish regulatory framework for concession and its exceptions.

2.1 Energy usage

Sweden has a high electricity consumption due to its northern location and an electricity-intensive base industry. The national electricity consumption 2016 was 140 TWh where the housing and service sector accounted for 52% (Ekonomifakta 2017). The buildings studied in this master thesis have different electricity usage depending on each buildings purpose. The following theory describes the parameters used in order to describe and compare the different buildings energy usage.

A_{temp}
The buildings specific energy usage is calculated based on the A_{temp} area. This area corresponds to the floor, wind and basement area that is heated to more than 10 °C (Boverket 2014a).

$Energy\ performance$
The energy performance measures the total space heating, air-conditioning, domestic water and electricity consumption over a year divided by the heated surface of the building (A_{temp}). The unit used is kWh/m^2 and year (Boverket 2017). The visualization of the energy performances is done by using the energy classification, which compares energy consumption in new buildings. This classification contains seven energy classes, which are based on the energy demands for new buildings based on the Swedish Building Regulation (BFS 2011:6), as seen in figure 3. The energy class C meets the requirements for a standard new building according to Swedish National board of housing, building and planning (Boverket 2014b).

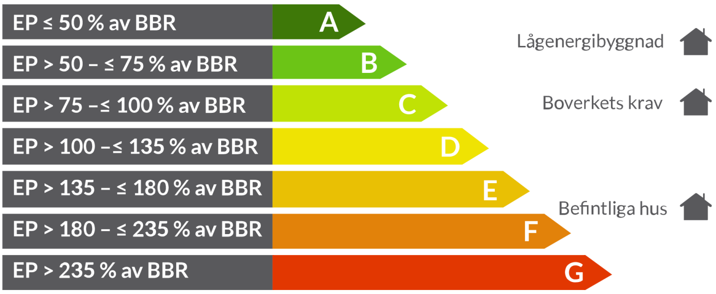


Figure 3: *Energy Performance Requirements (EP) for New Buildings (%) according to the Swedish national board of housing, building and planning (BBR). Low energy building (A&B), new building standard (C) and existing houses (D,E,F & G) (Boverkets 2014b).*

$Ventilation\ system$

The FTX system is a complete form of ventilation system that recovers and reuses the warm air by using a heat recovery unit (Svensk Ventilation 2017).The parameter Specific Fan Power (SFP) is used to measure the energy efficiency of the air movement system. SFP expresses the amount of electric power needed to drive the fans taking into account the volume of air, measured in kW/m^3/s (Mysen et al 2015).

Heating system

More than half of all homes and facilities in Sweden are heated by district heating. In a district heating plant, water is heated to distribute heat to the houses in the area connected by a district heating network. The fuel used consists of biomass and different types of residues such as forest felling, wood from the paper or wood industry or waste. The Combined Heat and Power system (CHP) increases the plant efficiency by generating both heat and electricity (Enskog 2017).

2.2 PV technique

A photovoltaic cell (PV) converts solar light into DC electricity by using the photovoltaic effect. The interconnection of various PV-cells forms a PV module, which can be connected either in series or in parallel. The solar module array together with the mounting structure, the inverter and the battery storage constitutes the PV system (NREL 2017a). The efficiency of a PV-cell can be defined as the amount of solar energy falling on the cell that is converted to electrical energy. The efficiency varies dependent on the wavelength, module material, temperature, reflection and resistance. The efficiency is defined by the following equation where P is the power (W), A the area (m^2) and G the irradiance (W/m^2) (McFadyen 2013).

$$Efficiency = \frac{P}{G * A} \tag{1}$$

This efficiency can be determined by using the current-voltage curve (I-V curve), which presents the current and voltage output of a PV cell by varying the external resistance from zero (short circuit) to infinity (open circuit), as seen in figure 4. The curve is performed based on Standard Test Conditions (STC) (Samlexsolar 2013).

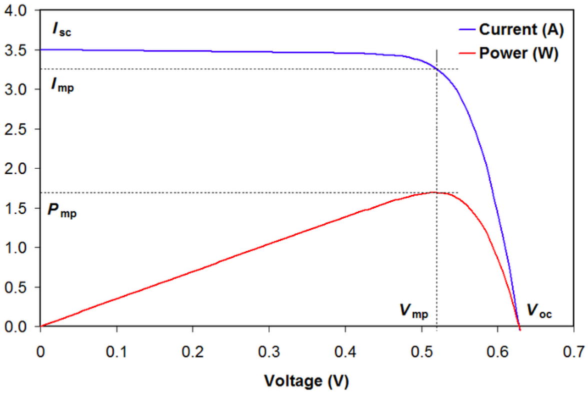


Figure 4: *Current-Voltage curve. The blue line presents the PV cell output current and the red line shows the power as a function of voltage (Wikipedia commons 2008)*

As seen in figure 4 the Short circuit current (I_{sc}) is the maximum current produced by a PV cell, which occurs when there is no resistance in the circuit. The voltage is then zero. On the other hand, the Open circuit voltage (V_{oc}) is the maximum voltage in a PV cell that occurs then the resistance is infinitely high and as a consequent there current is zero.

The power in a DC electrical circuit is defined as the voltage times the current:

$$Power(W) = Voltage(V) * Current(A) \tag{2}$$

The maximum power (P_{mp}) is defined in the I-V curve as the Maximum Power Point (MPP) where the voltage and current are expressed as V_{mp} and I_{mp}. The values of the Maximum power voltage (V_{mp}) and the Maximum power current (I_{mp}) are calculated by multiplying V_{oc} and I_{sc} with a factor which can vary between 0.75 to 0.9 for V_{mp} and 0.85 to 0.95 for I_{mp} (Samlexsolar 2013).

$$V_{mp} = (0.75–0.90) * V_{oc} \tag{3}$$

$$I_{mp} = (0.85–0.95) * I_{sc} \tag{4}$$

$$P_{mp} = V_{mp} * I_{mp} \tag{5}$$

The nominal efficiency of the PV cell can be defined as the ratio in the I-V curve between the maximum power point and the incident light power. This efficiency is calculated by using the Fill Factor (FF) which is defined as the maximum power divided by the product of V_{oc} and I_{sc}. The closer the FF ratio is to 1 the more electrical power the PV cell can provide to the system. (Jim Dunlop Solar 2012).

$$FF = \frac{Imp * Vmp}{Isc * Voc} \tag{6}$$

$$\textit{Nominal Efficiency} = \frac{Voc * Isc * FF}{G * A} \tag{7}$$

2.2.1 Own used PV

Two types of rates are used in order to describe the effectivity of a PV system in terms of how much of the produced electricity is used in the building and how much of the solar electricity represents the building's total electricity usage. Own used electricity, also known as "self-consumption", refers to the solar electricity that is used in the building at the time that the solar electricity is produced. Based on this electricity the following two rates are calculated:

Own usage rate: proportion of the produced PV electricity that is used in the building.

$$\textit{Own usage rate} = \frac{\textit{Own used electricity}}{\textit{PV production}} * 100 \tag{8}$$

Self-sufficient rate: proportion of the building's total amount of electricity that comes from the PV system.

$$\textit{Self-sufficiency rate} = \frac{\textit{Own used electricity}}{\textit{Electricity usage}} * 100 \tag{9}$$

If the solar electricity is higher than the buildings electricity usage the system has a PV surplus that is delivered into the grid according to the current Swedish legislation.

2.3 DC vs AC power

Since the late 1800's, the AC power has been the preferred global platform for electrical transmission over DC. Almost all electricity produced, transferred and used in Sweden is alternating current, AC. The reasons why AC became more popular than direct current, DC, was that with the technology available at that time AC could easily be transformed from low voltage levels to high and vice versa using a transformer. High voltage levels allowed the transmission of electricity through long distances and capacitors as well as inductors could be used in the electronic circuit (Lancett 2017). In recent years, with an increased PV market and new microgrid solutions, new interest in the DC grid has appeared (Nohrstedt 2017a). For example the technology for High Voltage Direct Current (HVDC) has been established, also enabling long distance power transmission, relevant for renewable generation like wind, solar and hydro (ABB 2018). The following section explains the advantages that DC power has compared to traditional AC.

Lower conversion losses
PV modules generate DC electric power, which has to be converted to AC by an inverter in order to deliver the electricity into the grid. The solar cell inverter has an efficiency around 96-98%, i.e losses between 2-4%. By using a DC power grid the conversion steps are reduced and the PV system energy efficiency is increased.

Cheaper power electronics
Fewer converter steps involves less and smaller components compared to AC systems, which saves natural resources and lowers the cost. A DC voltage product has about half the size and uses half of the amount of material compared to the corresponding AC voltage product.

Increased cable distance
Electrical power is defined as the voltage times the current. Higher voltage levels decreases the current, which reduces the cable losses and cost by using thinner cables. Different cable technologies are needed when transferring AC vs DC due to different current flow. 760 VDC voltage level enable up to four times longer transmission distance with the same loss level and same cable as compared to conventional 230 VAC systems, as seen in figure 5 (Ferroamp 2017b).

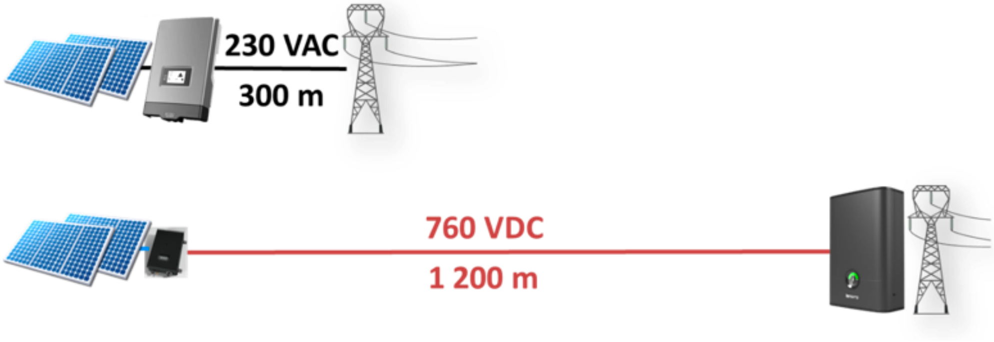


Figure 5: *Electrical cable distances DC vs AC (Ferroamp 2017b)*

Increased electrical quality and reliability
The electrical quality is increased by using a DC current with an unidirectional flow of electrical charges, which do not give rise to harmonics or interference. Additionally the sources of error are reduced by using less inverters.

DC-microgrid
As seen in figure 6, a DC-microgrid enables a shared usage of PV electricity and energy storage between nearby buildings. The PV system own usage and self produced rates can be increased by combining buildings with different load profiles and increasing the PV generation by placing the solar cells in different solar angles. Additionally, the energy storage system can be dimensioned for several properties (Ferroamp 2017b; Elinstalatören 2016) .

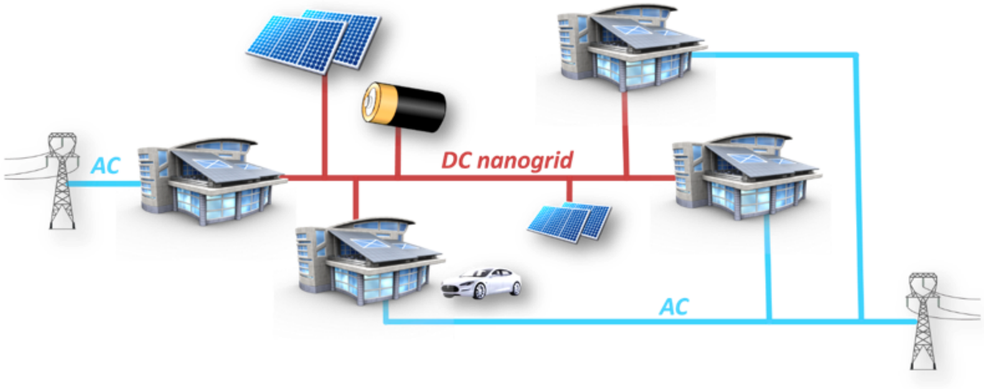


Figure 6: *DC-microgrid with shared PV system and energy storage (Ferroamp 2017b)*

2.4 DC-microgrid

Ferroamp is a Swedish company which aims to optimize the solar electricity utilization within a property through its “Energy Hub system” (Ehub) and DC-microgrid. The Energy Hub system aims to maximize the solar power investment by using an Adaptive Current Equalization (ACE), a bi-directional power inverter, battery storage, and an energy storage optimizer (ESO). The ACE increases the three phase supply efficiency, the battery storage is composed by Lithium Ion cells with an integrated Battery management system (BMS) and the bi-directional power inverter allows the conversion of AC from the grid to DC. Additionally, the system is equipped with a Solar String Optimizer (SSO) which optimizes the PV output by using a distributed Maximum Power Point Tracking (MPP). Ferroamp has estimated the following efficiency potential for its PV system technology (Ferroamp 2017b):

- 5-40% less power electronics
- 5-30% lower installation costs
- At least 50% reduction in conversion and cabling losses.

Furthermore, DC-microgrid of 760 V DC reduces the cabling losses by about 70% compared to 230 V AC and enables four times longer electricity transmission distance than standard (Ferroamp 2017a). In this project the Energy Hub system has been installed in the four new residential buildings which are connected to each other through a DC 380/760 V power line. The following figure shows the new buildings single line diagram.

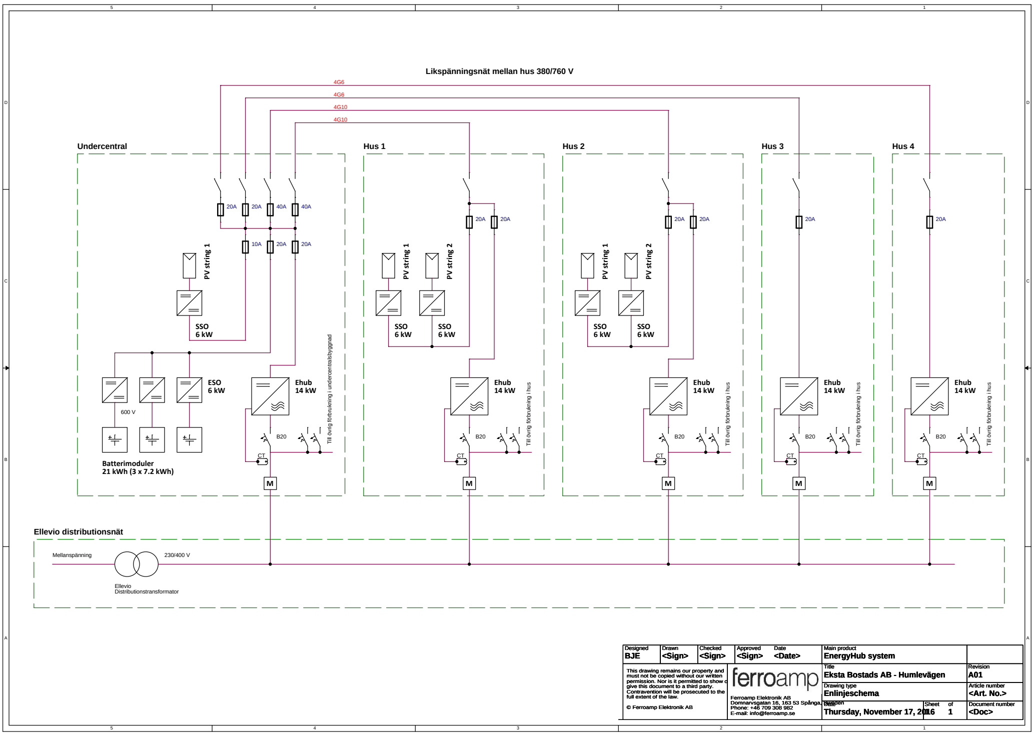


Figure 7: *Single line diagram new apartments Fjärås area (Karlström 2017)*

2.5 Swedish regulatory framework for concession

The Swedish electricity law (1997:857) describes the regulatory framework for concession of power lines as follows. The original text in Swedish is presented in Appendix A:

An electrical power-line may not be built or used without permission(Notisum 2017).

Permission for electricity transfer between buildings can be received for industrial plants, airports, farm properties and leisure activity. On the other hand, in the current legislation it is not permitted to transfer electricity between buildings in the same property (Regeringskansliet 2013). As a consequence, if a building generates more solar electricity than consumed or stored within the building, the surplus is delivered into the grid, which usually reduces the economical value of the self-produced electricity (Gåverud et al 2014).

The regulation 2007:215 present the exceptions for the law 1997:857. The exceptions 22A and 30 were relatively newly introduced aiming to facilitate the construction of renewable electricity generation, primarily wind power, but in the future also possible solar power. The exceptions refer to an internal power line which can be described as one or more power lines used by the owner for the transfer of electricity for own account (Regeringskansliet 2013).The original text in Swedish is presented in Appendix A:

22a § An internal power line connecting two or more electrical production facilities, which constitutes a functional unit, may be built and used without a network concession. Regulation (2008: 897).

30 § On the internal power lines referred in section 22a, transmission of electricity between the facilities can take place even if the facilities have different owners. Regulation (2008:897) (Regeringskansliet 2013).

In this master thesis, these exceptions are interpreted as valid for the demonstration area although not all buildings generated solar electricity. In addition to the exceptions, the electricity consumer has the option to choose its own electricity supplier, which also theoretically enables the transmission of the surplus electricity between buildings in the same property (Johnsson 2010). Furthermore, there is a national and European political will to promote solar energy. The Swedish government with the Moderate party, the Center party and the Christians democrats party have the goal for 2040 that solar electricity would represent 5-10% of the electricity mix (Regeringskansliet 2016). As explained by Elforsk, it is clear that the current regulatory framework for concession of power lines was created for a different type of energy system than the one that is about to emerge today, where consumers can also be electricity producers and electricity generation could be more efficient if independent from the grid (Gåverud et al 2014).

An example why the legislation should change in order to be up to date with the current electricity system is the power problem in the Swedish island Gotland. Gotland's energy company Geab has prohibited new renewable power generation from plugging into the grid since the mainland power cable is unable to transfer more electricity. This power problem could be solved by a combination of a microgrid and an exception in the regulatory framework for concession making it possible to create independent grid systems where solar electricity could be transferred between buildings (Nohrstedt 2017b).

3 Method

The following section presents the method used in order to achieve the project's results. The segment is divided in: literature study, legislation, electricity usage, PV production, PV electricity transmission potential and assumptions.

3.1 Literature study

A literature study was conducted focusing on the development of solar electricity in buildings in Sweden and Europe as well as the DC-microgrid technology. Furthermore, the possibilities with transferring electricity through DC-current in the context of grid concession law was researched. All search was performed using Google scholar or official websites.

3.2 Legislation

The analysis of the Swedish regulatory framework for concession was performed using the official law text from the website Notisum. Both the Swedish electricity law (1997:857) and it's exceptions (2007:215) were analyzed. Furthermore, the different law interpretations were discussed with Ferroamps vice president of sales and marketing, Mats Karlström.

3.3 Electricity usage

All calculations were performed during the time period September 2016 to August 2017. In order to facilitate the visualization, the results were presented from January to December.

New apartments

The electricity usage for the four new apartment buildings was calculated based on two studies. The first study was from Sveby, where the indicative instructions for energy calculations were described. The second study was financed by the Swedish construction industry development fund (SBUF) were the electricity usage in more than 1000 Swedish apartments between the time period 2008 to 2013 was collected (Bagge et al 2015). The yearly electricity usage in the four apartment buildings was assumed to be 30 kWh/m^2 (Sveby 2012). The daily variation per hour, presented in figure 8, was based on the average electricity usage in apartment buildings in the municipality Tanum situated 200 km from the demonstration area. The yearly variation was distributed as follow compared to standard: January 30% higher, February 20% higher, March 10% higher, April standard, May 10% lower, June 20% lower, July 30% lower, August 20% lower, September 10% lower, October standard, November 10% higher and December 20% higher (Sveby 2012).

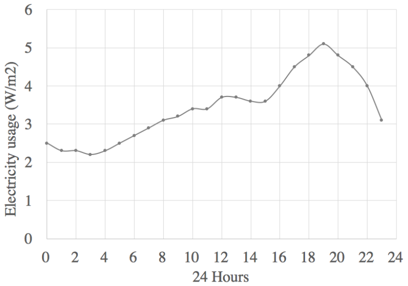


Figure 8: *Calculated daily electricity usage new apartments (W/m^2)*

The electricity load in the substation was assumed equal to a similar substation in another of Eksta's facilities. All calculations were performed using Excel.

Existing buildings

The measured hourly electricity usage in kWh for the preschool, community living and retirement home was given by the utility company Elevio for the designated time period (September 2016 to December 2017). For Eksta's expedition the measured electricity consumption for the same time period was given in kWh/month.

DC-microgrid

The DC-microgrid electricity usage in kWh/h, was calculated summarizing the electricity usage of all the buildings in the demonstration area (new residential buildings, preschool, community living, retirement home and expedition). 1% transmission losses were assumed according to Ferroamps recommendations.

$$\textit{DC-microgrid electricity usage} = \sum \textit{Electricity demonstration area} \tag{10}$$

3.4 PV production

All calculations were performed during the time period September 2016 to August 2017. In order to facilitate the visualization, the results were presented from January to December.

New apartments

The solar electricity generation for the residential buildings with a PV system (buildings 1,2) and the substation was calculated in the System Advisor Model (SAM) using the photovoltaic-residential model (NREL 2017b)). The system simulated the hourly solar electricity generation in kWh during a year. The weather file used was for Gothenburg situated 40 km away from Fjärås. The weather file collected weather information from 1991 to 2010. The PV module and the inverter used were CHSM6610M(BL) and SB3800TL-US-22 which were very similar to the products installed in the buildings, as seen in table 3. The system design such as the number of modules per string, azimuth and tilt was based on the real system. The simulated hourly solar electricity data was inserted in excel in order to compare with the buildings calculated electricity usage.

Existing buildings

The hourly PV electricity generation in kWh for the preschool, community living and retirement home was given by Eksta's PV measurements. Due to technical errors, approximately 3% of the PV data was missing.

DC-microgrid

The DC-microgrid PV electricity generation in kWh/h, was calculated summarizing the solar electricity of all the buildings with a PV system (building 1,2,substation, preschool, community living and retirement home).

$$\textit{DC-microgrid PV production} = \sum \textit{PV electricity demonstration area} \tag{11}$$

3.4.1 Surplus PV

The surplus PV in kWh/h, was calculated for all buildings and the microgrid with Excels's IF function:

$$\textit{Surplus PV=IF(PV production > Electricity usage; PV production - Electricity usage; 0)} \tag{12}$$

In order to compare the surplus PV if all buildings were connected through a DC-microgrid compared to individually the following fraction was used:

$$\% \; Surplus \; PV = \frac{Surplus \; PV}{PV \; production} * 100 \tag{13}$$

Duration diagram

In order to describe how often the surplus solar electricity occurred during a year, a duration diagram was created in Excel. The x-axis showed the number of days overproduction occurred during a year, the primary y-axis presented the overproduction in kWh/day and the secondary y-axis explained the percent of the total PV surplus.

3.4.2 Own usage rate and Self-sufficiency rate

The PV electricity usage in each buildings and the microgrid was determined by the own usage and self-sufficiency rates. The rates were calculated using equations 8 and 9. The Excel function IF was used in order to calculate the own used PV in kWh/h:

$$\textit{Own used PV =IF(PV production > Electricity usage;Electricity usage;PV production)} \tag{14}$$

3.5 PV electricity transmission potential

The difference between the own used solar electricity in kWh/year from the microgrid compared to all buildings individually showed how much PV electricity that could be transfered in the DC microgrid.

$$\textit{PV electricity DC microgrid = Own used PV microgrid - Own used PV individual buildings} \tag{15}$$

3.5.1 Electricity from the grid

In order to compare how much electricity in kWh/year that came from the grid if the buildings were connected through a DC microgrid vs individually, the following equation was used:

$$\textit{Electricity from the grid = Electricity usage - Own used PV} \tag{16}$$

3.6 Assumptions

The following assumptions were made during this master thesis:

- In order to find an exception in the Swedish regulatory framework for concession, it was assumed that Fjärås area could be considered as an electrical production facility although not all buildings have a PV system installed.
- All calculations, except for the expedition building, were performed using the time step 1 hour, kWh/h.
- The missing 3% PV generation data from the preschool, community living and retirement home was estimated assuming that the electricity generation was equal to the one the day before at the same hour for each building.
- The demonstration system was assumed to only include power from the PV system and the grid. No storage system was taken into consideration.
- When simulating the PV generation for the new apartments in SAM it was assumed accurate to use the standard SAM module which had very similar technical characteristics than the PV module installed in the buildings. Both modules are from the Chint Group and are compared in table 3.
- In the SAM simulation it was also assumed accurate to use the default inverter chosen for the PV system.
- The data for the electricity usage from Eksta's AB expedition was given in kWh/month. It was therefore assumed a constant electricity usage over the whole month.
- The yearly electricity consumption for the new apartments was assumed to be 30 kWh/m^2 based on the statistics from Svebys standard for apartment buildings (Sveby 2012).
- The 24h variation for the new apartments electricity usage was assumed to be similar to the average electricity usage in apartment buildings in Tanum. The hourly data was taken from a study performed by Lågan where energy data for 1000 apartments was collected from the years 2008 to 2013 (Bagge et al 2015).
- The annual variation for the electricity usage in the new apartments was assumed to be 30% higher in the winter months (according to SMHI December, January and February) and 30% lower in the summer months (according to SMHI June, July and August). This assumption was based on Svebys yearly electricity usage standard (Sverby 2012).
- The electricity usage at the substation in the new apartments area was assumed to be equal to a similar substation situated in another of Ekstas facilities. The data was provided by Eksta AB.

4 Case study

The demonstration area is situated in Fjärås at the municipality of Kungsbacka. The area contains four new apartment buildings, one substation and four existing buildings (preschool, community living, retirement home and Eksta AB expedition). All buildings belong to Eksta AB which is Kungsbackas municipality housing company. The company has long worked with environmental friendly accommodations using passive house standard and installing both solar thermal collectors and PV-systems (Eksta 2017a).

4.1 New apartments

Figure 9: *New construction Fjärås area. Buildings 1,2,3,4 and substation (UC). The substation is facing south (Eksta 2017b)*

The new construction contains four residential buildings constructed with a passive house technique and equipped with both solar thermal (building 4) and photovoltaic systems (buildings 1, 2 and the substation). Additionally, the electrical appliances installed in the apartments are energy efficient. The washing machine is equipped with a cold water connection, the laundry dryer has heat pump technique, which needs less power than a conventional product and the refrigerator and freezer are the best that can be found from an energy perspective in the market. Each apartment has individual ventilation units and floor heating in the living room, bathroom and bedroom, which ensures comfortable indoor temperature. All four buildings are equipped with an Energy Hub system from Ferroamp and interconnected with a DC power line. The PV-system is optimized with the solar string optimizer (SSO) and the solar electricity overproduction is planned to be stored in lithium ion cell batteries, which is not taken into account in this master thesis. In order to give the apartment owner the opportunity to influence its monthly costs, the consumption of electricity and hot and cold water is charged separately from the basic rent (Eksta 2017b).

4.1.1 Electricity usage

The following section presents the calculated electricity usage for the new buildings and substation. For all four residential buildings the electricity usage peak occurred at 19h, Swedish dinner time and the electricity usage was higher during the winter months.

Table 1 shows the energy information for buildings 1 and 3 separately due to that the results are the same for both buildings as they have the same area. Figure 10 shows the calculated average monthly and daily electricity usage for building 1 which shows the same results as building 3. The yearly maximum electricity usage was 2.14 kWh/h.

Table 1: Energy information building 1 and 3

Construction year	2017
Atemp	330.2 m^2
Energy performance	39.8 kWh/m^2, year
Electricity usage	9680 kWh/year
Ventilation system	FTX
Specific fan power (SFP)	0.7 kW/(m^3/s)
Heating system	District heating

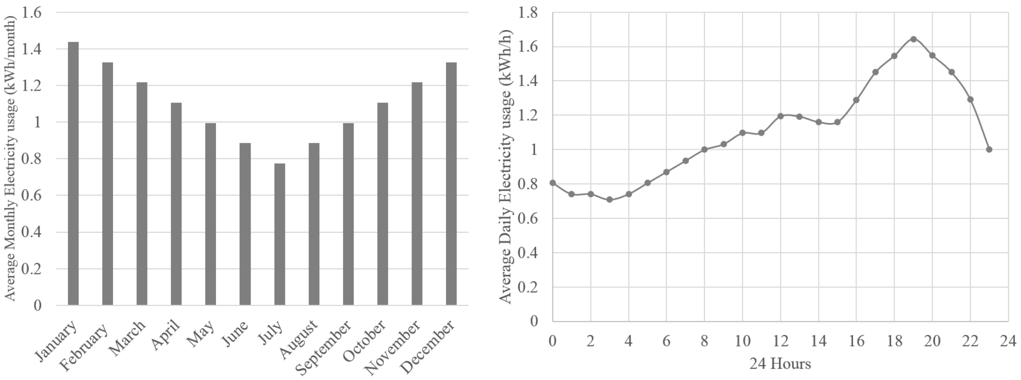


Figure 10: *Average monthly and daily electricity usage in apartment building 1 which shows the same results as building 3*

Table 2 presents the energy information for buildings 2 and 4 separately. Figure 11 shows the calculated average monthly and daily electricity usage for each building individually. The yearly maximum electricity usage was 2.13 kWh/h.

Table 2: Energy information building 2 and 4

Construction year	2017
Atemp	330.2 m^2
Energy performance	39.8 $\mathrm{kWh/m}^2$, year
Electricity usage	9650 kWh/year
Ventilation system	FTX
Specific fan power (SFP)	0.7 $\mathrm{kW/(m^3/s)}$
Heating system	District heating

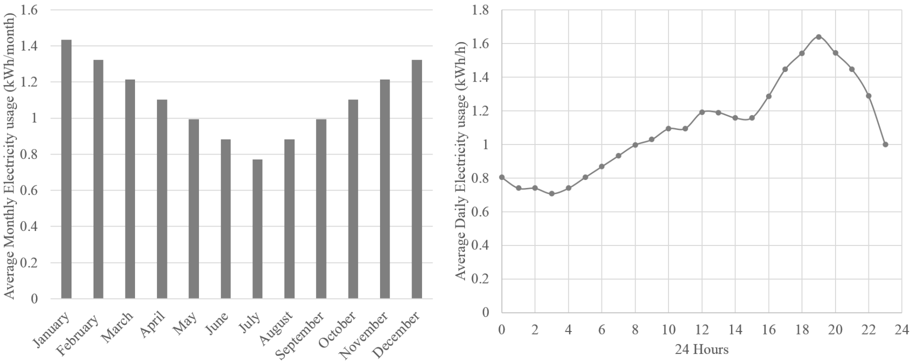


Figure 11: *Average monthly and daily electricity usage in apartment buildings 2 which shows the same results as building 4.*

Figure 12 presents the average monthly and daily electricity usage in the substation based on the electricity data from a similar substation. The electricity usage was higher during the winter months January and February. The difference between December and January is due to system improvements performed in 2016. For example, the pump was optimized by installing a frequency control temperature dependent device, drawing less electricity. On average the electricity top occurred at 12h when the solar pumps operated. The yearly maximum electricity usage was 2.65 kWh /h.

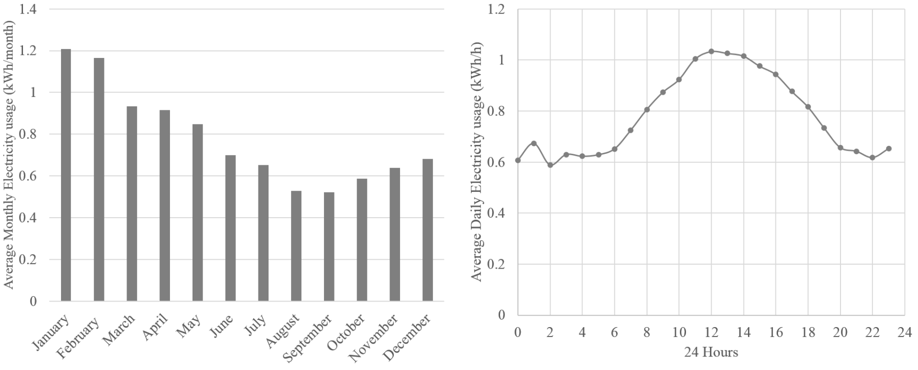


Figure 12: *Average monthly and daily electricity usage in substation*

4.1.2 PV system

This section presents the solar electricity system in buildings 1,2 and the substation. For all three buildings the solar electricity production was higher during the summer months and the average daily maximum was around 11 o'clock, approximately when the highest solar radiation occurs. Table 3 compares the PV module installed in the buildings (ASM6610M (BL)) and the PV module used in the system advisor model (SAM) in order to calculate the PV electricity generation (CHSM6610M(BL)).

Table 3: PV module installed in buildings 1,2 and substation vs PV module used in the SAM simulation. ASM6610M(BL) vs CHSM6610M(BL)

Module name	**Equipment in reality**	**Equipment in SAM**
Nominal efficiency	18.03%	18.09 %
Maximum power (Pmp)	295 W	295.3 W
Maximum power voltage (Vmp)	31.85 V	32.4 V
Maximum power current (Imp)	9.32 A	9.1 A
Open circuit voltage (Voc)	35.29 V	39.8 V
Temperature coefficient Voc	-0.32%	-0.32%
Short circuit current (Isc)	7.83 A	9.6 A
Temperature coefficient Isc	-0.042 %/K	-0.049%/K
Material	Monocrystaline	Monocrystaline
Module area	1.63 m^2	1.63 m^2

Table 4 shows the PV system information for building 1 and figure 13 presents the building's calculated average monthly and daily solar electricity generation over a year. The yearly maximum PV electricity was 3.76 kWh/h.

Table 4: PV System Design building 1

Tilt	30 degrees
Azimuth	80 degrees from south (south-west)
Annual PV generation	7750 kWh/year
PV system area	65.4 m^2

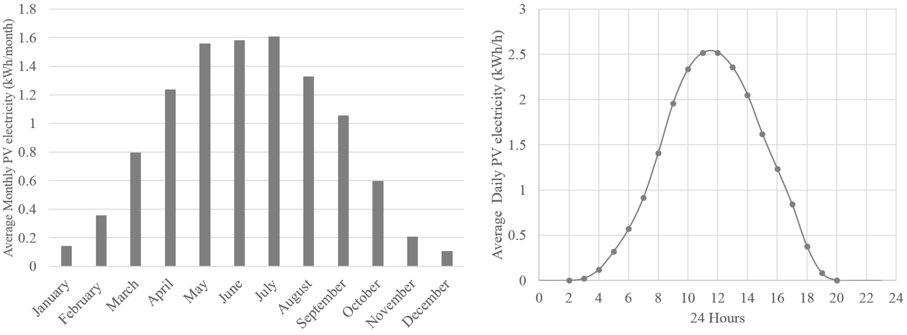


Figure 13: *Average monthly and daily PV electricity generation building 1*

Table 5 shows the PV system information for building 2 and figure 14 presents the building's calculated average monthly and daily solar electricity generation over a year. The yearly maximum PV electricity was 3.76 kWh/h.

Table 5: PV System Design building 2

Tilt	30 degrees
Azimuth	250 degrees from south (north-east)
Annual PV generation	7033 kWh/year
PV system area	65.4 m^2

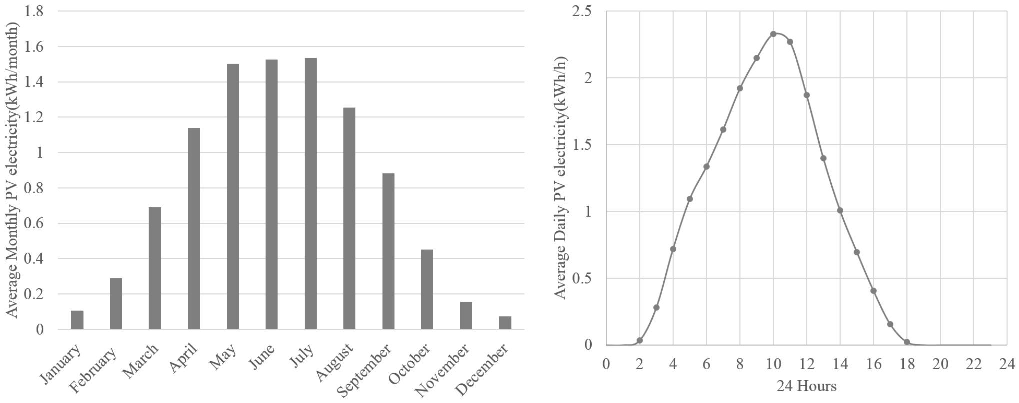


Figure 14: *Average monthly and daily PV electricity generation building 2*

Table 6 shows the PV system information for the substation and figure 15 presents the substation's calculated average monthly and daily solar electricity generation over a year. The yearly maximum PV electricity was 3.76 kWh/h.

Table 6: PV System Design substation

Tilt	33 degrees
Azimuth	0 degrees from south
Annual PV generation	5693 kWh/year
PV system area	32.7 m^2

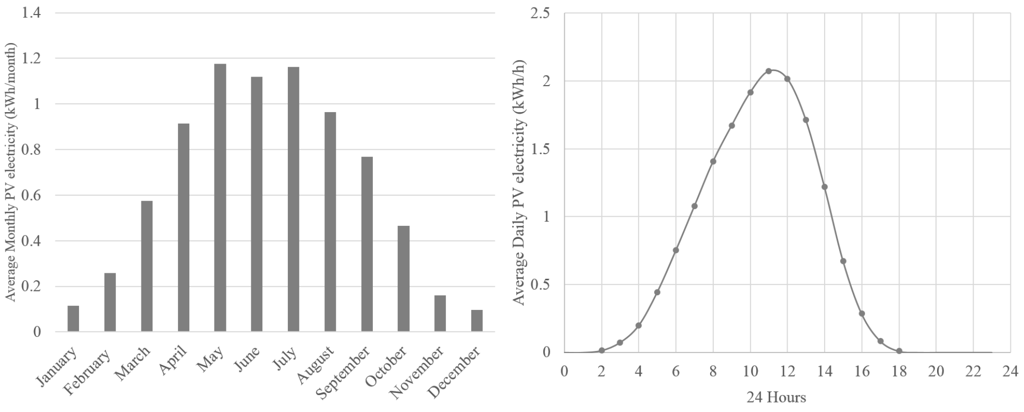


Figure 15: *Average monthly and daily PV electricity generation substation*

4.2 Preschool

The following subsection presents the preschool's electricity usage and solar electricity generation.

4.2.1 Electricity usage

Prästgårdsängen preschool started in autumn 2008. The building was constructed as a passive house. Additionally, the preschool is equipped with a PV system. The food served daily comes from Måhaga retirement home (Kungsbacka 2017a).

Table 7 presents the energy information for the building and figure 17 describes the measured average electricity usage of the preschool over a year versus 24h. The electricity usage varies during the year depending on the weather and light conditions, with a peak during the month of December and a valley during the summer months May, June and July. On average, the electricity usage peaks between 06-07h, which coincides with the school start. The yearly maximum electricity usage was 24 kWh/h.

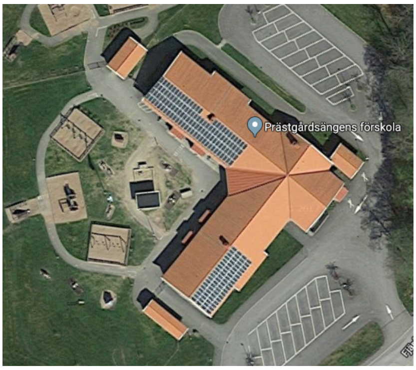


Figure 16: *Preschool Fjärås area*

Table 7: Energy information Preschool

Construction year	2008
Atemp	900 m^2
Energy performance	64 kWh/m^2, year. Energy class C
Electricity usage	46523 kWh/year
Ventilation system	FTX
Heating system	District heating

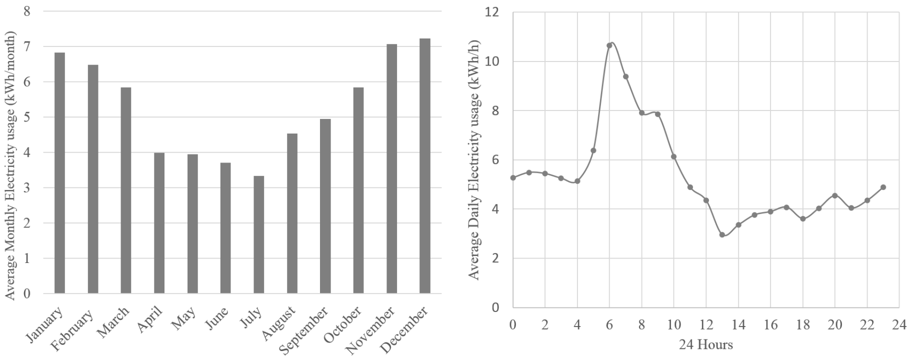


Figure 17: *Average monthly and daily electricity usage Preschool*

4.2.2 PV system

Table 8 shows the PV system information for the preschool and figure 18 presents the measured average monthly and daily solar electricity generation over the time period September 2016 to August 2017. The solar electricity production was higher during the summer months and the average daily maximum was at 12h. The yearly maximum PV electricity was 28 kWh/h.

Table 8: Preschools PV system information

Solar panel	ASM6610P
Nominal efficiency	16.20%
Maximum power (Pmp)	265 Wp
Maximum power voltage (Vmp)	31.16 V
Maximum power current (Imp)	8.57 A
Open circuit voltage (Voc)	36.20 V
Short circuit current (Isc)	7.21 A
Material	polycristalline
Annual PV generation	27076 kWh/year
PV system area	240 m^2

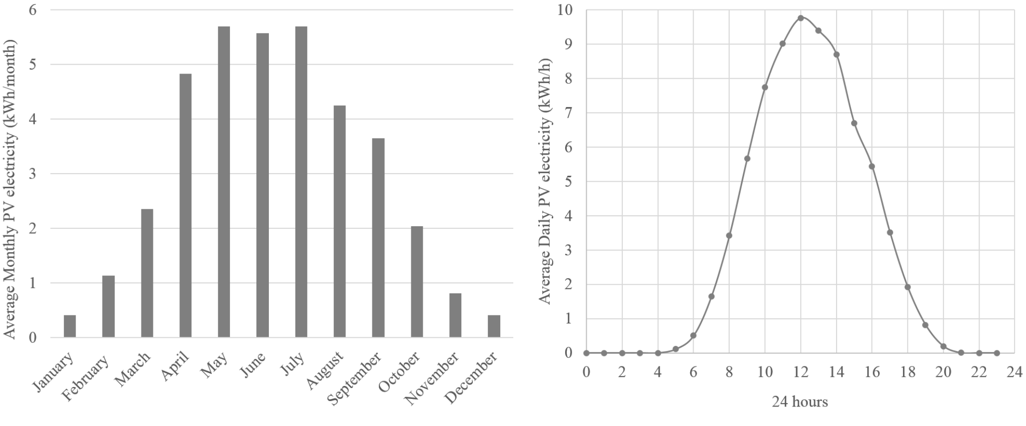


Figure 18: *Average monthly and daily PV electricity generation Preschool*

4.3 Community living

The following subsection describes the community living's electricity usage and solar electricity generation.

4.3.1 Electricity usage

Prästgårdsängens community living was constructed in 1994 and is also equipped with a PV system. The building electricity consumption during the year varies dependent on the weather and light conditions with a top in December and a minimum in June. The electricity consumption and PV electricity generation is lower than the neighboring buildings. In average the daily electricity consumption peak coincides with the Swedish dinner cooking time between 17-18h. The yearly maximum electricity usage was 7.61 kWh/h

Figure 19: *Community living Fjärås area*

Table 9: Energy information Community living

Construction year	1994
Atemp	444 m^2
Energy performance	179 kWh/m^2, year
Electricity usage	18413 kWh/year
Ventilation system	FTX
Heating system	District heating

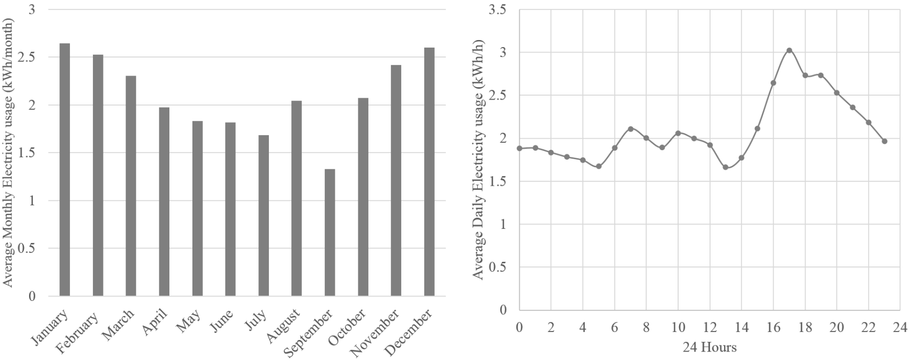


Figure 20: *Average monthly and daily electricity usage in the Community living*

4.3.2 PV system

Table 10 shows the PV system information for the community living and figure 21 presents the measured average monthly and daily solar electricity generation over the time period September 2016 to August 2017. The solar electricity production was higher during the summer months and the average daily maximum was at 13h. The yearly maximum PV electricity was 3 kWh/h.

Table 10: Community living PV system information

Solar panel	SOLARWATT BLUE 60P
Nominal efficiency	15.03%
Maximum power (Pmp)	265 Wp
Maximum power voltage (Vmp)	30.7 V
Maximum power current (Imp)	8.63 A
Open circuit voltage (Voc)	38.1 V
Short circuit current (Isc)	8.99 A
Material	polycristalline
Tilt	15 degrees
Azimuth	85 degrees from south (south-west)
Annual PV generation	3094 kWh/year
PV system area	23 m^2

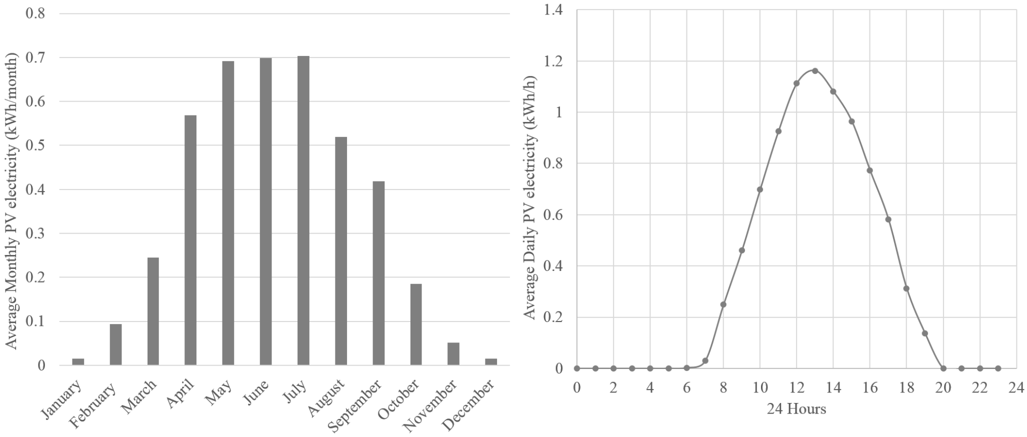


Figure 21: *Average monthly and daily PV electricity generation Community living*

4.4 Retirement home

The following subsection shows the retirement home's measured electricity usage and solar electricity generation.

4.4.1 Electricity usage

Måhaga retirement home was constructed in 1988 and has 58 apartments which are 32-47 square meters in size. All food is cooked in the retirement and lunch is also prepared for the preschool. The building is also equipped with a PV system (Kungsbacka 2017b).

Table 11 presents the energy information for the retirement home and figure 23 describes the measured average electricity usage of the retirement home over a year versus 24h. The electricity usage is relatively constant during the year with a top of 90 kWh/month in December. As the retirement home cooks lunch for its customers and the preschool on average the electricity peak is at 10h. Yearly maximum electricity usage, 90.88 kWh/h.

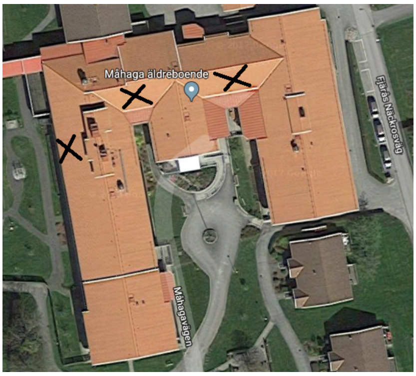


Figure 22: *Retirement home Fjärås area. The crosses represent the PV system.*

Table 11: Energy information Retirement home

Construction year	1988
Atemp	4123 m^2
Energy performance	143 kWh/m^2, year. Energy class D
Electricity usage	345325 kWh/year
Ventilation system	FTX
Heating system	District heating

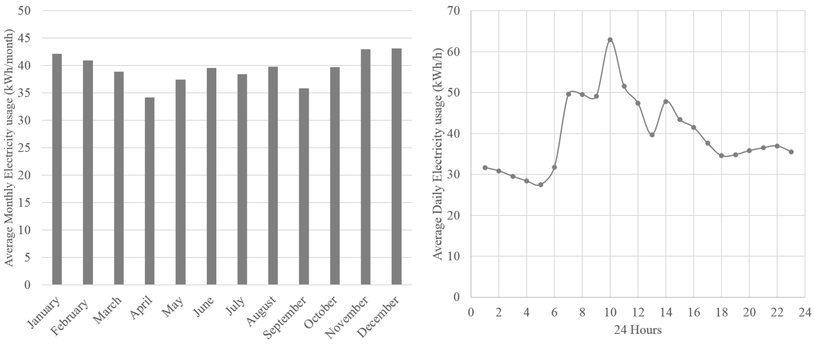


Figure 23: *Average monthly and daily electricity usage in the Retirement home.*

4.4.2 PV system

Table 12 shows the PV system information for the retirement home and figure 24 presents the measured average monthly and daily solar electricity generation over the time period September 2016 to August 2017. The solar electricity production was higher during the summer months and the average daily maximum was at 13h. The yearly maximum PV electricity was 33 kWh/h.

Table 12: Retirement home PV system information

	South-east roof	**South-west roof**
Solar panel	ASM6610P	ASM6610P
Nominal efficiency	16.20 %	16.20 %
Maximum power (Pmp)	265 Wp	265 Wp
Maximum power voltage (Vmp)	31.16 V	31.16 V
Maximum power current (Imp)	8.57 A	8.57 A
Open circuit voltage (Voc)	36.20 V	36.20 V
Short circuit current (Isc)	7.21 A	7.21 A
Material	polycristalline	polycristalline
Tilt	15 degrees	15 degrees
Azimuth	355 degrees from south	70 degrees from south
Annual PV generation	19485 kWh	16842 kWh
PV system area	137.41 m^2	107.58 m^2

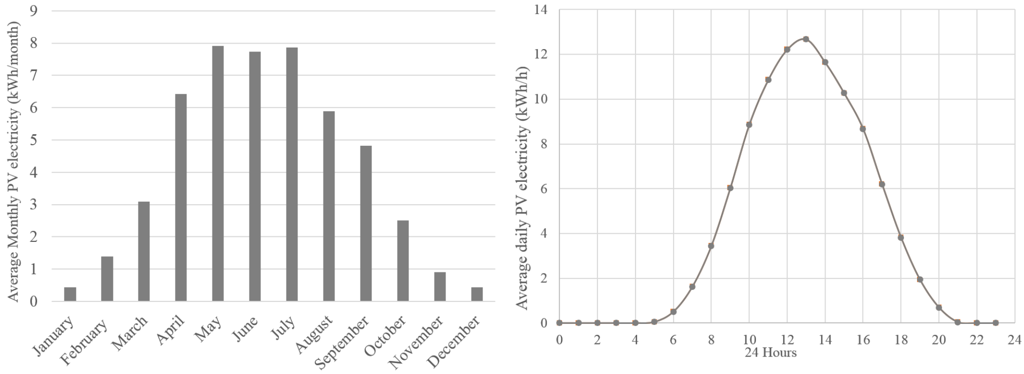


Figure 24: *Average monthly and daily PV electricity generation Retirement home*

4.5 Eksta AB expedition

The following subsection describes the expedition's measured electricity usage.

4.5.1 Electricity usage

Table 13 presents the energy information for the Eksta's AB expedition. The expedition's electricity usage information was only available in kWh/month, which is presented in table 14. The values were relatively constant during the whole studied time period (September 2016 - August 2017).

Table 13: Energy information Eksta expedition

Construction year	2011
Atemp	222 m^2
Energy performance	85 kWh/m^2, year. Energy class D
Electricity usage	1800 kWh/year
Ventilation system	FTX
Heating system	District heating

Table 14: Electricity usage expedition kWh/month

September 2016	943 kWh/month
October 2016	1020 kWh/month
November 2016	1070 kWh/month
December 2016	1114 kWh/month
January 2017	1071 kWh/month
February 2017	959 kWh/month
Mars 2017	1042 kWh/month
April2017	907 kWh/month
May 2017	1080 kWh/month
June 2017	907 kWh/month
July 2017	859 kWh/month
August 2017	931 kWh/month

4.6 DC-microgrid

The demonstration area consisted of buildings with different electricity usage patterns and power usage, dependent on each buildings purpose. For all buildings, the electricity usage varied with the Swedish weather and light conditions i.e higher electricity usage during the winter months (December, January and February). Figure 25 presents the average daily electricity patterns for the whole demonstration area where the retirement home had the highest consumption (100 547 kWh/year) and the substation the lowest (6 832 kWh/year).

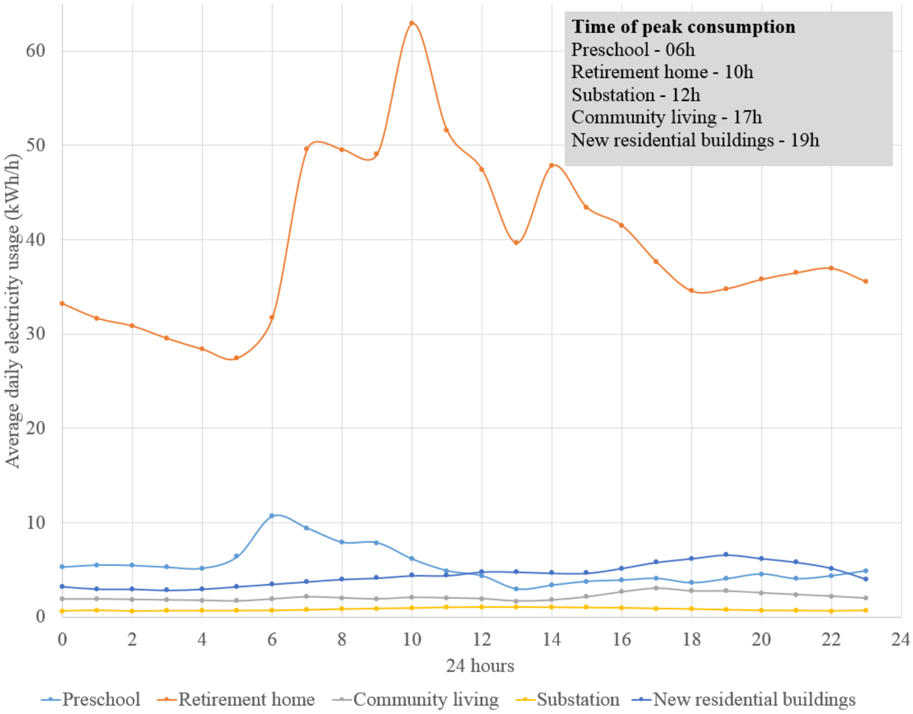


Figure 25: *Average daily electricity usage demonstration area.*

Figure 26 shows the average daily PV generation for all buildings in the demonstration area where the retirement home had the highest generation (36 327 kWh/year) and the community living the lowest (2 482kWh/year). For all buildings, the PV generation was dependent on the Swedish light and weather conditions with a higher electricity generation during the summer months (May, June and July) and an average daily PV generation peak around 12.pm (10.am to 1.pm) when the maximum solar radiation occurs.

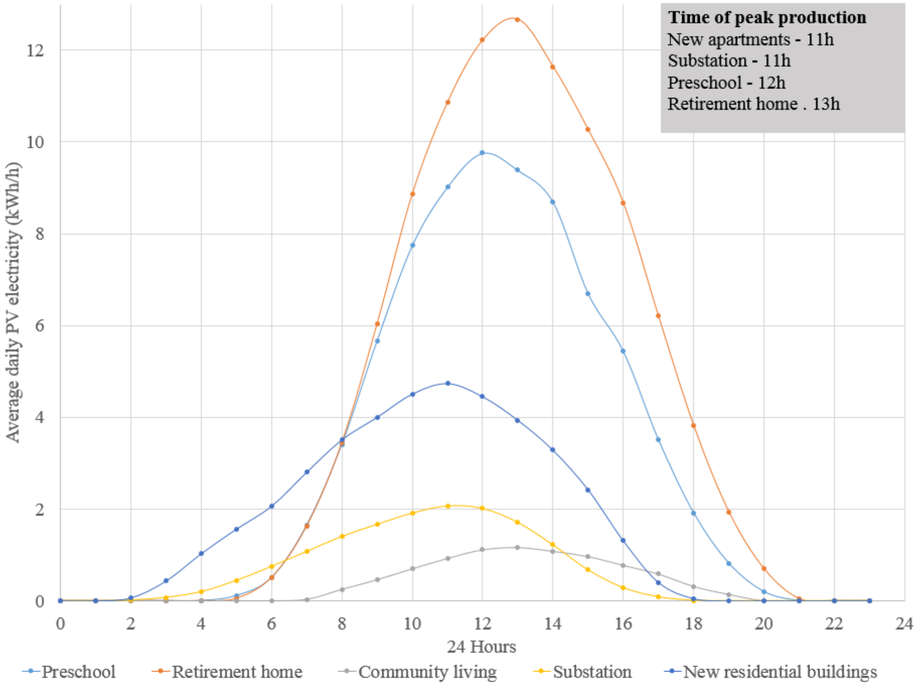


Figure 26: *Average daily PV electricity generation demonstration area.*

Figure 27 shows the average daily electricity usage and PV electricity generation in the theoretical case where all buildings were connected in a DC-microgrid. The electricity consumption and PV-generation was summarized for all buildings, resulting in a more homogeneously distributed electricity consumption and higher solar electricity generation. The yearly maximums were 119 kWh/h and 72 kWh/h respectively.

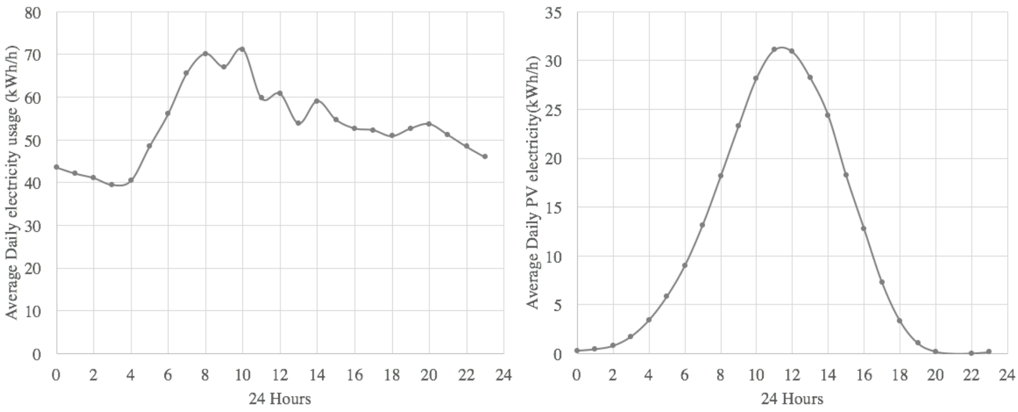


Figure 27: *Average daily electricity usage and PV electricity generation DC-microgrid*

5 Results

The following section presents the surplus PV electricity, own usage rate and self-sufficiency rate for all buildings individually and compares the results if the buildings are connected in a DC-microgrid vs individually.

5.1 Buildings individually

5.1.1 Own usage rate and Self-sufficiency rate

Table 15 shows the own usage and self-sufficiency rates for all buildings with an installed PV system in the demonstration area. According to equations 8 and 9 the rates are calculated by dividing the own used electricity with the PV production and electricity usage. Therefore, in order to understand the results the yearly electricity consumption and solar electricity production in kWh/year were also presented in table 15.

The preschool was the building with the lowest usage of its solar electricity and the retirement home had the highest PV usage. The new buildings and substation had the highest proportion of solar electricity in the buildings total electricity usage.

Table 15: Own usage rate and Self sufficiency rate for the buildings with PV system in the demonstration area.

	Own usage rate	*Self-sufficiency rate*	*PV production (kWh/year)*	*Electricity usage (kWh/year)*
Building 1	40%	33%	7 750	9 680
Building 2	42%	31%	7 733	9 650
Substation	44%	37 %	5 693	6 832
Preschool	22%	13 %	27 076	46 523
Community living	61%	10%	3 094	18 413
Retirement home	97%	10%	36 327	345 325

5.1.2 Surplus PV electricity

The following section presents the surplus PV electricity for all the buildings with a PV system in the demonstration area. The solar electricity overproduction is presented by two different diagrams, a duration diagram with the unit kWh/day and a bar diagram showing the total used PV production, surplus PV and electricity usage in kWh/month.

5.1.2.1 New apartments

Building 1
Building's 1 calculated PV system had solar electricity overproduction 270 days a year. The surplus varied from 0 to 30 kWh/day. 120 days a year the overproduction was between 20-30 kWh, which represented 68% of the total surplus PV.

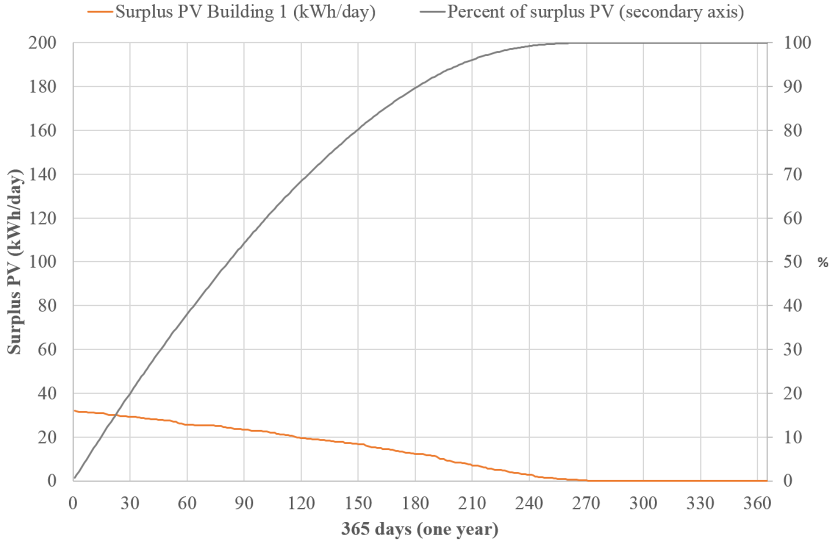


Figure 28: *Duration diagram surplus PV building 1.*

Figure 29 presents the calculated monthly electricity usage and PV production in building 1. The maximum monthly electricity consumption and production was 1 200 kWh/month. 60% of the PV production became surplus. The calculated electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 45.

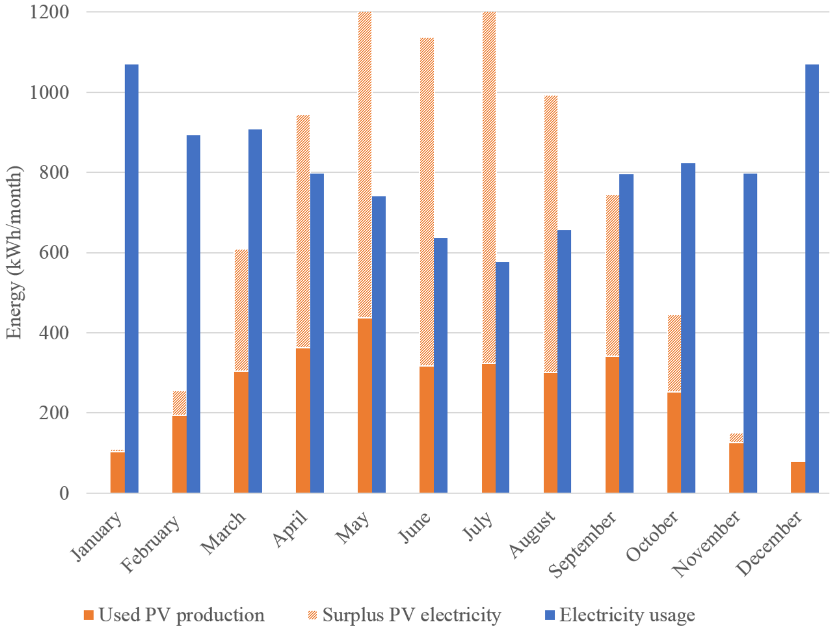


Figure 29: *Total PV production, PV surplus electricity and electricity usage per month over a year for building 1*

Building 2

Building's 2 calculated PV system had solar electricity overproduction 240 days a year. The surplus varied from 0 to 30 kWh/day. 120 days a year the overproduction was between 18-30 kWh, which represented approximately 73% of the total surplus PV.

Figure 31 presents the calculated monthly electricity usage and PV production in building 2. The maximum monthly electricity consumption and production was 1 150 kWh/month. 57% of the PV production became surplus. The calculated electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 46.

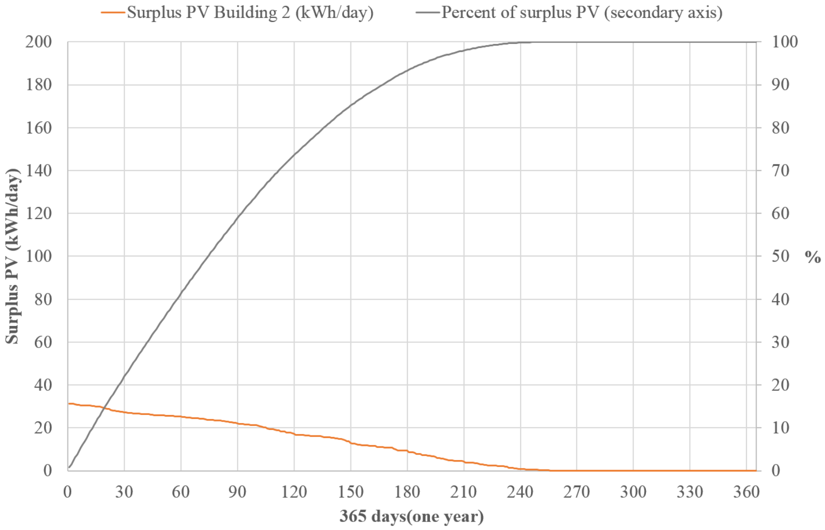


Figure 30: *Duration diagram surplus PV building 2.*

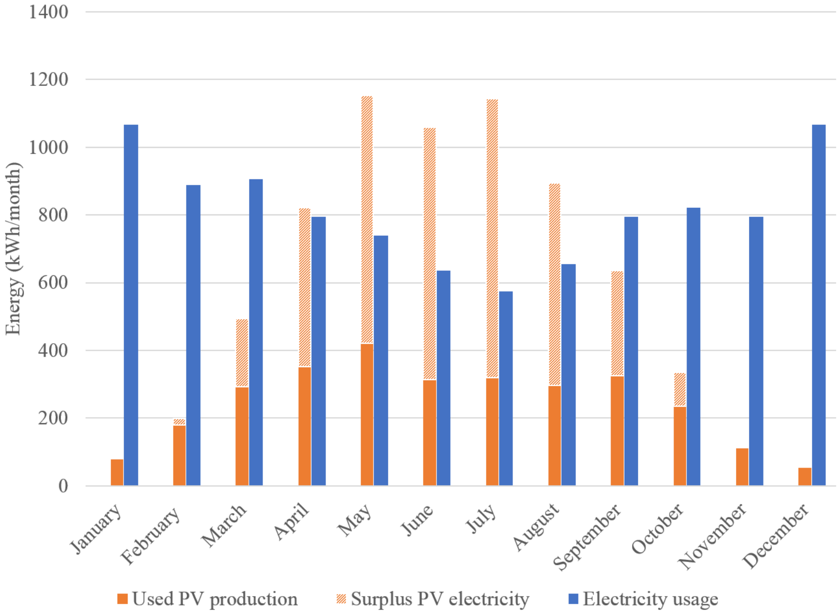


Figure 31: *Total PV production, PV surplus electricity and electricity usage per month over a year for building 2.*

Substation

The substation's calculated PV system had solar electricity overproduction 240 days a year. The surplus varied from 0 to 25 kWh/day. 120 days a year the overproduction was between 18-25 kWh, which represented approximately 73% of the total surplus PV.

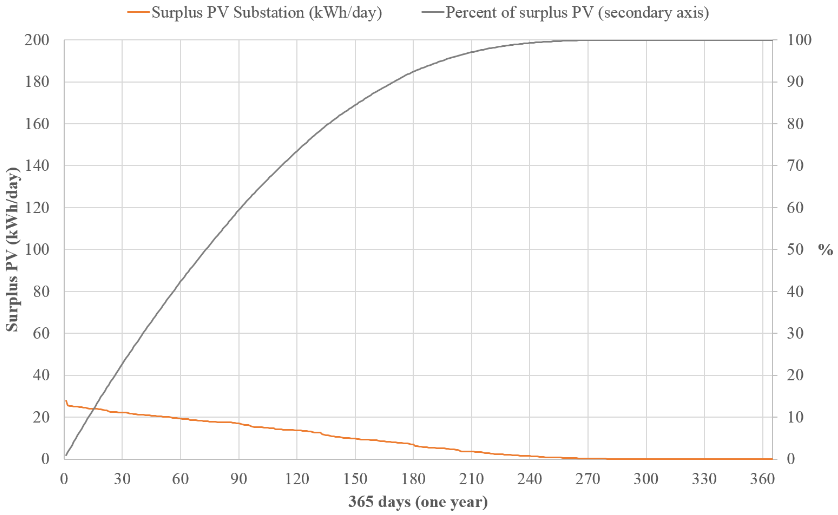


Figure 32: *Duration diagram surplus PV substation.*

Figure 33 presents the calculated monthly electricity usage and PV production in the substation. The maximum monthly electricity consumption and production was 900 kWh/month. 55% of the PV production became surplus. The calculated electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 47.

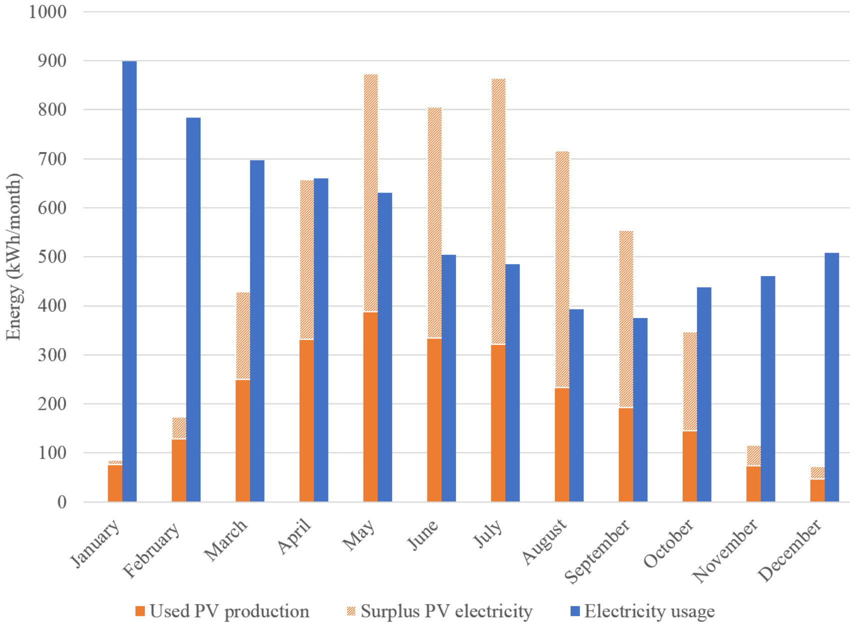


Figure 33: *Total PV production, PV surplus electricity and electricity usage per month over a year for substation.*

5.1.2.2 Preschool

The preschool's PV system had solar electricity overproduction 270 days a year. The surplus varied from 0 to 200 kWh/day. 120 days a year the overproduction was between 82-200 kWh which represented approximately 77% of the total surplus PV.

Figure 35 presents the monthly electricity usage and PV production in the preschool. The maximum monthly electricity consumption and production was 5 400 kWh/month. 77% of the PV production became surplus. The electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 48.

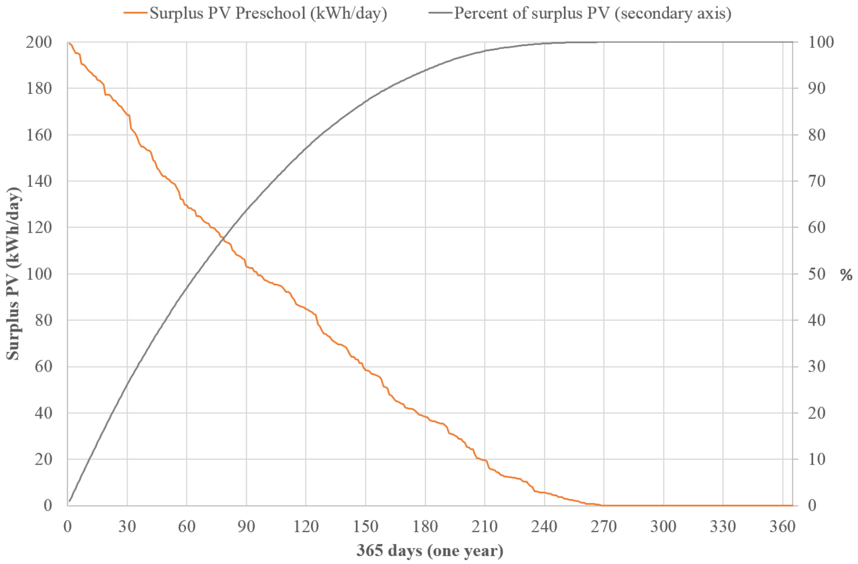


Figure 34: *Duration diagram surplus PV preschool.*

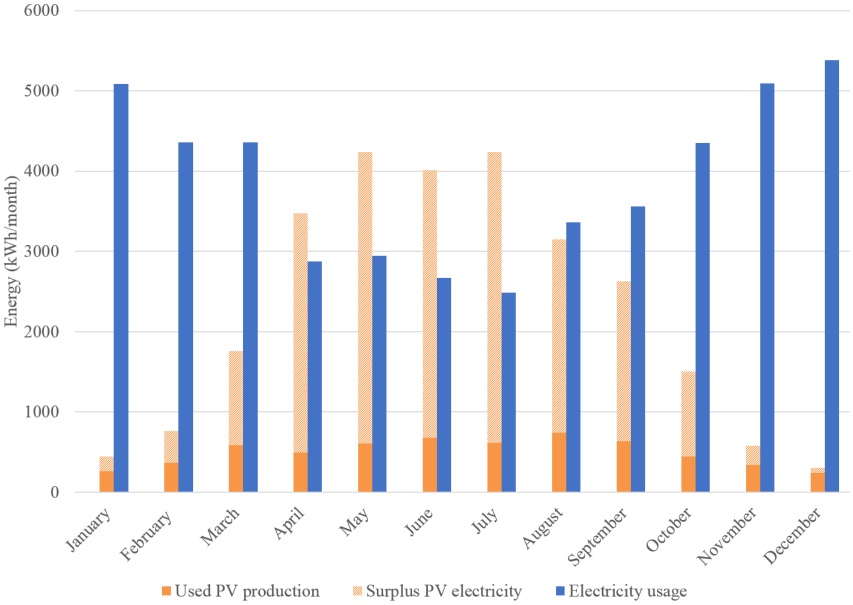


Figure 35: *Total PV production, PV surplus electricity and electricity usage per month over a year for the preschool.*

5.1.2.3 Community living

The community's living PV system had solar electricity overproduction 170 days a year. The surplus varied from 0 to 20 kWh/day. 120 days a year the overproduction was between 5-20 kWh, which represented approximately 92% of the total surplus PV.

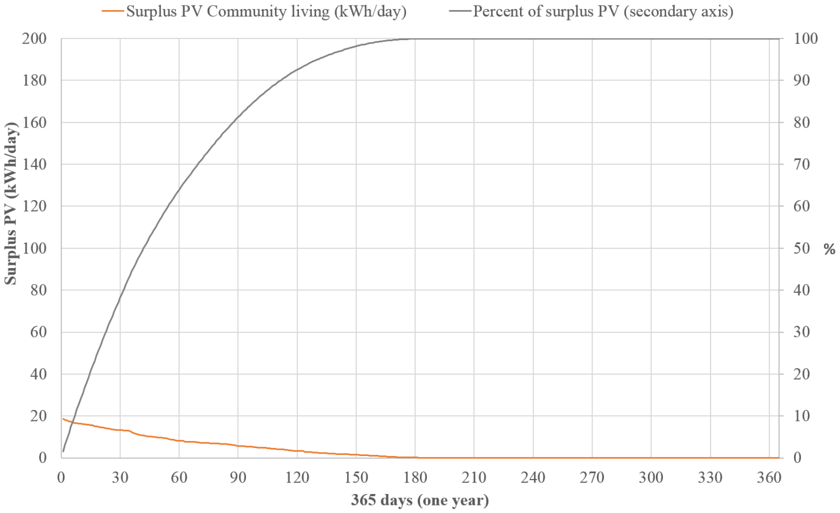


Figure 36: *Duration diagram surplus PV community living.*

Figure 37 presents the monthly electricity usage and PV production in the community living. The maximum monthly electricity consumption and production was 1 900 kWh/month. 40% of the PV production became surplus. The electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 49.

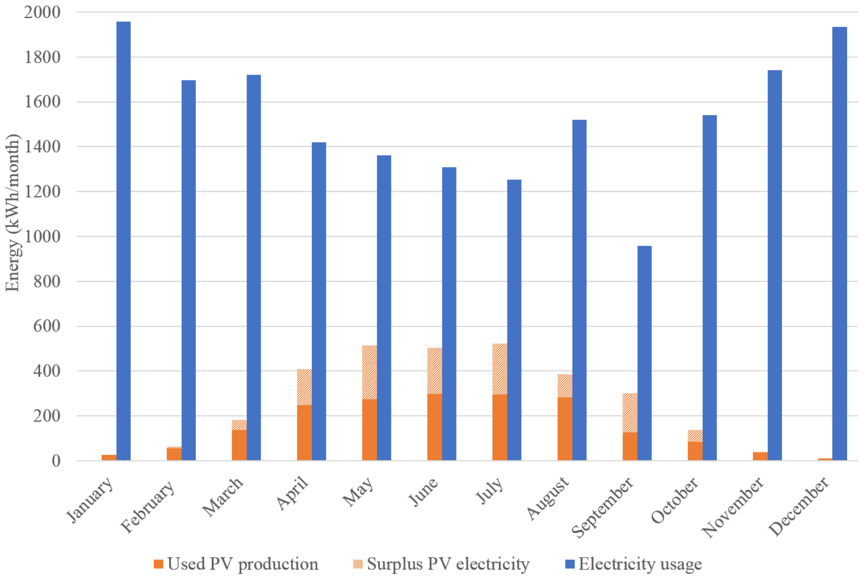


Figure 37: *Total PV production, PV surplus electricity and electricity usage per month over a year for the community living.*

5.1.2.4 Retirement home

The retirement's home PV system had solar electricity overproduction 60 days a year. The surplus varied from 0 to 90 kWh/day. 120 days a year the overproduction was between 0-90 kWh, which represented 100% of the total surplus PV.

Figure 39 presents the monthly electricity usage and PV production in the retirement home. The maximum monthly electricity consumption and production was 3 200 kWh/month. 3% of the PV production became surplus. The electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 50.

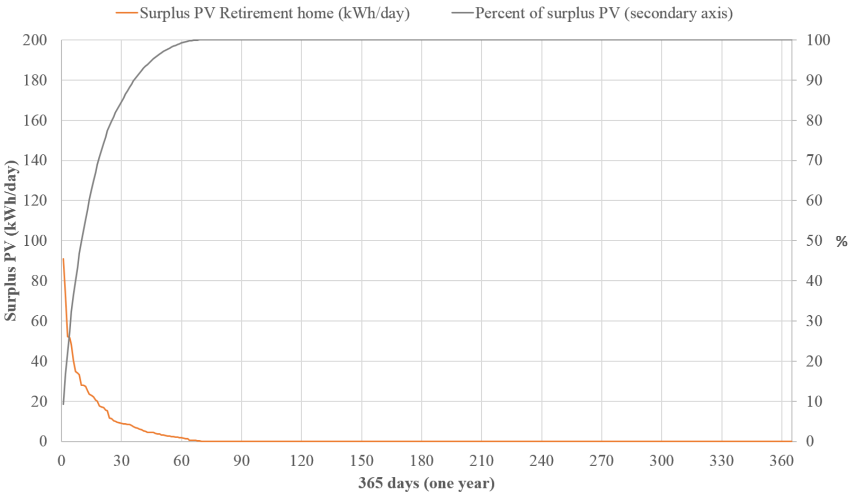


Figure 38: *Duration diagram surplus PV retirement home.*

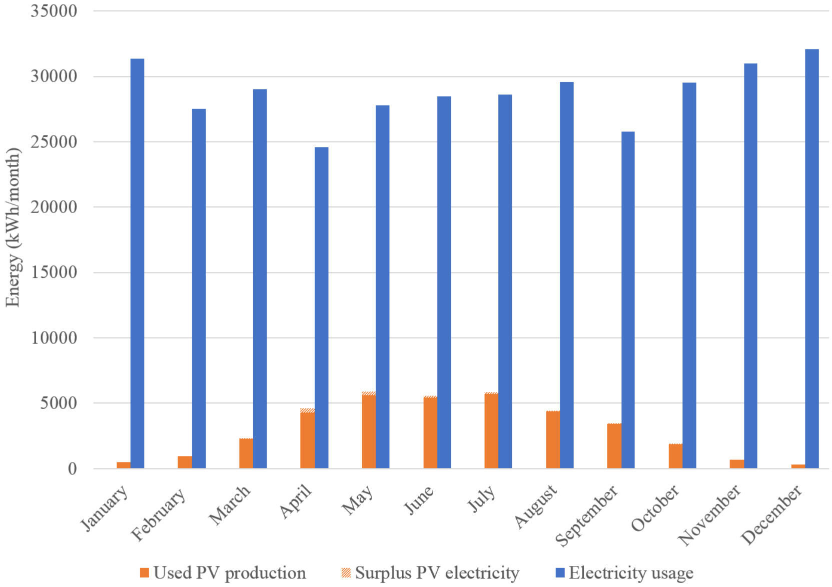


Figure 39: *Total PV production, PV surplus electricity and electricity usage per month over a year for the retirement home.*

5.2 Buildings in a DC-Microgrid

5.2.1 Own usage rate & Self-sufficiency rate

If all buildings were connected in a DC-microgrid the own usage rate increased in 32 percentage points,which equals 56%, and the self sufficiency-rate increased in 6 percentage points, which equals 54%. The solar electricity overproduction was reduced to a quarter, approximately 27 000 kWh/year difference as seen in figure 40.

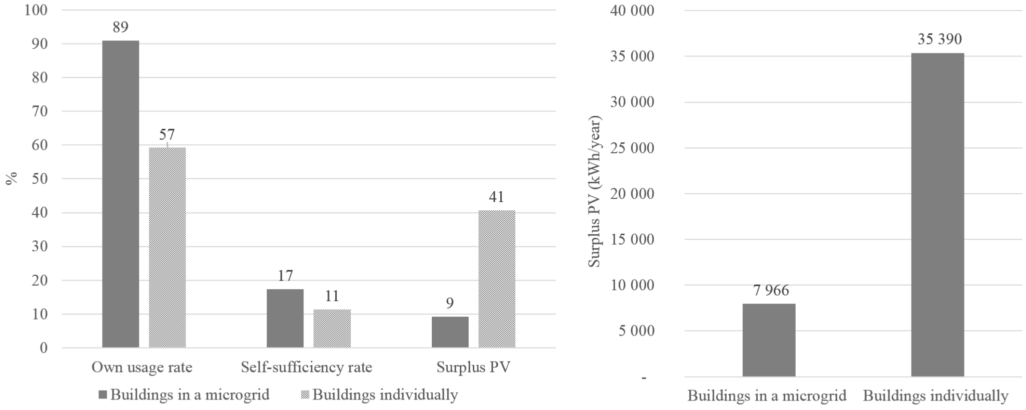


Figure 40: *Comparison own usage rate,self-sufficiency rates and surplus PV buildings in a DC-microgrid vs individually*

5.2.2 Surplus PV electricity

The following section compares the surplus PV electricity if all the buildings were connected in a DC-microgrid vs all buildings individually. As seen in figure 41, the solar electricity overproduction occurred 320 days a year if the buildings were not connected compared to 150 days if they were connected through a DC-microgrid. The surplus PV decreases with 100 kWh/day when using a DC-microgrid.

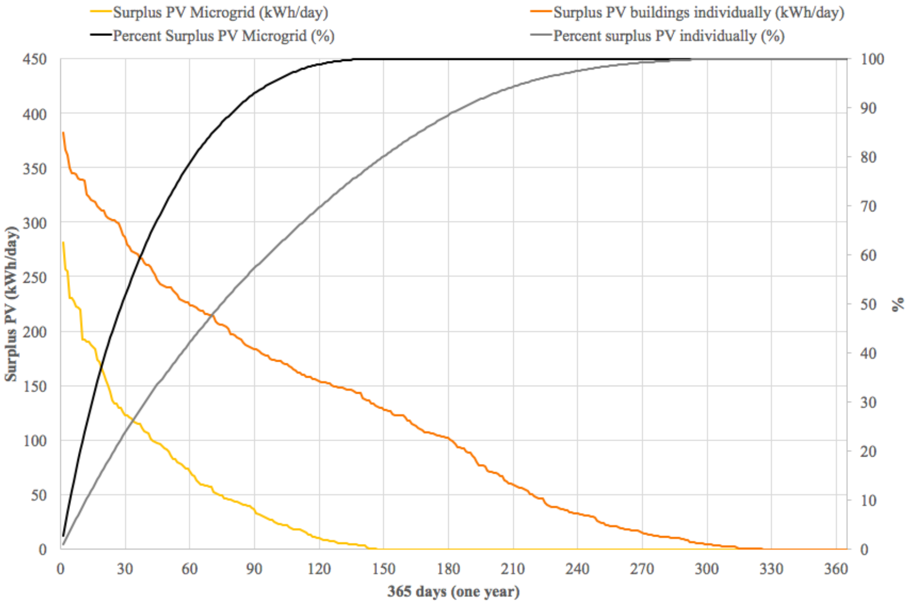


Figure 41: *Duration diagram surplus PV DC-microgrid vs buildings individually.*

Figure 42 shows the monthly electricity usage and PV production with a DC-microgrid (left) compared to buildings individually (right). The PV production and electricity usage are the same for both systems but the surplus PV varies. When the buildings were connected in a DC-microgrid 9% of the PV production became surplus compared to 41% if the buildings were not connected. The electricity usage and solar electricity generation in kWh/h is presented in Appendix B, figure 51.

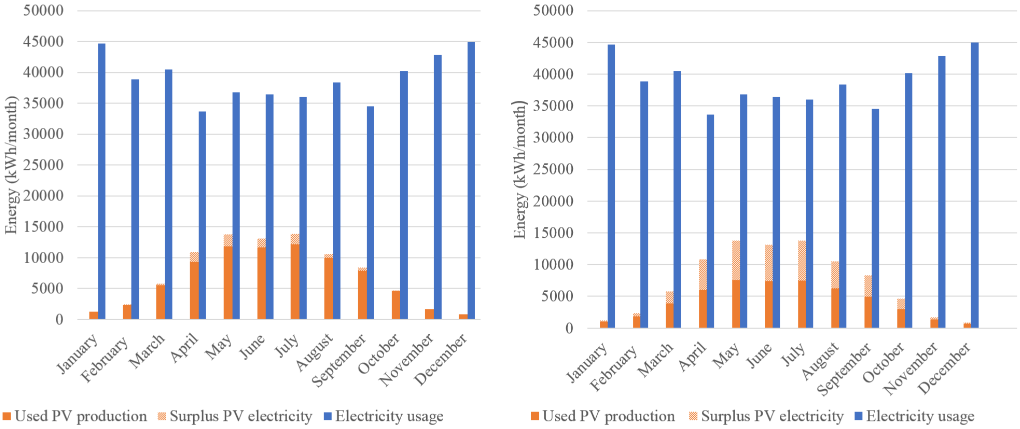
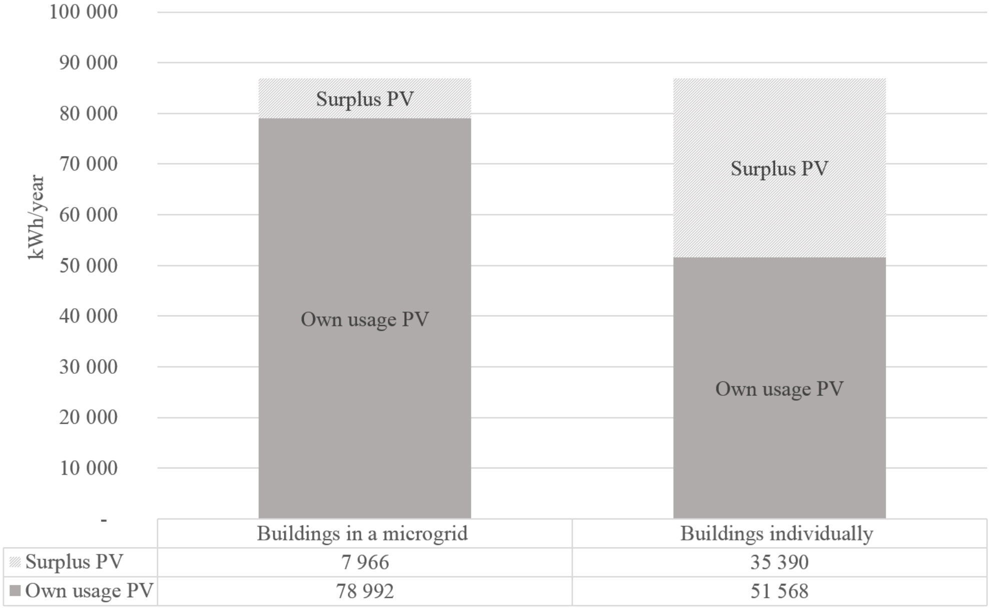


Figure 42: *Total PV production, PV surplus electricity and electricity usage per month over a year when the buildings are connected with a DC-microgrid (left) vs individually (right).*

5.2.3 PV electricity transmission potential

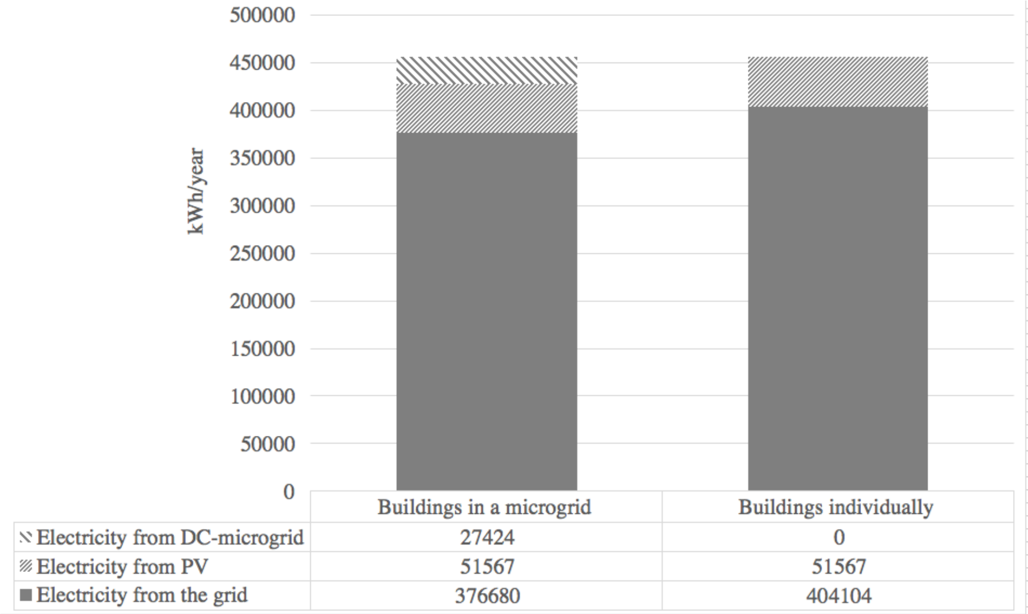
Figure 43 shows the change in the PV production usage if the buildings share their solar electricity in a DC-microgrid or without a microgrid. 91% of the solar electricity was used in the DC-microgrid compared to 59% if buildings were individually.



	Buildings in a microgrid	Buildings individually
▨ Surplus PV	7 966	35 390
■ Own usage PV	78 992	51 568

Figure 43: *PV production usage if all buildings were connected in a DC-microgrid (left) compared to buildings individually (right)*

Figure 44 shows the comparison between the electricity usage if the buildings were in a DC-microgrid vs the usage individually. 82% of the electricity was bought from the grid if the buildings were connected compared to 86% in an individual system. The 4 percentage point difference was the potential solar electricity that could be transfered between the buildings, electricity from the DC-microgrid. This electricity was calculated to approximately 27 000 kWh/year.



	Buildings in a microgrid	Buildings individually
⟍ Electricity from DC-microgrid	27424	0
▨ Electricity from PV	51567	51567
■ Electricity from the grid	376680	404104

Figure 44: *Electricity usage if all buildings were connected in a DC-microgrid (left) compared to buildings individually (right)*

5.2.3.1 Maximal potential

In order to achieve maximal PV electricity generation, the PV system could be maximized for each building's roof area, which could lead to an increased usage of the own produced solar electricity. With a DC-microgrid, the potential roof areas for PV installation are in the directions south, west and east compared to individual systems where only south roofs are useful.

A rough estimation of the maximal potential roof areas and its PV production was calculated using Google Maps and SAM. Table 16 compares the existing PV system area and yearly generation in each building vs the calculated increased potential area and solar electricity generation if the buildings were connected in a DC-microgrid. In this project approximately 30% of the total profitable PV area was used. By using the maximal profitable roof area the yearly solar electricity generation could approximately increase 46 000 kWh/year.

Table 16: Existing PV surface and generation vs potential increased PV surface and generation.

	Existing PV		**Potential increased PV**	
	m^2	**kWh/year**	**m^2**	**kWh/year**
Building 1	65.4	7 750	100	8 700
Building 2	65.4	7 033	100	9 300
Building 3	0	0	200	18 000
Substation	32.7	5 693	0	0
Preschool	240	27 076	210	18 000
Retirement home	245	36 327	798	53 000
Community living	23	3 094	230	26 000
Expedition	0	0	0	0
Total	**671**	**86 973**	**1 638**	**133 000**

6 Discussion

This master thesis was part of a project financed by the Swedish Energy Agency and managed by the housing company Eksta in collaboration with the consulting company WSP. The project started 2016.09.01 and is expected to finish 2019.10.31. The main aim of this master thesis was to optimize the utilization of own-used solar electricity by transferring the surplus PV between buildings in a demonstration area in a DC-microgrid. To achieve this objective, the Swedish regulatory framework for concession was analyzed in order to find exceptions that allow the transfer of solar electricity surplus between buildings in the same real state. A demonstration area belonging to Eksta and located in Fjärås, Kungsbacka, was used in order to simulate the transfer of solar electricity surplus. The area consisted of four new residential buildings, one substation, a preschool, a community living, a retirement home and Eksta's expedition building.

6.1 Swedish regulatory framework for concession

In section 2.5, the Swedish regulatory framework for concession and its exceptions were described. According to the current legislation, it is prohibited to build an electrical power line between buildings in the same real state. In order to facilitate the construction of primarily wind electricity but also in the future solar electricity two exceptions were introduced in 2007. The exception 22A states that an internal electrical power line can be constructed when connecting to electrical production facilities. Furthermore, exception 30 explains that in the internal powerline referred in 22A, transmission of electricity between facilities can take place.

The exceptions were interpreted as valid for the demonstration area although not all buildings generated solar electricity. It is relevant to take into consideration that the law was created in 1997 for a different electricity system than the one that is about to emerge today where prosumers and microgrid systems have an important role. Also, it exists both national and European goals in order to increase the usage of solar electricity such as the Swedish goal to have solar electricity standing for 5-10% (7-14 TWh) of the national electricity mix by 2040.

6.2 Electricity usage

As seen in figure 25, the consumption peaks varied dependent on the building's purpose. The preschool had the first consumption peak, 6-7.am, at the school start, followed by the retirement home at 10.am when the lunch was cooked for the whole building and the preschool. The substation had its maximum consumption at 12.pm when the solar pumps were operated at their maximum. Thereafter, the community living had its electricity peak at 5.pm when preparing the dinner for the residents. Finally, the new residential apartments had their average daily consumption peak at 7.pm when the residents were back from work. When connecting all buildings in a DC-microgrid, the electricity consumption for all buildings was summarized resulting in a more homogeneously distributed electricity usage, as seen in figure 27. A more stable electricity consumption allows a higher usage of the own produced solar electricity.

Each building's electricity usage could become more efficient when increasing the consumers awareness and using more energy efficient technology. Behavioral change can be promoted through various types of incentives such as information, legislation or financial incentives. For example, dynamic pricing enables the consumer to pay its electricity dependent on its power usage and the market price. This pricing system could be combined with an electricity management tool e.g. a smart meter, that informs the customer about its electricity consumption and Nordpool's prices. The smart meter enables bidirectional communication between the supplier and the customer, which can reduce overall demand for electricity or redistribute the electricity consumption. This could be a relevant solution for the new residential buildings and the community living where the flexible electrical loads such as dishwasher, washing machine and dryer could be shifted to night time, when the market prices and electricity consumption are lower.

6.3 PV electricity

The solar electricity generation for each building varied dependent on the building's PV system design such as type of module, number of modules, tilt and azimuth. As seen in figure 26, the average daily maximum solar generation varied dependent on the PV system's azimuth and tilt. The demonstration area PV generation peak started at 11.am with the new residential apartments and finished at 13.pm with the community and retirement home. Also, the retirement home had the highest solar electricity generation (36 327 kWh/year) and the community living the lowest (2 482 kWh/year). When combining all buildings in a DC-microgrid, all PV generation was summarized leading to a higher solar electricity production allowing an increased usage of the self produced electricity.

6.3.1 Own usage rate and Self-sufficiency rate

Table 15 shows the own usage rate and self-sufficiency rate for all buildings individually. As expressed in equation 8 and 9, both rates are a fraction of the own used electricity divided by the PV production and the electricity usage respectively. The own used electricity in each building depends on several factors:

- The amount of electricity used in the building
- The electricity usage pattern
- The amount of solar electricity generated in the building
- The solar electricity generation pattern

The retirement home had the highest own usage rate, 97%, as the building's electricity consumption peak (10.am) matched its solar electricity generation maximum (11.am to 14.pm). On the contrary, the preschool had the lowest own usage rate as its electricity peak occurred at 6.am and its solar electricity generation peak at 12.pm.

The new residential buildings and substation had the highest self-sufficiency rates (31%, 33 % and 37 %) as the difference between the buildings electricity consumption and generation was the smallest in the demonstration area, 2000 kWh/year and 200 kWh/year respectively, and their daily electricity power variation was also low, 1 kWh/h. The retirement home together with the community living had the lowest self-sufficiency rate as their electricity consumption and generation differed the most and for the retirement home the average daily power variation was the highest in the demonstration area, 35 kWh/h.

As seen in figure 27, if all buildings were connected in a DC-microgrid the summarized electricity usage would be more stable and the PV generation higher. A more stable electricity consumption and a higher solar electricity generation enables a higher usage of the own produced solar electricity which leads to higher own usage and self-sufficiency rates. This optimization is described in figure 40, where it can be concluded that with a DC-microgrid in the current demonstration area, the own usage rate and self-sufficiency rate increase 32 and 6 percentage points respectively.

By directly using the produced solar electricity instead of delivering it to the grid or to battery storage, the losses are reduced and the system's efficiency is increased. The transfer of electricity in a DC-microgrid accounts for 1% losses compared to battery storage, 4%, or the inverter 2-4%. In the theoretical case that 100% of the produced PV electricity was used in the demonstration area, only DC products could be used. This involves less and smaller components which saves natural resources and lowers the cost.

6.3.2 Surplus PV

When combining all buildings in a DC-microgrid the solar electricity overproduction is reduced to a quarter, approximately 27 000 kWh/year, as seen in figure 40. By analyzing the duration diagrams in figures 28, 30, 32, 34, 36 and 38 the surplus PV can be categorized according to power in kWh/day and occurrence. The preschool had the highest solar electricity overproduction according to power with a maximum surplus of 2000 kWh/day followed by the retirement home (90 kWh/day), the new residential apartments (30 kWh/day), the substation (25 kWh/day) and last the community living (20 kWh/day). The preschool also had the highest surplus PV occurrence 270 days a year, followed by the new residential apartments (250 days), the substation (240 days), the community living (170 days) and last the retirement home (60 days).

Figures 29, 31, 33, 35, 37 and 39 shows the percent of the total solar electricity generation that became surplus. 77% of the preschools PV generation became surplus followed by the new apartments (60%), the substation (55%), the community living (40%), and last the retirement home (3%).

As seen in figure 41, in the theoretical scenario that all buildings in the demonstration area were connected in a DC-microgrid the number of days of overproduction could be reduced 165 days in a year and the maximum power could decrease from 380 kWh/day to 275 kWh/day. Furthermore, as shown in figure 42, only 9% of the solar electricity generation becomes overproduction in the DC-microgrid compared to 41% if not connected.

From a real estate owner's perspective, maximize the usage of the own produced solar electricity is important in order to increase the economic benefits of the PV system and reduce the electricity bought from the grid. By directly using the produced solar electricity, variable cost e.g. energy tax, network charge or VAT are avoided. If the surplus PV is instead delivered into the grid, it can usually only be sold for the market spot price. Therefore in this case, the own-used PV has a greater value than the surplus. As the solar electricity surplus is complementary to the own used electricity, the advantages of a decreased surplus PV are similar to the ones described for an increase of own used PV electricity. The system's efficiency increases due to lower loses. Additionally, storage system such as lithion ion cell batteries, could be dimensioned for less surplus PV, which has both environmental and economical advantages.

6.3.3 Solar electricity transmission potential

The main purpose of this master thesis was to analyze how the self-usage of solar electricity varies when connecting all buildings in the demonstration area in a DC-microgrid. As seen in figure 43, if all buildings have a shared electricity production and generation, 90% of the PV electricity would be used compared to 61% with the current individual system. This increase of own used electricity corresponds to 27 000 kWh/year.

In the current individual system, the electricity surplus is delivered into the grid which is less energy efficient and economically profitable. As discussed in the previous subsection, for a real state owner, such as Eksta AB, the own used electricity has a greater economical value than the surplus. Figure 44 shows that currently 86% of the total electricity usage is delivered from the grid compared to 82% if interconnected. Once again, the 4 percentage points difference represent the 27 000 kWh/year solar electricity that could be transferred in the DC-microgrid instead of delivered from the grid.

In other words, the results from this master thesis concludes that when using a DC-microgrid the demonstration area's self usage of solar electricity increases. This leads to lower surplus PV and less grid electricity which increases the system's energy, environmental and economical efficiency. Therefore, in order to increase the usage of solar electricity in Sweden, microgrid solutions could be an important tool. Although, the regulatory and economical aspects, such as a change in the Swedish regulatory framework for concession, are more urgent and have a more important role for the current energy transition.

6.4 Improvements

It is important to consider that all the results were based on the current PV system installed in the demonstration area. Not all potential roof areas for PV installation were used, facing south, west and east. Table 16 shows the yearly solar electricity generation from the current vs potential roof areas for each building. It was concluded that in this project the results were based on a PV system that accounted for 30% of the total useful PV area. In the theoretical scenario that the maximal PV roof area was used, the solar electricity generation could increase approximately 46 000 kWh/year. This presents an increase in solar electricity generation but do not show the increase of own-used solar electricity which is more relevant for Eksta AB.

Further optimization of the demonstration area's electricity consumption and generation could be achieved by increasing the electricity efficiency and by connecting the solar electricity surplus to an energy storage system. Battery storage solutions are provided by Ferroamp and are already installed in the new residential buildings. Additional optimization could be achieved through a common energy storage system for the entire demonstration area. The accuracy of the results would have been higher if all the calculations were based on real electricity usage and solar electricity generation data in kWh/h, which was not the case for the new residential buildings or the expedition.

7 Conclusion

The first objective of this master thesis was to analyze the Swedish regulatory framework for concession and its exceptions, from where it was assumed that the exceptions 22A and 30 were valid for the demonstration area in order to build an electrical power line enabling the transfer of solar electricity.

The electricity usage for all buildings varied dependent on the building's purpose and the Swedish weather and light conditions. The electrical peaks were spread from 6.am to 19.pm with different power usages. When connecting all buildings in a DC-microgrid the electricity consumption became more stable. Each building's solar electricity generation varied dependent on its PV system design and the Swedish weather and light conditions. Dependent on the PV systems azimuth and tilt the power peaks varied from 10.am to 13.pm with different power generations. When combining all buildings in a DC-microgrid, all PV generation was summarized leading to a higher solar electricity production.

A more homogeneously distributed electricity consumption and a higher solar electricity generation, using a DC-microgrid, led to a higher usage of the own produced electricity. As a consequence, the own usage and self-sufficiency rates were increased by 32 and 6 percentage points respectively. Also, by interconnecting the entire demonstration area, the number of days that surplus PV occurred diminished 165 days and the maximum surplus power was reduced 100 kWh/day. Furthermore, it was concluded that in a DC-microgrid the solar overproduction represented 9% of the total solar electricity generation compared to 41% in the current individual system. This difference was calculated to 27 000 kWh/year which represented the demonstrations area's electricity usage that could come from solar electricity instead of delivered from the grid, i.e. the increase in own used PV.

In conclusion, the results from this master thesis show that when using a DC-microgrid the demonstration area's self usage of solar electricity increases. This leads to lower surplus PV and less grid electricity which increases the system's energy, environmental and economical efficiency. Therefore, in order to increase the usage of solar electricity in Sweden, microgrid solutions could be an important tool. Although, the regulatory and economical aspects, such as a change in the Swedish regulatory framework for concession, are more urgent and have a more important role for the current energy transition.

7.1 Future work

In November 2018 the electricity usage and PV generation for the residential buildings are going to be analyzed based on real data. Also calculations taking into consideration battery storage solutions are going to be performed. Furthermore, a life cycle cost analysis (LCCA) is going to be done in order to analyze the economical benefits of the DC-microgrid system. By the end of the project, the most salient results are going to be disseminated in relevant technical newspapers and conferences.

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9 Appendix

9.1 Appendix A

2 kap. Nätkoncession m.m.

1 § En elektrisk starkströmsledning får inte byggas eller användas utan tillstånd (nätkoncession) (Notisum 2017).

Förordning (2007:215) om undantag från kravet på nätkoncession enligt ellagen (1997:857)

22 a § Ett internt nät som förbinder två eller flera elektriska anläggningar för produktion, vilka utgör en funktionell enhet, får byggas och användas utan nätkoncession. Förordning (2008:897)(Regeringskansliet 2013).

30 § På ett sådant internt nät som avses i 22 a § får överföring av el mellan anläggningarna äga rum även om de anläggningar som ingår i den funktionella enheten har olika innehavare. Detta gäller även om nätet i sin helhet ursprungligen inte har använts för överföring av el uteslutande för egen räkning. Förordning (2008:897)(Regeringskansliet 2013).

9.2 Appendix B

9.2.1 New residential apartments

Building 1

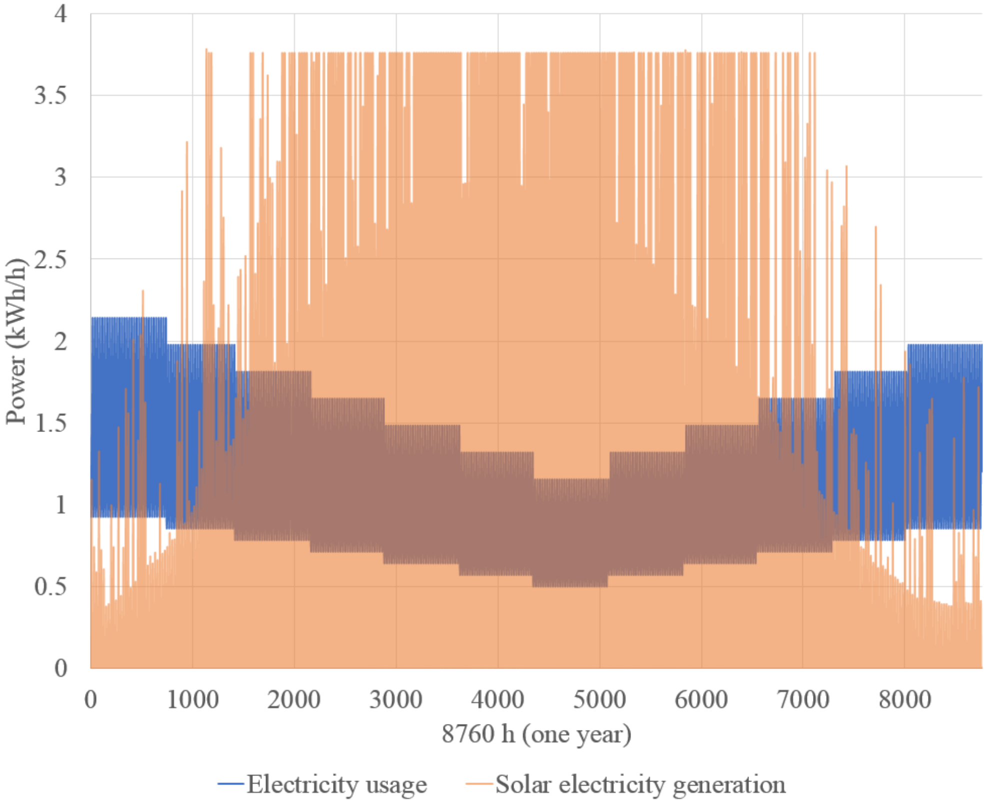

Figure 45: *Buildings 1 hourly PV production and electricity usage over a year (kWh/h)*

Building 2

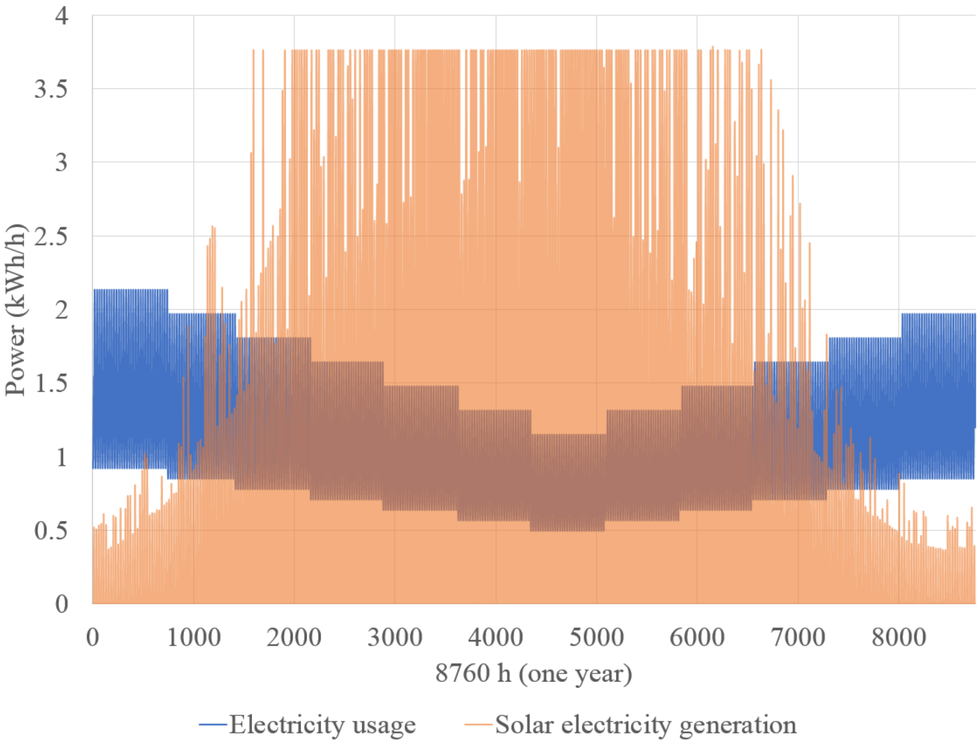

Figure 46: *Buildings 2 hourly PV production and electricity usage over a year (kWh/h)*

Substation

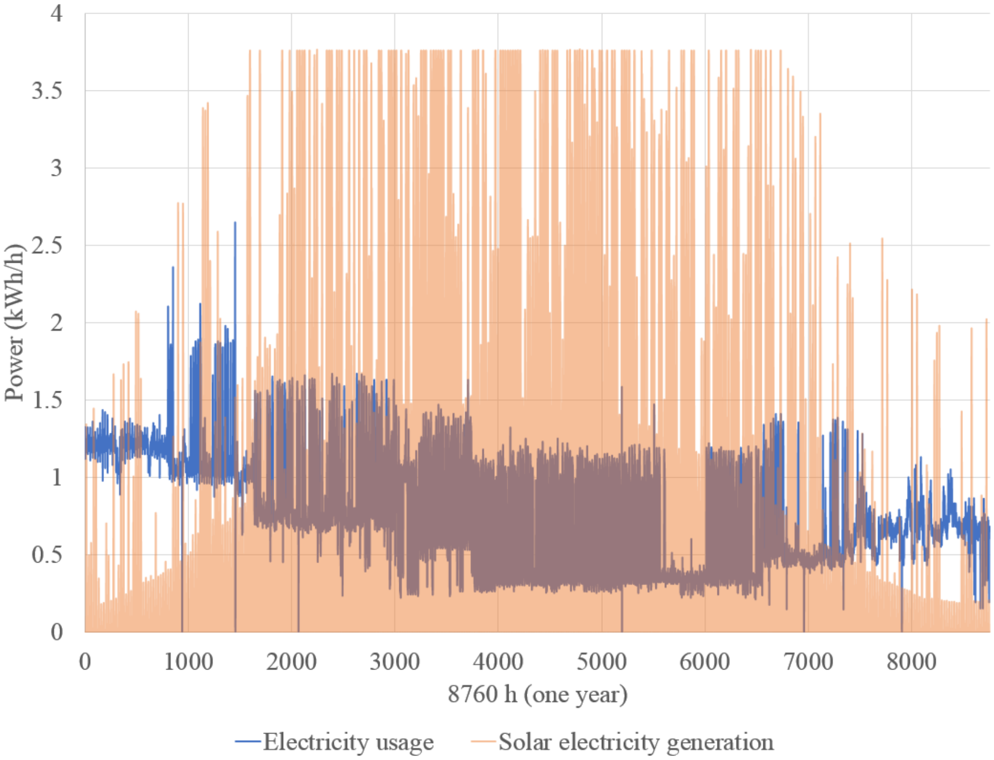

Figure 47: *Substation hourly PV production and electricity usage over a year (kWh/h)*

9.2.2 Preschool

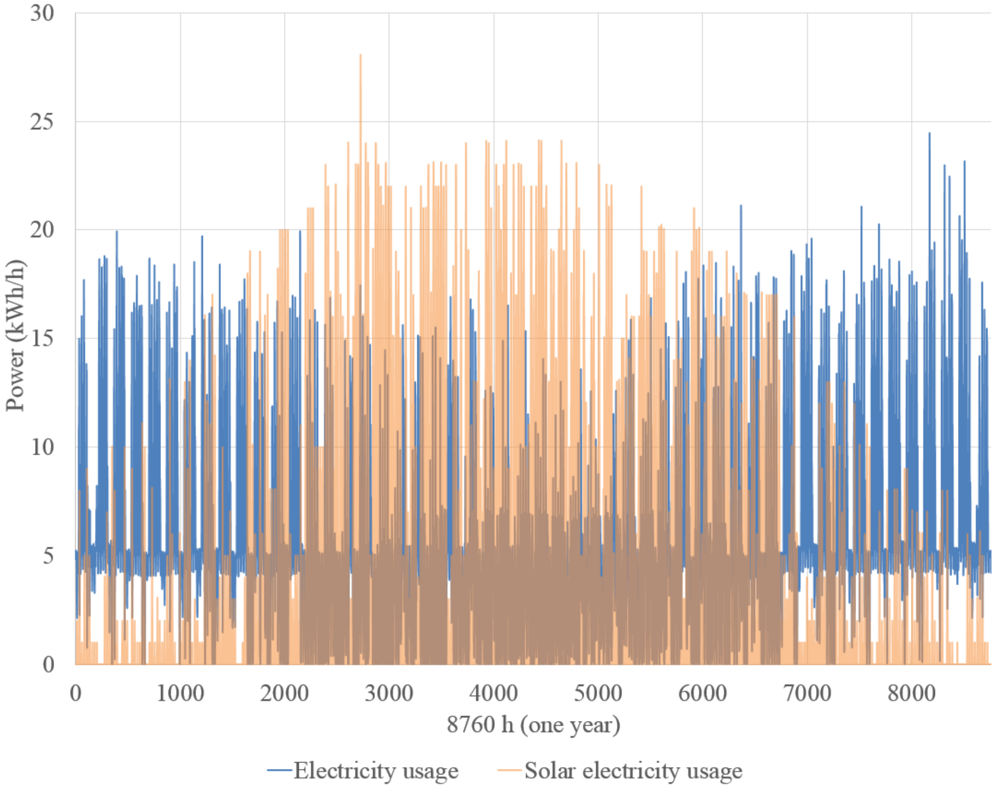

Figure 48: *Preschools hourly PV production and electricity usage over a year (kWh/h)*

9.2.3 Community living

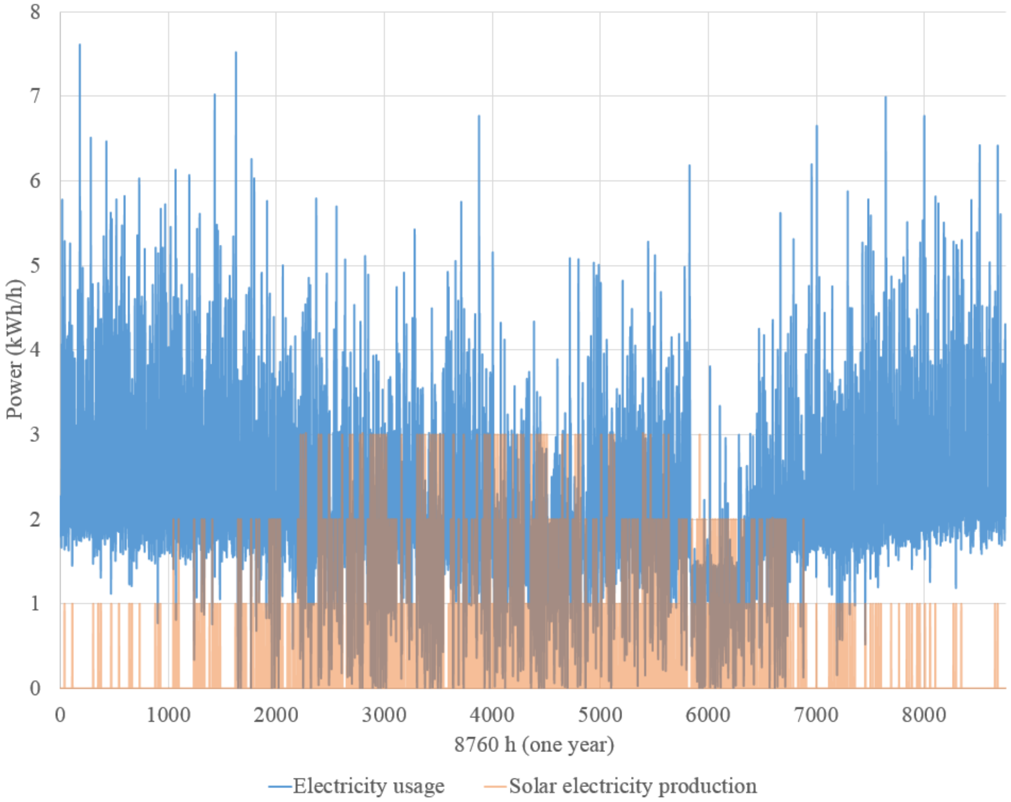

Figure 49: *Community living hourly PV production and electricity usage over a year (kWh/h)*

9.2.4 Retirement home

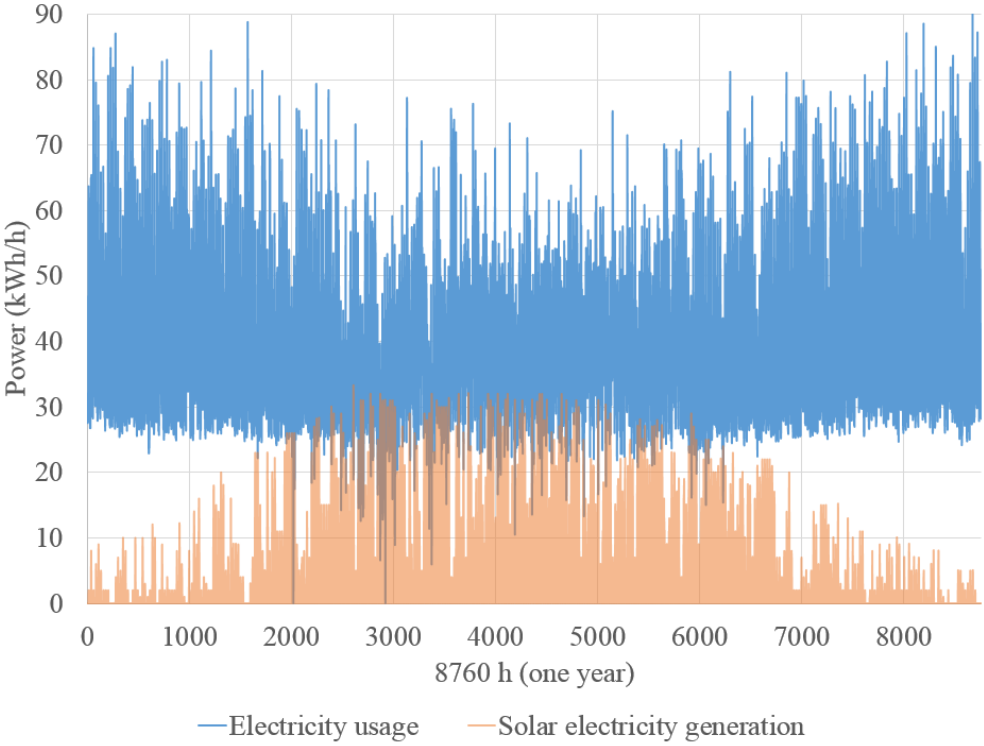

Figure 50: *Retirement home hourly PV production and electricity usage over a year (kWh/h)*

9.2.5 DC-microgrid

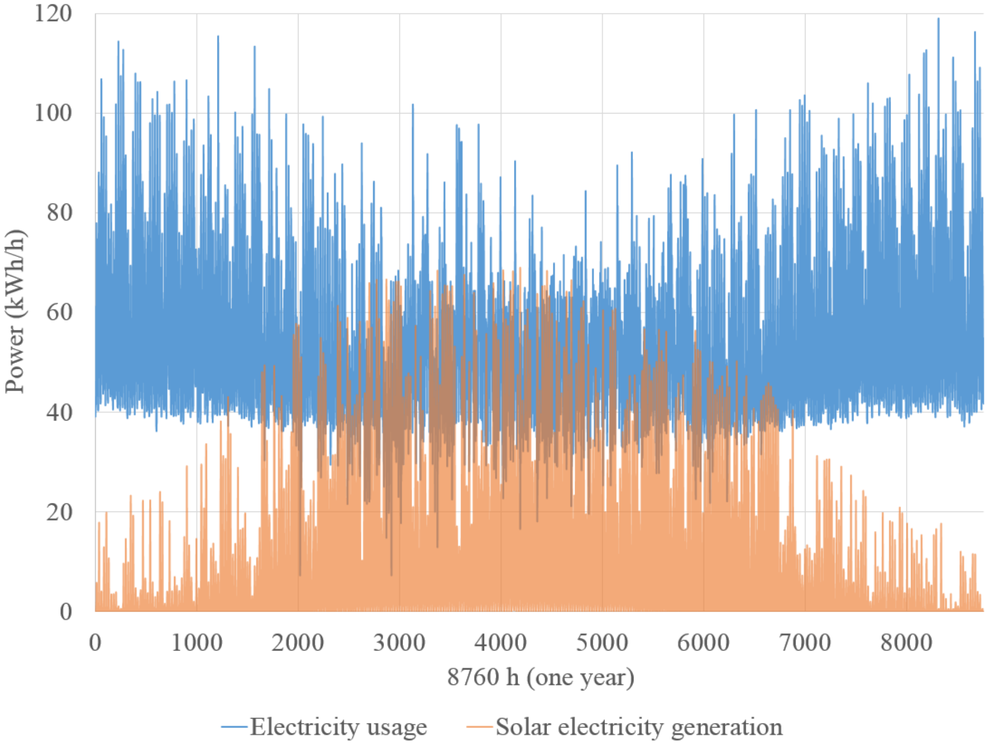

Figure 51: *DC-microgrid hourly PV production and electricity usage over a year (kWh/h)*