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Economic and Environmental Analysis of PV Electricity Storage in Sweden

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Abstract

Renewable energies, and among them solar photovoltaics, are becoming more important in the last years due to the lack of fossil fuels and the environmental impact of them. PV installed capacity is increasing over and over in some countries and the prices of the installation are decreasing while the prices of the electricity are predicted to increase. Electricity use in buildings account for an important part of all electricity use in the world. This two facts make the PV installation in the rooftops of buildings a good opportunity to reduce the purchase of electricity from the grid.

The aim of the thesis is to analyze the profitability and the environmental impact (when using a hot water accumulator) of a PV system with different storage systems placed in the rooftop of two dwellings located in Gävle (Sweden). The storage systems can be either batteries or hot water accumulators. The purpose of the storage system is to increase the self-consumption rate of the PV system and to save the highest amount of money possible. It is also studied the difference of installing PbA and Li-ion batteries, and the reliability of the data used in the simulation of the alternative systems with the help of the software PVsyst.

Results show that the profitability of the proposed three alternative PV systems with storage is not higher than the PV system without storage. The reason for this has been found in the low prices of electricity and DH nowadays. Moreover, the impact of decreasing the heating demand from DH network does not benefit the environment, because the electricity has to be produced in power plants that produce more pollutants. It can be said also that the data obtained in PVsyst has been determined reliable and that the difference between the two types of batteries is not conclusive.

It can be concluded that if the cost of the PV systems or the batteries would decrease, the profitability will be higher. Furthermore, the increase in the price of electricity, DH or governmental subsidies would improve the results.

Key words: PV system, battery storage, hot water accumulator, economic analysis, environmental impact.

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Nomenclature

A	Amps
CHP	Combined Heat and Power
C_{nom}	Nominal capacity (Ah)
CO_2	Carbon Dioxide
DH	District Heating
DHW	Domestic Hot Water
DoD	Depth of Discharge
ESS	Energy Storage Systems
EU	European Union
Li-ion	Litium-Ion
MPPT	Maximum Power Point Tracking
PbA	Lead acid
PR	Performance Ratio
PV	Solar Photovoltaic
SOC	State of Charge
TES	Thermal Energy Storage
Tmax	Maximum temperature in the tank
Tmin	Minimum temperature in the tank
Tout	Temperature out of the tank
Tsurr	Temperature outside the tank (room temperature)
V	Volts
W	Watt

1. Introduction

1.1. Introduction background

Nowadays, the use of energy is required for most of the activities developed by humans. Energy offers a world of amenities but at the same time it makes people totally dependent on it. In this changing world is it is being watched how energy prices are steadily increasing for several reasons: conflicts in the countries of origin of fuels (Middle East, Russia, Argentina), political decisions (increased taxes), etc.

Furthermore, the constant increase of electricity demand has its risks due to the energy resources that are been used to produce electricity. Fossil fuels are the most used energy resource as shown in Figure 1 [1]. A lot of countries have a dependence of energy as a result of the lack of fossil fuels available in their land.

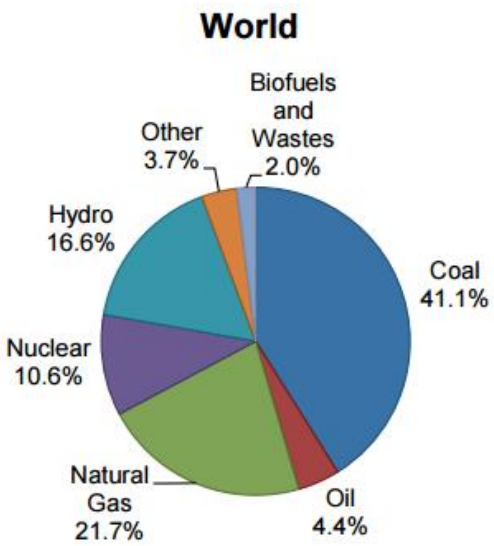

Figure 1: Worldwide production of energy by energy resource [1]

This data of energy dependency is alarming due to the fact that fossil fuels are scarce and forecasts indicate that the prices of these will continue rising in the coming years even tough at the moment the prices are low.

In this scenario renewable energies are a good solution. Within renewable energies, solar photovoltaic (PV) systems are widely known for their ability to generate electric power through the absorption of energy from the sun radiation. It is becoming more popular to install PV systems in the rooftop of buildings in order to reduce the amount of electricity purchased from the electric grid. Besides reducing the bought electricity from the grid, it is also of high importance to self-consume the highest possible amount of electricity produced because the sold electricity price is commonly lower than retail electricity prices.

1.2. Aim of the thesis

The aim of the thesis is to make a sizing and an analysis of the profitability of a PV system installation in two different buildings located in Gävle (Sweden), taking into account the energy consumption of them. In order to increase the self-consumption, the analysis is done using different storage systems. In the analysis, it is calculated the profitability of the three alternative systems proposed, which involve battery systems and a hot water storage tank. The analysis also includes, for the cases where the hot water accumulator is used, an estimation of the environmental impacts when district heating is used for space heating and domestic hot water. The data that will make able the calculations is taken hourly.

1.3. Limitations

One of the most important limitations is that the analysis has been done taken data from 2015, which means that installing this systems during another year could change slightly the results.

Meteorological data gives an uncertainty in the results. The data is from Gävle in general, not for the exact place where the dwellings are located, and the single family house installation that is the one which provides the data for simulations is not even located in Gävle, so this can result in a difference when comparing real data with PVsyst results.

Another drawback has been found when using PVsyst software. When drawing the buildings in 3D is not possible to import the 3D and the drawing options are not much. This means that the buildings cannot be drawn completely perfect, so the results will differ from the reality.

Moreover, simulations done in PVsyst also differ from the reality in a certain point. PVsyst does not consider the behavior of the PV panels when there is dust, dirt or snow. Given the fact that the buildings used in the simulation are placed in Gävle, where it snows plenty of times during winter, the obtained results cannot be considered exact.

Also, the lack of data available about the batteries can be an inconvenient for the determination of the profitability of the complete system. Additionally, it has not been taking into account that the batteries suffer decadence of their properties, so the analysis provides better results than the ones that a real system would offer.

2. Theoretical background

2.1. Residential sector energy use

The residential sector consumes mainly secondary energy. The energy form found in nature that has not been subjected to any conversion or transformation process is known as primary energy. On the other side, secondary energy is referred to the energy that comes from the transformation of primary or other secondary energies [2]. The main users of secondary energy in a residential building are:

- Space heating and space cooling: energy required in an attempt to keep the buildings at a comfortable temperature and air quality. Buildings need heating and cooling to face the thermal losses they suffer across the envelope because of conduction and radiation effects, along with air infiltrations.
- Domestic hot water (DHW): energy needed to heat water to a suitable temperature for tenants and appliance uses.
- Appliances, lighting and operation: energy used for normal applications (e.g. freezer and toaster), for lighting and for operating applications (e.g. fans and pumps).

The main reasons for the difference in the amount of energy used in the residential sector are the size and location. The quantity and type of energy utilized in houses is mostly associated with climate, architectural design, energy systems and socioeconomic status of the inhabitants [3].

In Europe, the housing sector is a powerful group in the amount of energy use due to the 26.8% of all the energy that it uses [4]. Moreover, buildings account for half of worldwide electricity request [5].

2.2. Renewable energies

Renewable energy is generally defined as energy generated from natural resources derived directly or indirectly from the sun or from other natural movements and mechanisms of the environment. Natural resources are sunlight, wind, tides, water, various forms of biomass and geothermal heat, which are naturally replenished [6].

Since renewable energies are alternative to fossil fuels, they are frequently understood as alternative energies. Nevertheless, generally the term alternative is designated to energies that have low environmental impact, so that means they do not damage the environment. For these reason, the term is not entirely adequate if it is used for all renewable energies because they may or may not harm the environment.

Renewable energy technologies have a huge potential as a result of the globally spread resources in comparison with the conventional sources such as natural gas, coal and oil, which are more geographically concentrated. The number of resources that countries worldwide have is different, but no one has less than one abundant renewable resource and a lot have a huge portfolio of them.

The expectations for the renewable energies are to prosper significantly in the near future. The main reason for that is that renewable energy technologies are an essential part of a collection of alternatives that are necessary for accomplishing a secure and sustainable energy mix, together with energy efficiency and low contamination. The diversification of renewable energies is the key to provide the world with a quantity of benefits that have not been totally assumed in present energy market prices.

Moreover, main benefits are related with environmental problems, which include greenhouse gas emissions and local pollutants, economic development of countries and accessibility to energy all over the world with off-grid systems.

As result of the described benefits, the contribution of the renewable energy sources has increased, achieving in 2013 a generation of approximately 25.4 % of the EU-28's (European Union) whole electricity use [7].

Among EU-28 members, Sweden is an example of the high penetration of renewable energies in the generation of electricity, producing the 61.8% of all the used electricity, fundamentally because of hydropower and biomass [7]. It is also important to mention the contribution of wind (7%) and nuclear power (43%) [8], because they are CO_2 emission free resources.

2.2.1. Solar energy and radiation

Sun is a source which provides a lot of energy, which makes its energy, known as solar energy, the most abundant renewable energy source in the Earth. Doing a simple comparison, it can be said that the energy that the sun delivers is 6200 times the primary energy consumed by people in 2008, because of the 885 million TWh that annually reaches the surface of the planet [9].

Furthermore, the solar radiation that reaches the earth's surface is about 1000W/m^2 in clear conditions when the sun is close to the zenith.

Solar radiation that reaches the earth has two components: direct or "beam" radiation, which comes directly from the sun; and diffuse radiation, which comes indirectly after being scattered by the atmosphere. PV systems can use "global" irradiance to generate electricity, which is the sum of direct and diffuse radiations.

Although the solar radiation is very rich, global irradiance quantity is not the same in different areas of the world which makes of great importance to place the PV systems in concreate places to amortize as much as possible the installation.

2.2.1.1. PV systems

Within renewable energies and of all the systems that can convert solar radiation into energy, PV has become the fastest emergent source for electricity generation. PV cell is the essential element of PV systems. Essentially, as it has been illustrated in Figure 2 [10], a PV cell is made of a semiconductor diode which P–N junction is exposed to the light.

The conversion of sunlight into electric current in a PV cell is direct and it does not generate any air or water contamination. The number of semiconductor material layers a PV cells is made of is no less than two but at least one of them has a positive charge and another a negative one. When light reaches the cell, the semiconductor atoms absorb some of the photons from the light. The absorption releases electrons from the cell's negative layer. The electrons then flow through an external circuit and go back into the positive layer producing electric current [11].

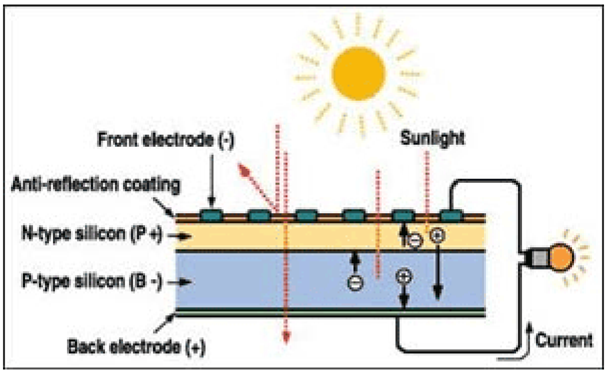

Figure 2: Physical structure of PV cell [10]

Since the standard PV cells produces a voltage of approximately 0.6V [12], there is a need of connecting more than one in order to achieve a practical output voltage needed for most applications. The interconnection of all the PV cells together is known as module, which is a sealed weatherproof package. The connection of the cells is normally made in series. A series connection provides an output voltage of the sum of all the cells connected but the current maintains constant. It happens the opposite with a parallel wired, the voltage is constant and the current is the sum of all the current of the cells.

Only with the modules is difficult to get the desired voltage and current, so modules are connected in series into strings and strings can be connected in parallel to achieve a suitable current. As it can be observed in Figure 3 [11], the new scheme is named PV array. Modularity of PV systems makes easier to accomplish the extensive diversity of electric needs required by engineers [13].

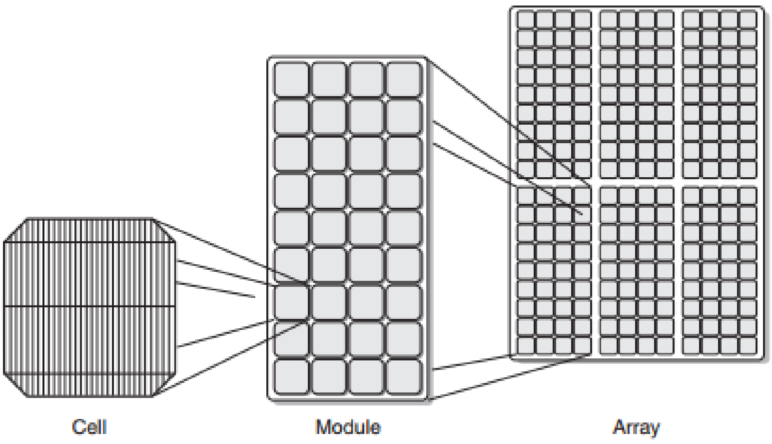

Figure 3: Configuration of PV systems [11]

2.2.1.2. Type of PV modules

The most important PV modules types are monocrystalline silicon, polycrystalline silicon and thin film. Among all, silicon based solar modules are nowadays the most worldwide spread type of modules, and thin-film solar cells only cover a small share of the market.

Comparing silicon cells, monocrystalline has the highest efficiency but polycrystalline, although the efficiency is lower, are cheaper. For this reason, it is important not only to analyze the price of the installation per W_p installed, but the price per kWh produced also.

2.2.1.3. MPPT

The current from a solar cell is linearly proportional to the solar radiation whereas the voltage increases or decreases logarithmically with increased or decreased solar radiation, respectively [14].

The power that can be obtained from a solar cell or from a module array is the product of the voltage and current generated. To find which point of the curve gives the maximum product of voltage and current, it is used a maximum power point tracker (MPPT), which varies the voltage to find the highest output of power.

2.2.1.4. Efficiency and performance of solar cells

Nominal efficiency is related to the power generated under so-called “Standard Test Conditions” (STC) – module temperature of 25°C, vertical irradiance of 1 000 W/m^2, air mass of 1.5 and a specific irradiance spectrum. When the temperature rises, as it does for a cell in sunlight, the open voltage decreases and current increases. Since the decrease of the voltage is larger than the increase of the current, the efficiency and hence the power output decreases with a higher temperature.

The actual output depends on the solar resource, the orientation of the modules and the “Performance Ratio” (PR) of the system, which takes into account all efficiency losses resulting from actual module temperature, module mismatch, varying irradiance conditions, dirt, line resistance and conversion losses in the inverter. Well-designed PV plants achieve average PR of 80% to 90% throughout the year [9].

Another fact that affects the performance is the tilt. Tilting equator-facing modules can reduce disparities and increase the annual energy received on PV systems, especially at high latitudes, although this varies with meteorological patterns and the ratio of diffuse versus direct light. Tracking the sun on one axis or two axes further increases the amount of energy received by the modules.

2.2.2. District heating (DH)

A district heating plant is often, as it can be seen in Figure 4 [15], a combined heat and power plant (CHP) which provides heat in an intelligent and environmentally friendly way. By co-producing heat and power in the same process, the heat that would otherwise be wasted in electricity production is utilized. This leaves energy savings of up to 30% [16] because it avoids the use of boilers in buildings.

Furthermore, for producing the heat, DH can use any energy source. Some renewable resources like biomass, solar energy and waste are becoming more utilized in DH services both completely or as a complement to traditional fossil fuels.

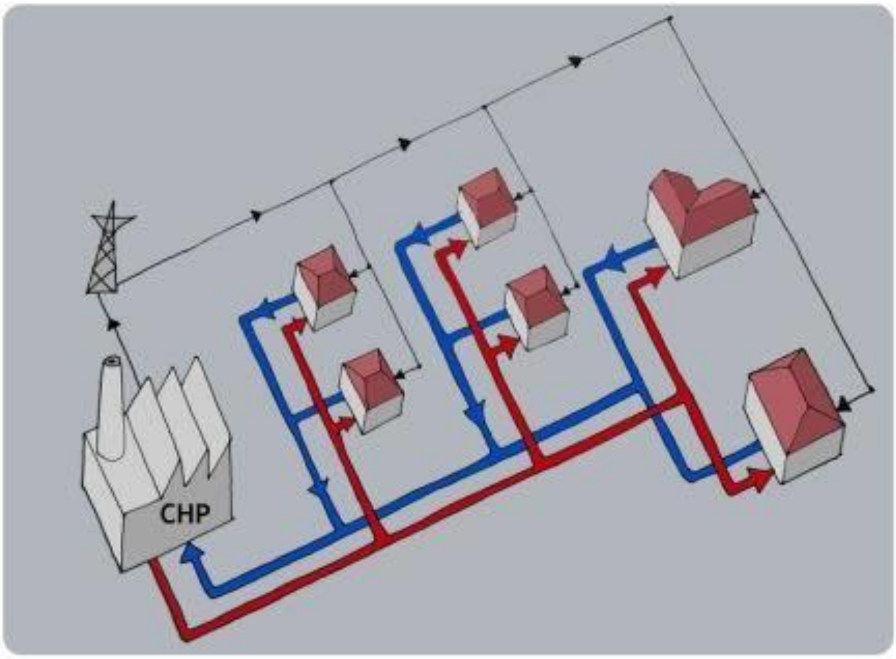

Figure 4: DH network distribution [15]

In a DH pipeline, the heat producing plant drives heated supply water or steam to users where it is used as a heating source and as a heater of DHW. The heating of the DHW is done through a heat exchanger in which the heated supply water transfers its heat to the water coming out of the taps.

For the purpose of heating, the supply water can be used directly or with a heat exchanger, which transfers the heat to an internal circulation. After using the supply water, it decreases its temperature basically due to the heat transfer to the DHW or to the heating system, and is returned back to the district heating plant. The DH supply water flows in a closed circuit of pipes.

DH has experienced a steady development during the years and now accounts for more than half of all heating for buildings in Sweden. Given the climate problems that the country presently face, DH is predicted to suffer even a bigger expansion [17]

2.3. Energy Storage Systems (ESS) for improving self-consumption ratio

Self-consumption ratio is defined as the share of the total PV production consumed by the PV system owner. With the actual profile of electricity demand of the households in Sweden, which was calculated in a research and can be observed in Figure 5 [18], solar production hours do not match with the electricity needed in the building at all time, and as it can be seen, in winter is worser because of the number of hours of light in Sweden. Thus the ratio of self-consumption of 100% can only be reached if the system is small, in other words, if the PV panels electricity production at every instant of the year is equal or less than the electricity demand of the building.

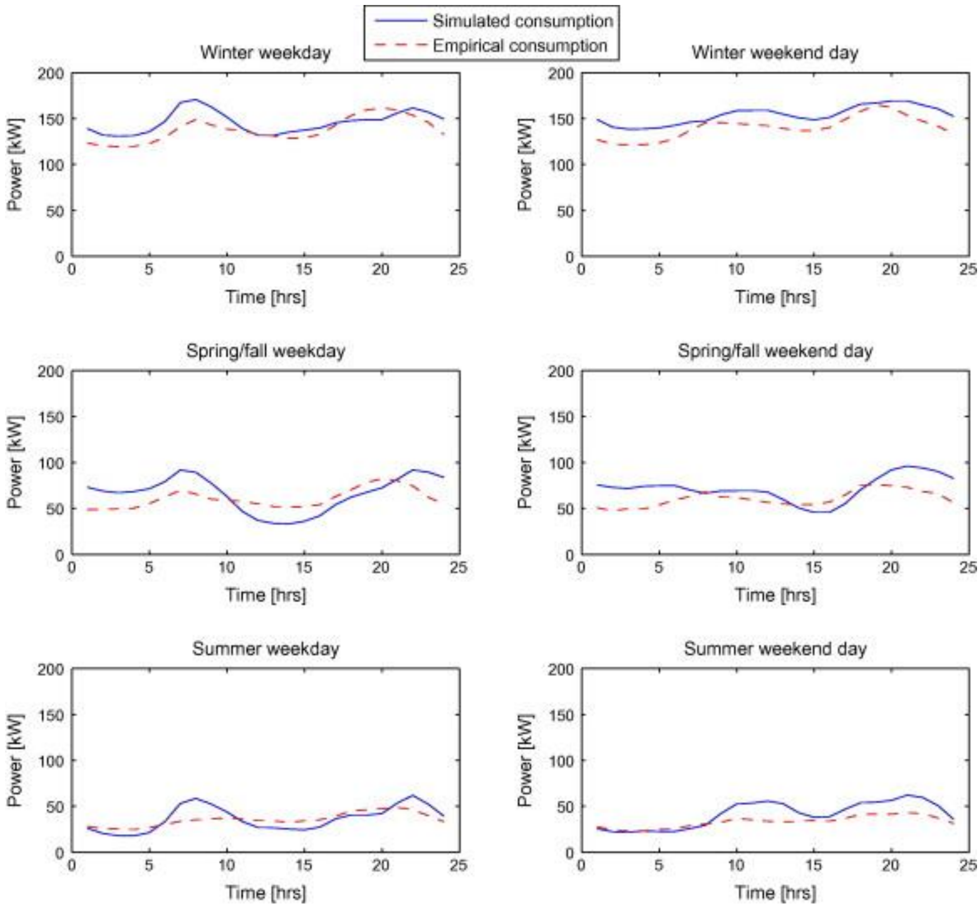

Figure 5: 24h average electricity use profiles for the three type days in Swedish households [18]

ESS systems are the solution in order to improve this ratio. Currently there are several ways to store energy, like electrochemical, electrical, mechanical and thermal potential systems.

2.3.1. Batteries

Electrochemical batteries are the most commonly used ESS for the type of application proposed in this thesis, mainly because of its characteristics of power, energy and price.

These batteries store energy in the form of direct current (DC) and they are based on oxidation-reduction reactions which take place in electrodes that are separated by an electrolyte [19]. The main features of these devices are listed below [20]:

- Specific energy (Wh/kg): Energy that a battery can store per unit mass. It is one of the main advantages of electrochemical batteries as other types have lower energy density.
- Specific power (W/kg): Power that can deliver a battery per unit mass.
- Battery capacity (Ah): The amount of electrical charge that a battery can store. The amount of electric charge is measured in Coulombs (C), and is the product of current by time. The capacity of a battery is specified depending on the time in which the battery is capable of supplying said amount of energy. Usually are typical values like C_{10} or C_{20} which indicate how many amperes (A) can be extracted from the battery during that time (10 and 20 hours respectively).
- Number of cycles of loading and unloading / Life span: Time that the battery can maintain its performance over predetermined thresholds. Also defined as the number of times the battery can be loaded / unloaded regaining its full capacity after use.
- Performance (%): Fraction of electricity that the battery returns in proportion to the energy that has been necessary to load it.
- Self-discharge: Loss of battery power when held in circuit open. Generally the self-discharge is expressed in terms of percentage of energy loss with respect to the rated capacity in a time period one month. In addition, some types of batteries have the "memory effect" in which in each charging voltage or storage capacity is limited. This happens due to high currents, high temperatures, etc. which cause the aging of the device, thus precluding the use of all its energy.
- DoD (Depth Of Discharge): Is the discharged energy ratio relative to the amount of energy that can be stored.
- Cost (€/kWh): Battery cost per unit of stored energy.

By their nature, when compared with other technologies, they are not devices capable of absorbing large power peaks in the loads or provide them in the needed times without affecting negatively its life [20].

Another important drawback is the high toxicity of some heavy metals that are part of different types of batteries, which constitute a serious environmental problem. This does not happen in the case of lead acid (PbA) batteries because lead is 100% recyclable, although the recycling process is not done as much as it should to preserve the environment.

As mentioned before, there are many types of battery technologies, but in this thesis will be tested the most significant ones, which are PbA and lithium-ion (Li-Ion) [21].

2.3.1.1. PbA batteries

PbA batteries are the most developed and used electrochemical battery systems, what leads the batteries to have a maturity that no other technology does. Its main advantages are its low price and low requirement of maintenance.

The main drawback is that they have a low specific energy 30Wh/kg and that they are also excessively influenced by the temperature.It Is of a great importance to maintain the temperature of the electrolyte near 25°C due to the fact that at this temperature is reached the optimum balance between efficiency and life of the battery.

The number of cycles of charging/discharging depends on the DoD. When it decreases, number of cycles increases. For a given DoD, the most robust battery provides the highest number of cycles but still a low number of cycles [20].

2.3.1.2. Li-ion batteries

Li-ion batteries are the batteries which present the biggest advantages in energy and specific power, storage efficiency, discharge performance and absence of memory effect. The self-discharge is also a positive feature of this technology because after six month of resting, they can still get to retain 80% of its load [22].

In addition to these advantages, they have others as the low maintenance and the ability to operate with a high number of regeneration cycles.

These batteries have a high voltage per cell because each cell provides 3.7V [23]. This voltage undergoes a small linear discharge throughout the discharge, thus obviates the need for control circuits and facilitates to know the amount of energy the batteries stored.

The weak point of these batteries is as a result of their low discharge capacity, the cost and life expectancy. They are expensive devices and with relatively short duration of about 4000 cycles. So although they are promising in the future, its technology still has a lot to grow.

Another negative aspect is the use of flammable organic electrolytes which causes a rapid degradation and an increase in the sensitivity to high temperatures, which can origin a destruction by inflammation or even explosion. The danger requires the inclusion of additional safety devices, resulting in a higher cost which limits the extent of its use.

Finally, a comparative table of the main characteristics of the analyzed electrochemical battery technologies is shown in Table 1 [22].

Table 1: Comparison of the main parameters of the batteries

Technology	Voltage per cell [V]	Specific energy [Wh/kg]	Efficiency [%]	Self-discharge per month [% of total]	N° of cycles of lifetime
PbA	2	30-50	80-90	2-5	1500
Li-Ion	3.7	100-265	95-100	1	4000

2.3.2. Hot water accumulators

Hot water accumulators are a way of Thermal Energy Storage (TES). TES allows excess thermal energy to be collected for later use, hours, days or months later. It also allows the storage of electricity as heat. In district heating networks like the ones installed in Sweden, hot water accumulators can be connected to the network in order to store the electricity. In this case it is used to store the electricity excess produced in the panels and that is not used in the dwelling.

Among the heat storage, the most common method is the sensible storage. The storage is done changing the temperature of what is called the storage material, which can be water, air, oil, rock beds, bricks, concrete, or sand. In this thesis it is going to be used a water accumulator. Depending on the temperature difference, the mass of the storage medium, and its heat capacity, the quantity of energy stored is calculated with the equation 1.

$$Q = m \cdot Cp \cdot \Delta T \quad (1)$$

Where:

- C_p: specific heat of the storage medium (J/kg·°C)
- ΔT: the temperature gradient (°C)
- m: mass of storage material (kg).

The TES is used to pre-heat the incoming water used for domestic hot water by using an electric resistance element. The connection to the district heating system is assumed to follow the Swedish DH Associations principle for connecting solar thermal systems to heat domestic hot water by using thermal storage but without connection of the hot water circulation to the tank [24]. To avoid legionella risk, the incoming water is assumed to be heated in a closed loop system, see Figure 6.

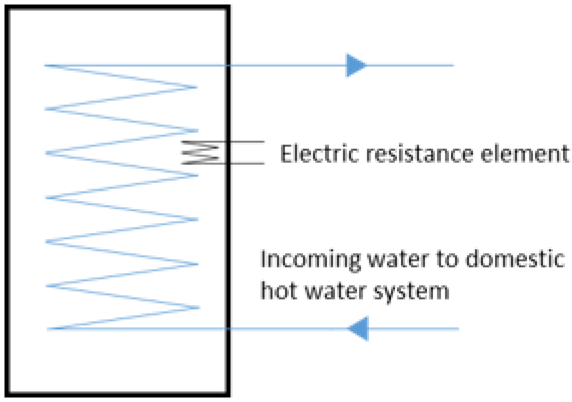

Figure 6: The principle of the thermal storage accumulator where the incoming water to the domestic hot water system is pre-heated.

The water naturally stratifies due to the increasing density at the lower temperatures: the hot water flows to the top, the cold water remains at the bottom, and the intermediate region is the thermocline. The thermal stratification in the water storage tank is typically affected by various factors but it can be enhanced through various ways, such as membranes, internal weirs, baffles, labyrinths, series tank, empty tanks, and thermally stratified systems [16] and [17]. In the tank that is going to be used in this study, as a result of the tanks temperatures, the size of the tank and mostly because of the continuous moves inside the tank, this phenomenon can be neglected.

3. Method

Solar production monitored data of an installed PV system for the analysis has been acquired from a single family house located in Älvkarleby (Sweden). The PV system is placed on the roof and has a maximum power of $2.6kW_p$.

As mentioned before, the buildings that have been analyzed are two dwellings. They are located in Sätra, Gävle (Sweden). The buildings are shown in Figure 7. Sätra 1 is a five floor tower block and Sätra 2 is a three floor slab block.

Figure 7: Buildings Sätra 1 and Sätra 2,respectively

Data of the use of electricity in the dwellings is only related to the common areas of the building (basement, laundry room, stairs, floor, fans for ventilation, pumps for the heating system, etc.). In contrast, the measured data of heat demand in all the buildings is of the entire buildings.

In the simulation of the PV system, it has been chosen an installation which could be multiple of 2.6kWp, which is the power of the reference installation. In Sätra 1, the installed power has been supposed of $15.6kW_p$ and in Sätra 2, of $33.8kW_p$. This values have been selected after designing the layout of the panels on each rooftop, taking into account the available space in the roof, the possible shadings and the inhabitants of the buildings.

3.1. Validation of the results

For the validation of the results obtained in the simulation of all the alternative systems that are going to be proposed, it is necessary to note if the data used as solar production is good enough. The validation has been made using PVsyst, a software designed to be used by architects, engineers, and researchers [25].

When starting a new project in PVsyst, the program asks for the location where the installation is going to be simulated. Since the program does not have the meteorological data of Gävle, it has been indispensable to acquire the hourly values of irradiation, temperature and wind velocity from the source Meteonorm, which offers access to accurate data for any place on Earth: Irradiation, temperature and more climate parameters are available [26].

Meteonorm is a comprehensive meteorological reference. It gives access to a catalogue of meteorological data for solar applications and system design at any desired location in the world. It has a proven experience in the development of meteorological databases for energy applications. From monthly values (station data, interpolated data or imported data), Meteonorm calculates hourly values of all parameters using a stochastic model. The resulting time series correspond to “typical years” used for system design. All the data is written to ASCII files which has been exported to PVsyst.

Regarding the inclination of the PV panels, it has been designed for a plane tilt of 10° due to the facility to install panels with that tilt in a rooftop. It has been proven that the relation between the price of the installation and the production of energy is more profitable with the designed tilt [27].

On the other hand, the PV systems have been designed with PV modules of Helios Energy Europe. The characteristics of the type of module chosen are shown in Table 2 [25] and the I-V curves with the maximum power point is in Figure 8 [25].

Table 2: Characteristics of PV modules

Technology	Si-monocrystalline
Maximum power [W_p]	420
Length [mm]	1976
Width [mm]	1310

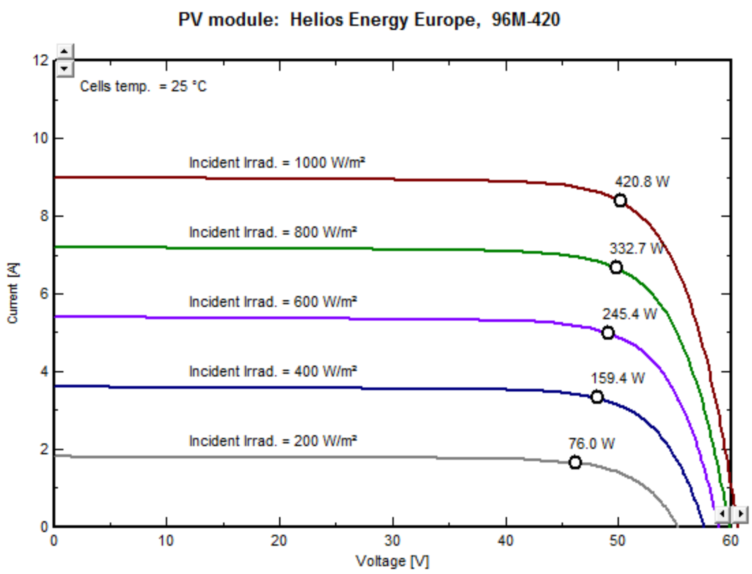

Figure 8: I-V curves of chosen PV modules [25]

The PV electricity production is in DC, so for some domestic applications it has to be transformed into AC. For that reason, it has been chosen SMA inverters as a reference in PVsyst. It has sized the system with the correct inverter size, which in each building is different due to the configuration of the modules. The modules in both dwellings have been divided in strings, so this way each inverter converts the electricity production of each string. All the PV modules configurations in the rooftop of the dwellings and the exact inverters parameters are shown in Appendix 1.

After determining if the solar production data used is correct, the analysis of the annual electricity use and heat demand in the three different buildings has been carried out with MATLAB® software, which will be the key also to analyze and design the proposed systems [28]. Moreover, the analysis of the systems that are going to be proposed have been made using the explained MATLAB® software.

Once the analysis has been made, it has been designed the three systems that are going to be analyzed in the thesis. Each of them differs from the rest in the form to store the electricity production of the PV system. All of the analyzed configurations are shown in Figure 9, Figure 10 and Figure 11.

In the first alternative system it is only going to be used a battery storage and in the second and third one a hot water tank to store excess electricity as heat.

3.2. Alternative system 1

The simulation of the first system has been done by following one of the storage-control algorithms that has been followed in some found researches [29].

First, if the electricity demand of the building is lower than the one produced in the PV panels, the energy that is produced by the PV system will be used, if demanded, to satisfy the required building electricity. The rest of the electricity not used for the momentary demand will be then used to charge the batteries to the maximum. In the last place, the surplus electricity will be injected to the grid.

In the opposite case, when the electricity required in the dwelling is higher than the production of electricity by the PV system, all the produced electricity will be used to satisfy the demand and the batteries will be discharged to use the stored electricity. If yet the demand is not satisfied, the surplus will be purchased to the grid.

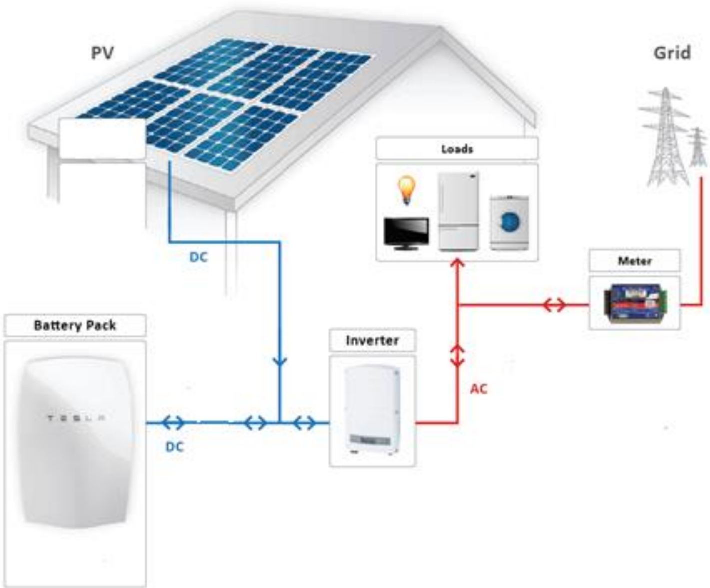

Figure 9: Scheme of alternative system 1

When using a battery storage it has been studied the behavior of two different types of batteries, PbA and Li-ion. The parameters used in the simulation of the battery performance are shown in Table 3 [30].

Table 3: Technical input data for PbA and Li-ion battery technologies

Technology	PbA	Li-ion
State of charge range [ΔSOC]	0.5	0.8
Maximum state of charge	0.9	0.9
Minimum state of charge	0.4	0.1
Maximum charge current [A]	$0.2 \cdot C_{nom}$	$3 \cdot C_{nom}$
Maximum discharge current [A]	$0.4 \cdot C_{nom}$	$3 \cdot C_{nom}$
Price [£/kWh]	140	350

One of the requirements of the battery system is that it does not remain for long times below 30% load because this may cause the sulfation of the battery and so its fault.

To estimate the SOC (the complement of DoD) of each battery it has been supposed that the battery capacity remains unchanged throughout its life. This is not so in reality, as the PbA batteries lose ability throughout their life. Although it has been taken into account that the capacity is not independent of which current with they are been discharged because, they cannot supply all its energy available if they are discharged with certain currents.

This relationship between the current that is discharged and the maximum energy that can be given (maximum capacity) is described by Peukert's law [31]. This law states that larger discharge currents, the lower the battery capacity, or in other words, lower the maximum energy that can be extracted from the battery. This does not mean that there is no remaining energy in the battery, but the fact of discharging it with high current (faster discharge) makes impossible to extract all the energy due to the voltage drop that the battery suffers in these conditions. The voltage of a battery cannot lose a certain limit as the battery requires a minimum voltage to work. Therefore, the capacity is affected by the voltage drop caused by the internal resistance of the battery, as its value increases as the battery is discharged.

This phenomenon occurs in all PbA batteries and therefore each manufacturer often gives the battery capacity depending on the hours during which you want to discharge the battery without actually reducing stress to the minimum. The data capacity supply battery manufacturers are called with a C (Capacity in Ah) and is followed by a numerical subscript indicating the hours of maximum discharge. Dividing the capacity battery discharge between the hours the maximum current which can be obtained dicharge each battery during that time.

There have been developed many more accurate methods for calculating the SOC having into account the relationship between the discharge current and the time duration of the discharge but they are very complex methods for this analysis and therefore not taken into account in simulation.

It is also desirable that the batteries are not left for long periods in a certain load without being charged at all. Performing this analysis it will be analyzed which is the behavior of this batteries.

One of the critical factors of the batteries is the number of downloads suffering, and most importantly, which is the depth of such discharge. The useful life will greatly influence the annual price of the proposed system and, therefore in the determination whether or not there would be economic savings.

3.3. Alternative system 2

The following algorithm control has been used in the alternative system 2. Solar energy production is used to cover the demand of electricity of the building at first. The hours when the electricity use is higher than the produced one, the electricity that is missing is purchased from the grid. In the opposite case, when there is electricity available from the PV panels, it is used to heat the water of the tank to satisfy the demand of heat in the buildings at that moment. If still there is spare electricity available, it is used to heat the water in the tank to its maximum designed temperature, to store the electricity as heat for later use.

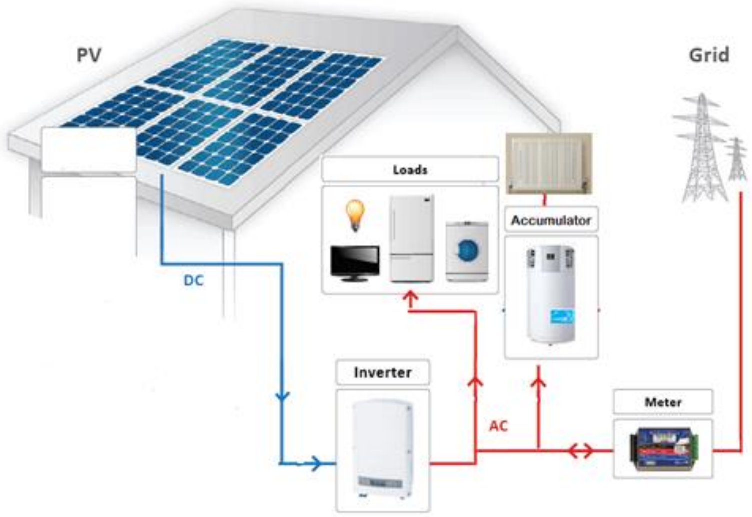

Figure 10: Scheme of the alternative system 2

The parameters used in the model of the hot water tank are shown in Table 4.

Table 4: Hot water tank parameters

Tmin	5°C
Tmax	90°C
Tout	65°C
Tsurr	20°C

When the tank is at Tmin it means that it is not possible to extract any heat from the water in the tank, so everything has to be bought from district heating. Contrary, when the temperature in the tank is Tmax it does not exit the possibility of heating more water. This forces to inject to the grid the additional electrical energy, and when there is a demand of heat to discharge the tank of water.

It has to be taken into account the losses that the tank will have. It has been supposed negligible the extra heat when the tank temperature is lower than the Tsurr. It does not happen the same when the temperature in the tank is higher than Tsurr, where the losses can be high.

The loses of the tank follow the next formula [32],

$$Q_{loss} = U \cdot A \cdot (T_{tank} - T_{surr})$$

Where:

- A: area of the tank
- U: thermal transmittance, which is defined as the rate of transfer of heat through one square meter of a structure divided by the difference in temperature across the structure. In this case for the tank the value has been supposed of 0.33W/m^2.

The tank has been chosen from a catalogue of NIBE brand. The diameter of the 500 liter accumulator is of 0.67m [33].

3.4. Alternative system 3

In the last case, all the electricity produced by the PV system is used to heat the water in the accumulator. The heat demand is satisfy first and then the extra electricity is used to heat the water that is going to be stored in the tank until it is required by the building.

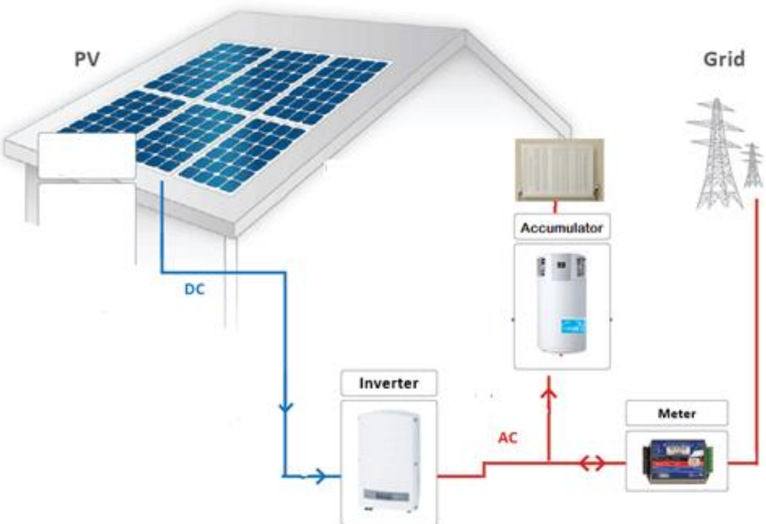

Figure 11: Scheme of alternative system 3

3.5. Economic evaluation

For the economic analysis of the three proposed systems it has been necessary to search for the prices of electricity and district heating.

The profitability of the systems has been calculated doing a comparison of the cost for the energy need that the buildings are paying in the moment and the cost of all the alternative installation and the cost of the energy that they are not going to buy with the implementation of the new system.

The price for electricity that a user in a residential building pays is 1SEK/kWh [34].The price for selling electricity is the spot price of electricity. The electricity spot price mean value of the last three years is 275SEK/MWh. This value has been calculated taking into account mean values in Table 5 due to the fact that, although people commonly think electricity is cheaper during summer, it is not valid, as seen in Table 5 [35] .

Table 5: Electricity spot prices of Sweden [35]

Elspot prices in [SEK/MWh]	2015	2014	2013
January	281.8	290.1	357.3
February	266.6	267.1	335.9
March	233.1	235.27	371.3
April	235.5	245.5	369.7
May	208.1	317.1	315.8
June	137.8	286.1	296.3
July	84.9	274.6	296.1
August	137.0	317.4	351.2
September	195.8	335.3	387.1
October	209.1	286.5	361.6
November	224.6	278.5	328.1
December	169.5	296.0	291.9
Mean value of the year	198.6	285.8	338.5

On the other hand, the price for district heating in Sweden, it varies among the different district heating companies, basically depending on the owner type which can be the municipality, the state or a private owner [36]. The mean value calculated is of around 0.77SEK/kWh, and it is the one that is going to be used in the economic evaluation [37].

Besides that, for the calculations that have been carried out, the economic subsidies that Swedish government gives to increase the electricity produced by renewable energies have been included in the analysis. The mentioned economic subsidy is called electricity certificate system and is a market-based support system. In Sweden for every MWh electricity produced from a renewable source, it is given an electricity certificate, which has an economic compensation. There are some obligations that has to be fulfilled but they do not affect directly this kind of installation so they will be neglected. The mean price of each certificate in 2014 was 180SEK. This price is the one that is going to be used in the economic analysis of the alternative systems [8].

Moreover, in Sweden, it exits what is called tax reduction. This reduction also benefits the producers of renewable electricity who buy and inject electricity in the same point. The conditions for being a beneficiary are to have a main fuse of maximum 100A, to inject to the grid a maximum of 30000kWh per connection point and that the amount of kWh fed into the grid during a calendar year do not exceed the amount of purchased kWh. The amount of the fee is 0.6SEK/kWh [38].

Another remuneration that can be obtained for producing energy using renewable resources is given by the grid owners. It has been estimated that for the energy sold to the grid, it can be gained approximately 50SEK/MWh [34]. The main reason for this fee is that when producing in the same point as consumed, there are avoided losses in the grid due to the distribution and transport of electricity.

The installation of the PV panels and the correspondent inverter for converting the DC into AC has an estimated cost of around 15SEK/W_p [39]. This value includes also, among others, the inverter, installation work or VAT as it can be observed in Figure 12 [39]. The values are expressed in percentage.

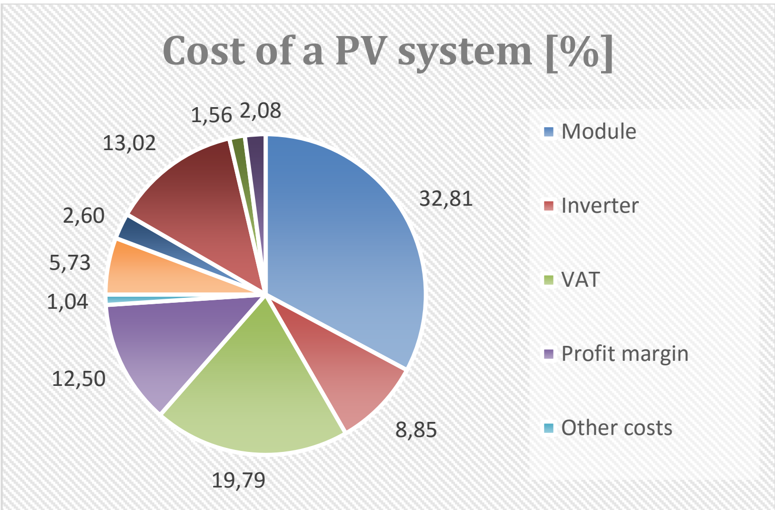

Figure 12: Cost of a PV system [%] [39]

The determination of the useful life of all the designed systems is of great importance due to the repercussion that the price per year of the components has in the profitability of the systems. In case of the PV panels installation, as found in some research [40], it has been supposed that the years that it will last is of around 25. As in the price of the PV system it is included the inverter and the maintenance of this, it can be also estimated that with that price it will last 25 years, although is not true and it will be changed earlier.

As for the price and useful life of the storage systems, the price of batteries that have been used are the mean values for the PbA and Li-ion that are indicated in Table 3. It is also indicated the number of cycles that each battery can suffer. So it has been calculated the number of cycles that they suffer per year for the determination of the number of years that can be last. If the number of years they can last is higher than 7, it has been taken 7 years of duration, basically due to the manufacturers characteristics, which normally say that batteries have to be changed after between 7 and 10 years of use.

Finally, it has been designed the system using a commonly tank manufacturer in Sweden. The brand is NIBE and to be exact the type of accumulator used is NIBE VPB. Depending on the size of the tank the prices are the ones presented in Table 6 [33]. In the analysis there have been considered different sizes of accumulators to see which one will give the best results in self-consumption and in economic savings.

Table 6: Price of different sizes of accumulator [33]

Type of accumulator	Price [SEK]
VPB 500	28200
VPB 750	39000
VPB 1000	51250

The durability of a tank like the one used in this thesis has been determined, like in the PV system, of 25 years.

Table 7: Main economic and useful life factors affecting the alternative systems

Type of cost	Concept	Cost	Useful life
System costs	PV system	15 SEK/W_p	25 years
	Batteries PbA	1649 SEK/kWh	1500 cycles/7 years
	Batteries Li-Ion	4708 SEK/kWh	4000 cycles/7 years
	Accumulator 500 liter	28200 SEK	25 years
Energy costs	Purchased electricity	1000 SEK/MWh	
	District heating	770 SEK/MWh	
	Spot electricity price	275 SEK/MWh	
Swedish government subsidies	Electricity certificate	180 SEK/MWh	
	Tax reduction	600 SEK/MWh	
	Grid losses	50 SEK/MWh	

3.6. Environmental evaluation

It has been analyzed the environmental impact of the reduction of district heating demand in the DH network in Gävle. For that purpose, the production units which take part have to be analyzed. All of them with their most important characteristics for the analysis are shown in Table 8 [41].

Table 8: Data for production units in the Gävle DHS [41]

Production unit	Fuel	Maximum heat capacity	Efficiency	Power to heat ratio
Waste heat from Billerud Korsnäs AB	-	23 MW	-	-
Flue gas condenser Bomhus Energi AB	-	40 MW	-	-
Black liquor evaporator Billerud Korsnäs AB	-	36 MW	-	-
CHP Bomhus Energi AB	Bark	150 MW	88%	0,3
CHP Johannes	Biofuels	77 MW	88%	0,3
Flue gas condenser Johannes	-	20 MW	-	-
Electricity boiler Billerud Korsnäs AB	-	50 MW	-	-
Peak and reserves Billerud Korsnäs AB	Oil	120 MW	90%	-
Peak and reserves Gävle Energi AB	Oil	60 MW	90%	-
Peak and reserves Gävle Energi AB	Bio-oil	74 MW	90%	-

It has been used a developed method [42] for the determination of which is the electricity producing plant which gives hourly the heat necessary to cover the peak load. After that, as it has been previously calculated the quantity of heat that with the PV system together with the accumulator is avoid to consume, it is calculated the kilograms of CO_2 that are not produced in excess.

It has to be taken into account that CHP plants, apart from heat, they also produce electricity. If this electricity is not produced in this plants, it has to be produced somewhere else, where the fossil fuels are used, so the analysis will provide the result.

Table 9: CO_2 emissions for electricity and fuels [41]

	CO_2 eq(kg/MWh)
Electricity mix Sweden, Norway,Denmark, Finland	95
Natural gas combined cycle condensing power	480
Coal condensing power	960
Tops and branches	15
Recycled waste wood	15
Bark	15
Oil	300
Bio-oil	15

4. Results

4.1. Validation of results in PVsyst

The comparison of the most important parameters that have been obtained in PVsyst simulation and the ones of the real PV system are shown for Sätra 1 in Table 10.

Table 10: Validation of results in Sätra 1

Sätra 1	Measure data in real PV system	PVsyst results	
PV installation [kW_p]	15.6	13.4	15.1
		1.7	
Tilt [°]	28	10	
		90	
Orientation	20-30% West	South	
Produced Energy [MWh/year]	12	9.1	10.1
		1	
Specific energy production [kWh/kW_p/year]	767	678	669
		600	

The same results are shown in Table 11 for Sätra 2.

Table 11: Validation of results in Sätra 2

Sätra 2	Measure data in real PV system	PVsyst results
PV installation [kWp]	33.8	33.6
Tilt [°]	28	10
Orientation	20-30% West	South
Produced Energy [MWh/year]	25.9	25.2
Specific energy production [kWh/kWp/year]	767	749

The production of electricity after it has been converted to AC is shown as produced energy together with other parameters in Table 12 and Table 13. As it can be observed the measured quantity of energy is higher than the simulated one in both dwellings. This can be due to the kW_p installed in the real PV system, which are higher in both cases. Nevertheless taking into account that the real PV system has problems with shadowing, temperature and in the search of the MPPT, it is supposed to be superior the produced energy in the simulation in PVsyst, or at least closer. Moreover, the PV orientation is also a drawback because the real PV system is not oriented as the simulated solar panels in the dwellings, so this should make the south orientated panels to get more radiation. Although the results are supposed to be higher in the simulated PV system, it is not accomplished.

The main reason for this situation can be related with the difference in the tilt between the measured PV system and the simulated ones are different. As it has been calculated the tilt influences the maximum irradiation that can received. The optimum tilt for Sweden has been pointed between 20° and 55° [43], so the tilt of the real system is closer to that value than the 10° or 90° of the simulated system. The study shows that with the optimum tilt the produced energy is higher, so in the real PV system the production is higher. As mentioned before, the reason for the 10° of tilt in the simulated PV system is attributable to the profitability of the systems, and for that reason it can be trusted that the real measures can be used for the analysis of the alternative systems.

4.2. Analysis of electricity use

The annual electricity use for Sätra 1 and Sätra 2 can be seen in Figure 13 and Figure 15.

Sätra 1 has aproximately an minimum power demand of 1kW every day. And the maximun power demand is of about 20 kW due to the laundry room. During one day where the laundry room is used the load is much higher than the days where it is not used as it is shown in Figure 14.

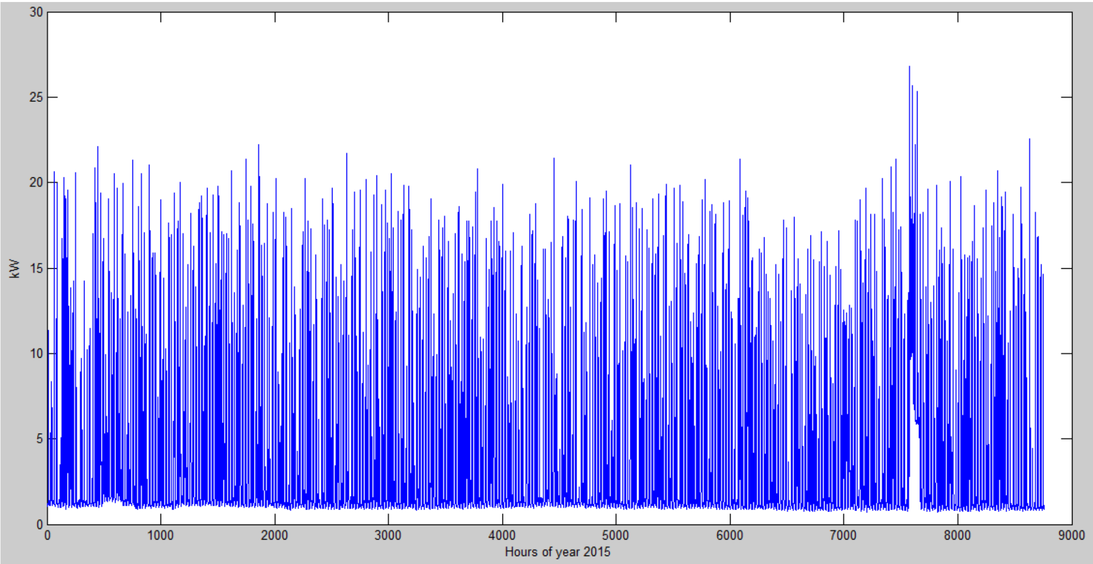

Figure 13: Annual electricity use in Sätra 1

Among all the year, with the objetive of analizing the differences between seasons, the electricity use of two typical winter and summer days in Sätra 1,respectively, are showed in Figure 14.

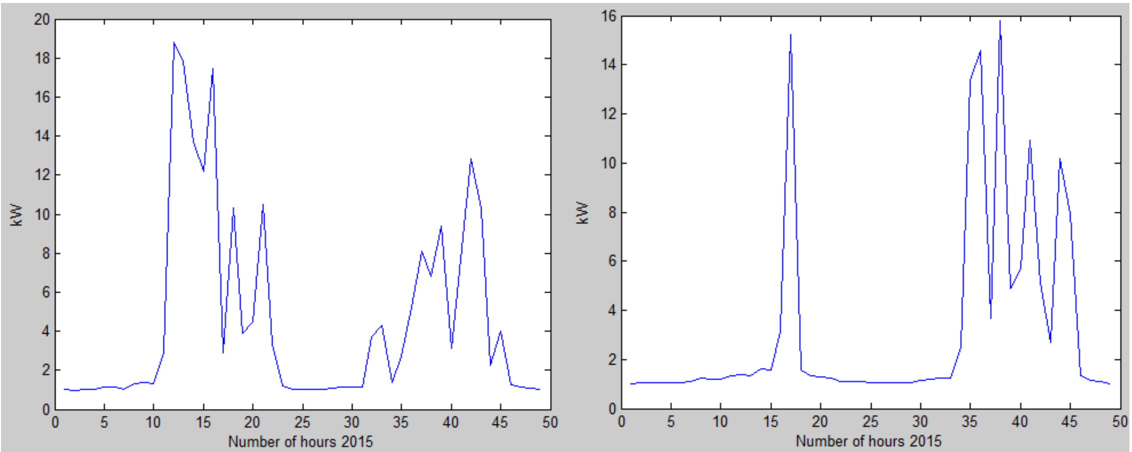

Figure 14: Electricity use in Sätra 1 in two typical days in winter and summer respectively

The use of electricity in winter and summer as it can be noted does not differ a lot, because the minimum value is not 0 at any moment, there is always a demand of electricity. In summer is a little bit lower the maximum peak, but the profile is almost the same. Normally, during one day there are 4 peaks of power demand, which as said can be related with the laundry room, because this peaks are during sunlight hours, and not at night.

For the three floor tower block (Sätra 2) building the electricity use can be seen in Figure 15.

Analyzing Sätra 2 in Figure 15, it can be seen that it has a higher minimum power demand than Sätra 1. At the contrary, the maximum demand is lower, of approximately 5.5kW. The main reason is that this second building does not have a laundry room in it.

It is also notable the absence of data in the first hours of the year where the power suddenly decreases to 0kW. It has been supposed that this day the system went down during a few hours, but it has been neglected in the analysis because it does not change the result significantly due to the fact that the production in winter is low, so the storage systems are not used.

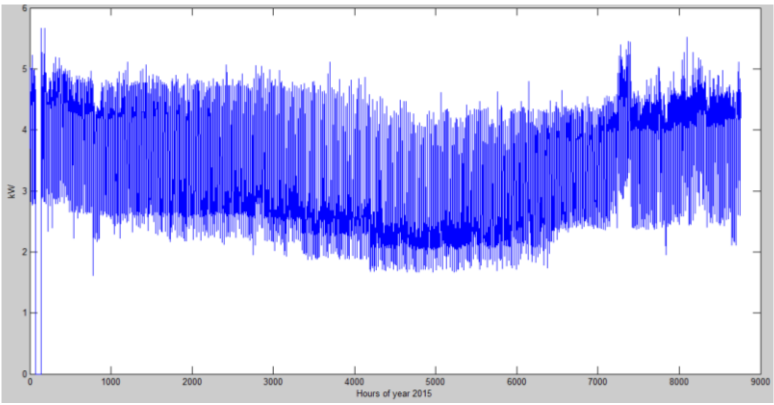

Figure 15: Annual electricity use in Sätra 2

That makes the profile of electricity demand of one day to be like other day of the year. Although, during summer time (hours 4000-6000 approximately) it can be seen a small decrease that can be related with the increase in the number of hours that there is sun or even in the vacations of the neighbors. The rest of the year the profile of the demand is more or less like presented in Figure 15.

In the same way as for the Sätra 1, it has been illustrated the electricity use in Figure 16 of two typical summer and winter days.

The main difference between winter and summer is the number of hours where it is required the day peak. In winter these hours are higher than in summer, most probably because of the need of lights. It can be noted also that the maximum peaks in all of the seasons are during night. In this thesis the use of electricity in the building has not been investigated and there are no good explanations for the peaks during the night. An assumption is that it exists a seasonal load such as outdoor lightning that has been forgotten to switch off and is running during summer.

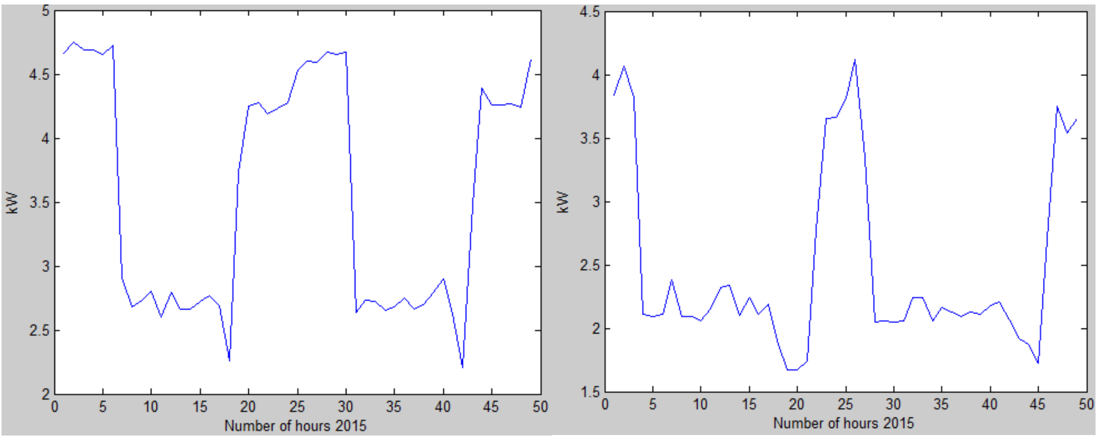

Figure 16: Electricity use in Sätra 2 in two typical days in winter and summer respectively

4.3. Alternative system 1

In the proposed alternative system 1, as mentioned, it is consumed first the electricity in the building and if there is spare electricity, it is stored in batteries.

For the analysis of the alternative system 1 in Sätra 1, it has been plot in Figure 17 the dwelling electricity use, the simulated solar production, the energy that can be injected to the battery or used from it (energy battery) and the electricity buy and sell at every hour of the year.

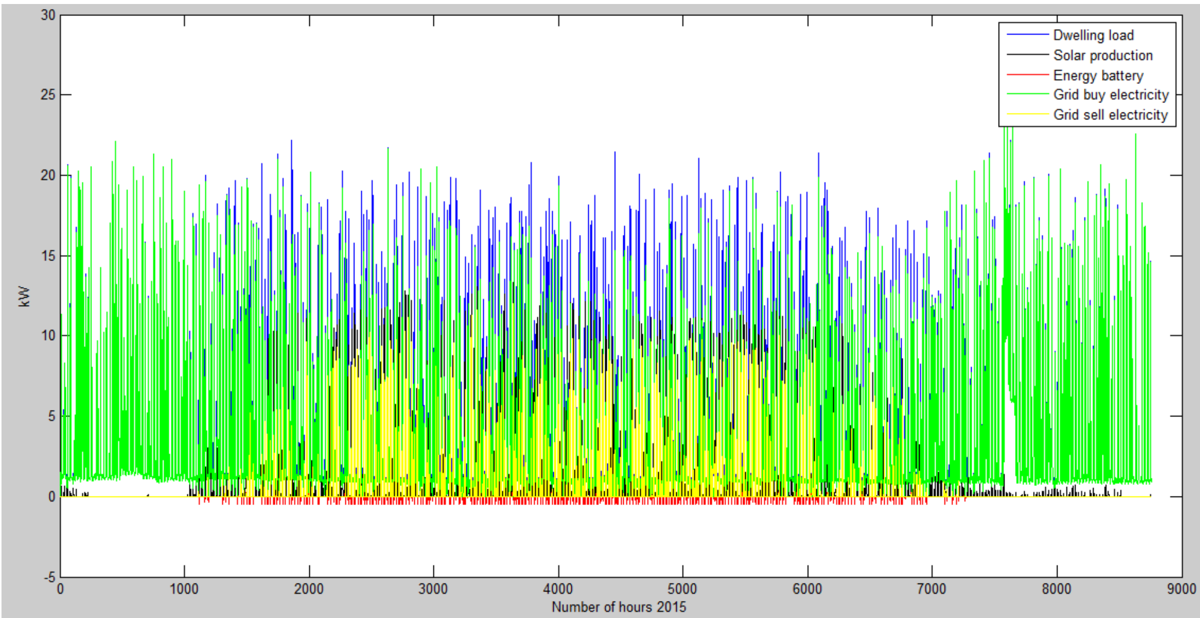

Figure 17: Annual behavior of the PV system with PbA batteries in Sätra 1

As it can be observed, when the load of the Sätra 1 is higher than the solar production, battery has a negative "energy battery" which means that they are been discharged. Contrary, when the solar production is higher, the "energy battery" as it occurs during some hours of 2015 (Figure 18) is positive, so it is been charged the battery.

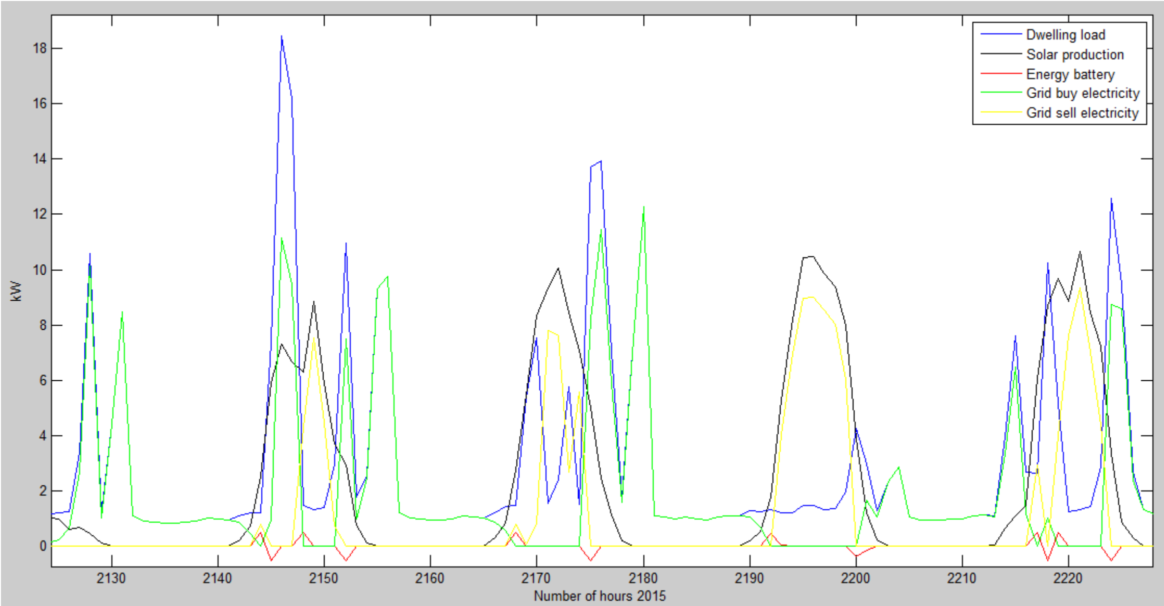

Figure 18: Behavior of the PV system with PbA batteries in Sätra 1 during some hours of 2015

As a result it has been calculated the battery size that gives the highest self-consumption rate which provides winnings to the system. This results are shown in Table 12 with other important parameters of the PV system with PbA batteries, Li-ion batteries and without storage. Furthermore it has been calculated the profitability of the system without batteries and governmental subsidies. It has to be stood out that if the self-consumption rate is decreased in the systems with batteries, the earnings will be higher. In the case without storage, the highest achievable self-consumption rate is shown. That value cannot be increased without a storage system, but it can be decreased if some more electricity is sold to the grid and not consumed in the building. To decrease the self-consumption rate in that case would not make sense since the price of the buying electricity from the grid is higher than the price for selling it, so that will mean a decrease in the winnings or even money loses each year.

Table 12: Results of PV system with and without batteries for Sätra 1

Battery type	**PV system with PbA batteries**	**PV system with Li-ion batteries**	**PV system without storage**	**PV system without storage and subsidies**
PV-production [kWh]	11900	11900	11900	11900
Battery size [kWh]	6.5	5	0	0
Grid sell electricity with battery system[kWh]	3500	3340	4460	4460
Self-consumption rate	71	72	63	63
Economic savings [SEK/year]	130	82	3160	-630

As it is clearly shown in the results, the most profitable system is the one without batteries, altough the self-consumption rate is less than with batteries.

For Sätra 2, it has been made the same analysis than in Sätra 1, which can be seen in Figure 19.

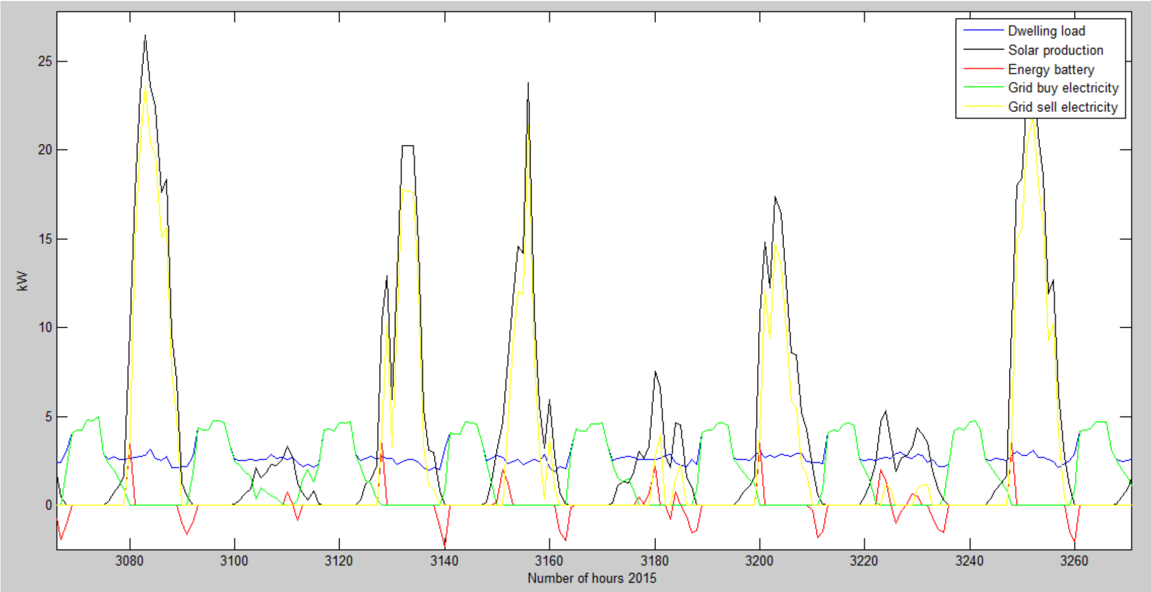

Figure 19: Behavior of the PV system with PbA batteries in Sätra 2 during some hours of 2015

Solar production is higher than in building 1 because of the solar capacity installed, and also can be said that during a lot of hours of summer the production of electricity is higher than the demand of the dwelling.

The results of the different type of batteries, for no storage and for no storage and subsidies in Sätra 2 are shown in Table 13. As well as for the Sätra 1, it has been calculated the maximum self-consumption rate which leads to not loosing money every year.

Table 13: Results of PV-system with and without batteries for Sätra 2

Battery type	PV system with PbA batteries	PV system with Li-ion batteries	PV system without storage	PV system without storage and subsidies
PV-production [kWh]	25900	25900	25900	25900
Battery size [kWh]	23	13	0	0
Grid sell electricity with battery system[kWh]	16090	16330	18800	18800
Self-consumption rate	38	37	27	27
Economic savings [SEK/year]	150	40	8000	-7980

In this case also the most profitable system is the one which does not implicate the use of batteries. The self-consumption rate is far lower than in Sätra 1 because the possible installation is higher and as it has been analyzed the maximum power required in the building is lower than the maximum that the PV system can produce.

Since the behavior of the two kind of batteries are different, it has been studied for a given self-consumption rate in the two buildings which is the required battery size and the economic profitability that can be achieved in that conditions. All of the results for both buildings are in Table 14 and Table 15.

Table 14: Comparison between PbA and Li-ion battery technology for Sätra 1

	PbA battery system	Li-ion battery system
Battery size [kWh]	6.5	4.2
Self-consumption rate [%]	71	71
System winnings [SEK/year]	120	570

Table 15: Comparison between PbA and Li-ion battery technology for Sätra 2

	PbA battery system	Li-ion battery system
Battery size [kWh]	20.8	13
Self-consumption rate [%]	37	37
System winnings [SEK/year]	900	40

It can not be concluded seing the results which kind of battery works better in all of the cases. It can be achieve a highest self-consumption rate with less battery size in the case of Li-ion batteries but as for the price the result is no clear. It depends a lot in the quantitiy of cycles that they suffer each year, because even tough for the number of cycles they could last more than 7 years, for a lot more reasons that have been explained before it is not possible.

4.4. Alternative system 2

In system 2, the solar production is used to cover the electricity demand of the building and then to cover the heat demand, so as it can be seen the spare electricity that goes to the heating system is the same that in the alternative system 1 could go to the batteries. Grid buy electricity is higher in this case because there is no electricity storage system.

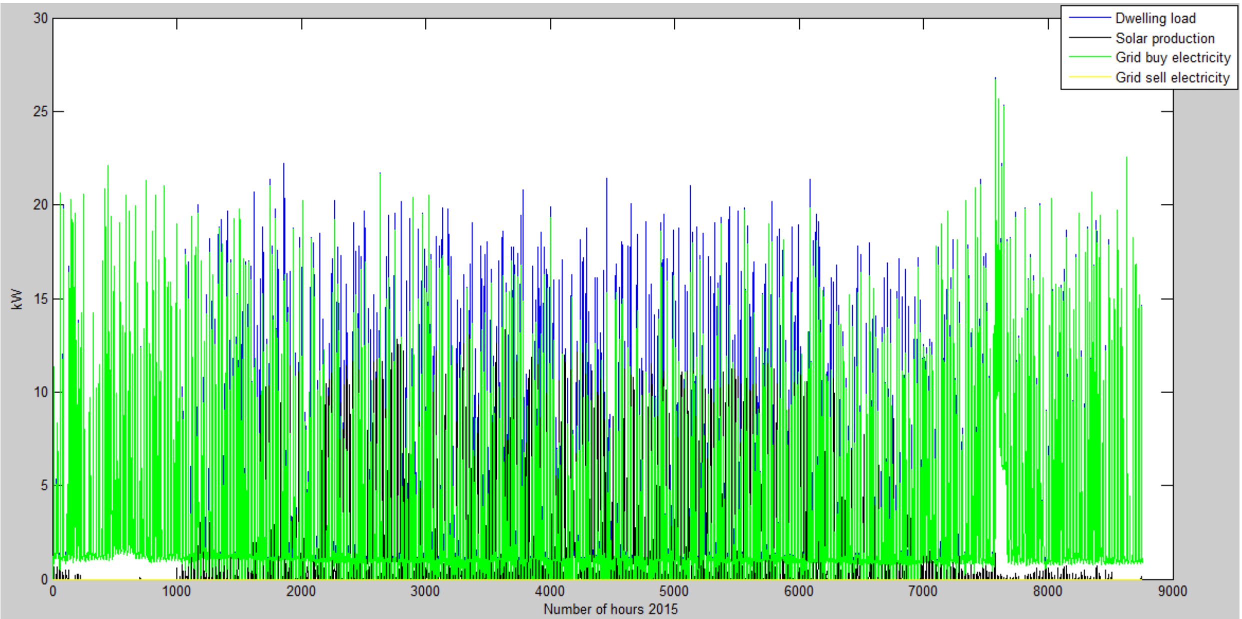

Figure 20: Annual bbehavior of the PV system of the alternative systems 2 in Sätra 1

In Sätra 1 the heat demand is higher than the electricity from the PV system (Electricity to the tank) which can satisfy the heat demand. This fact can be easily apreciated in Figure 21.

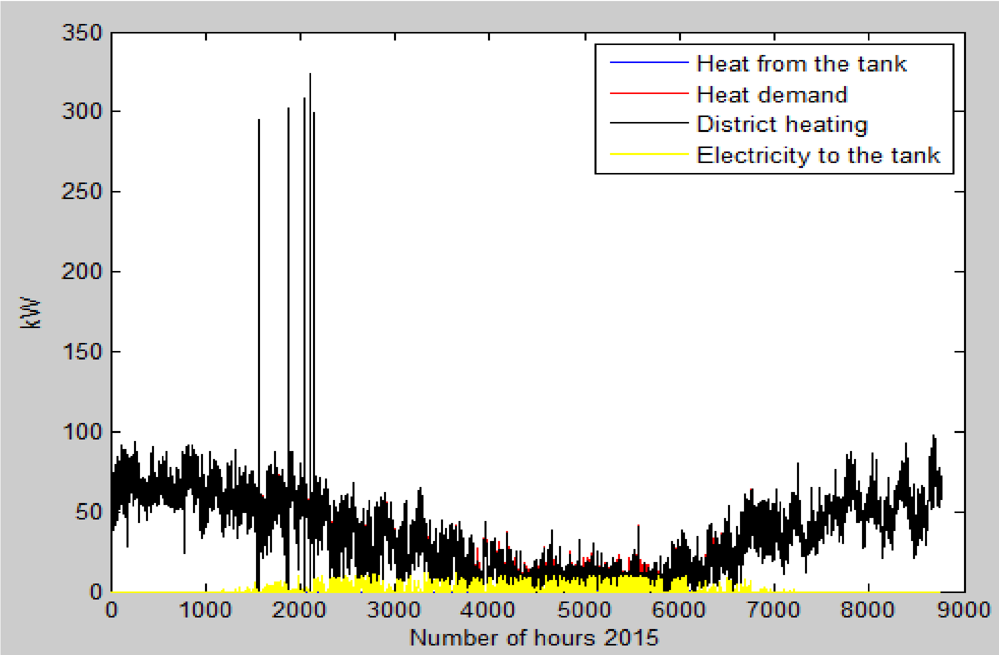

Figure 21: Annual bbehavior of the heating system in alternative system 2 in Sätra 1

Aparently is not required the use of an accumulator, but if it is analyzed the system in a short period as in Figure 22, it can be noted that sometimes the demand does not match with the electricity available at the same time, so an accumulator is the best way to solve the problem.

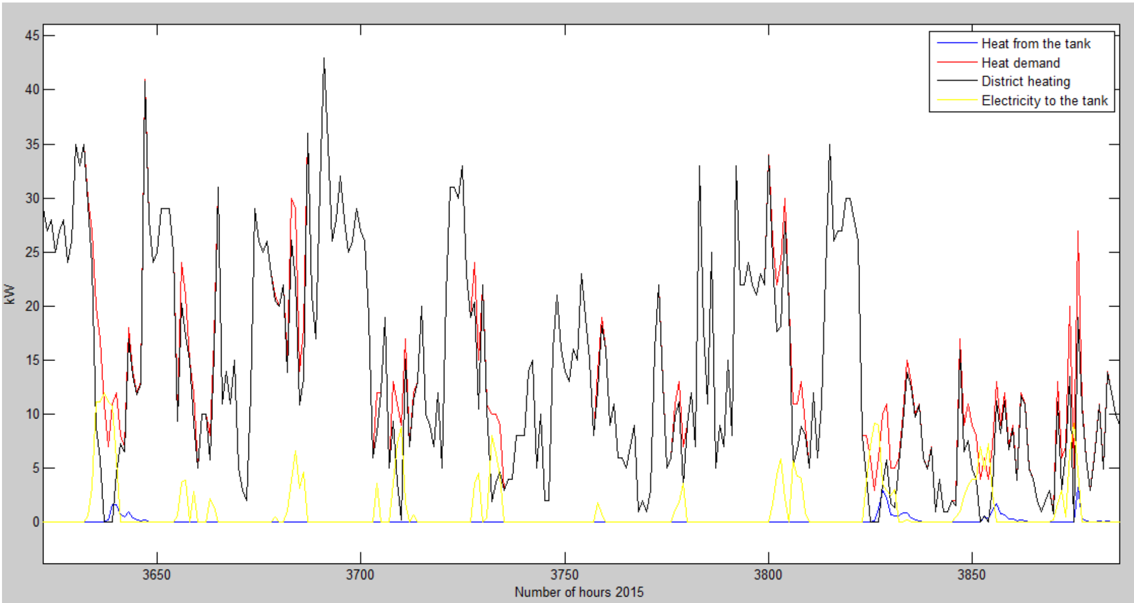

Figure 22: Behavior of the heating system in alternative system 2 in Sätra 1 during some hours of 2015

The temperature of the tank at every hour of the year is shown in the next figure (Figure 23). Altough the maximum designed temperature is 90°C, the maximum temperature in the tank is of around 31°C. That means that all the excess electricity after its use in the building goes to the heating system, but to cover the instant demand of heat and not to be stored for later use. The main reason for that is the lack of electricity, because the storage is used in summer, when there is no need of space heating in the house.

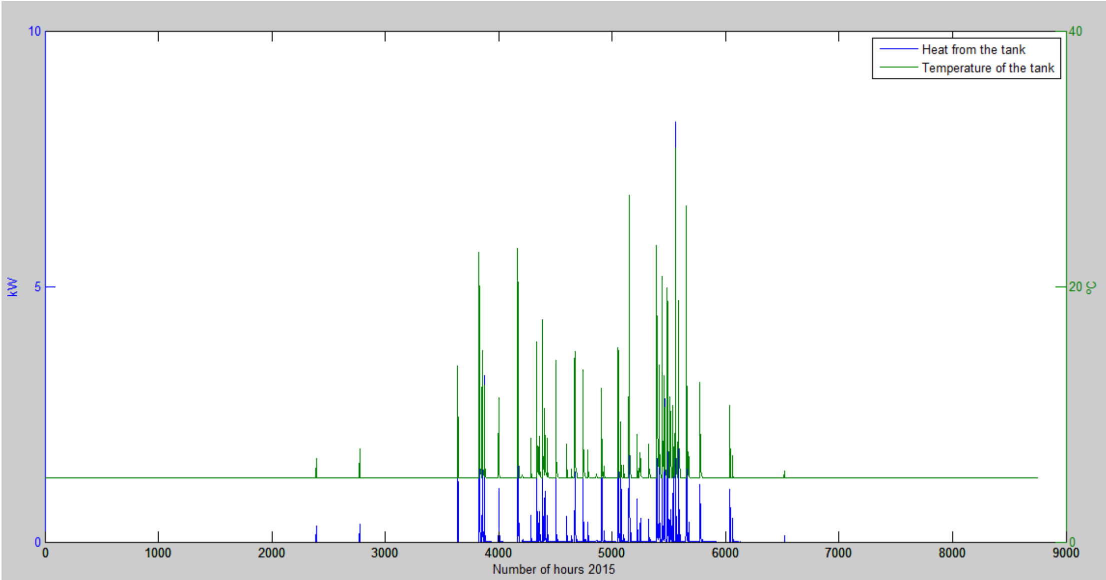

Figure 23: Annual temperature in the hot water accumulator for alternative system 2 for Sätra 1

In Figure 24 can be seen that there is no need of selling electricity to the grid because the load is normally higher than the production, and the spare goes to the heating system.

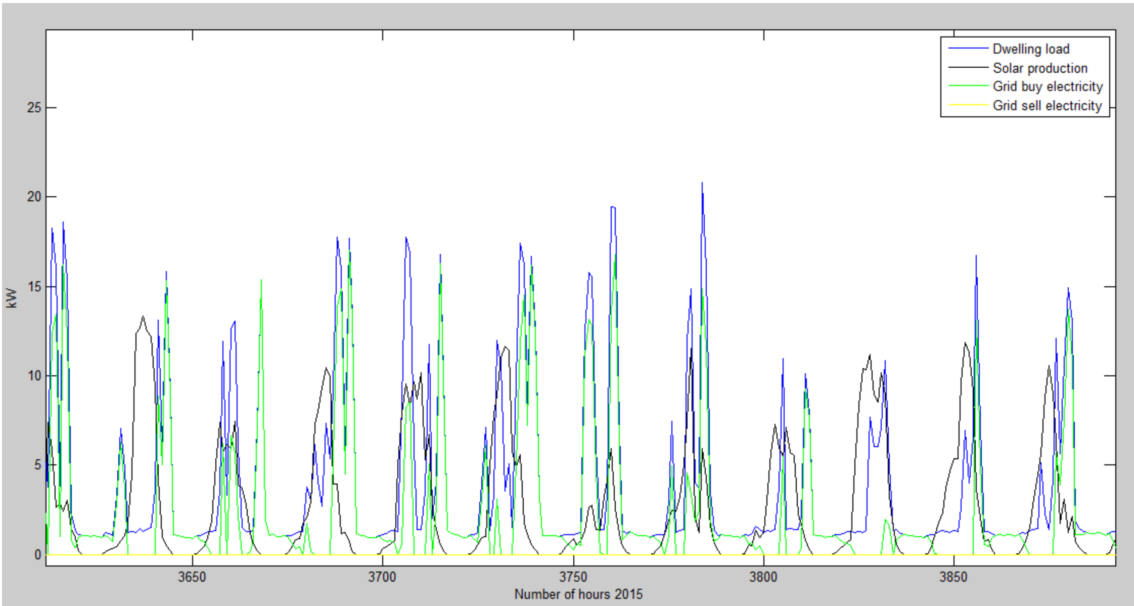

Figure 24 : Behavior of the PV system of alternative system 2 in Sätra 1 during some hours of 2015

Being the sold electricity to the grid 0 means that self-consumption rate is of 100%. With this characteristics the system would provide a winnings of 450SEK and a negative environmental impact as shown in Table 16.

Table 16:Self-consumption rate, economic and environmental impact for alternative system 2 in Sätra 1

Sätra 1	**Self-consumption rate[%]**	**Economic savings [SEK/year]**	**Environmental impact [CO_2 kg/year]**
500 litre accumulator	100	450	-210

For Sätra 2 the cover of the heating demand can be seen in Figure 25

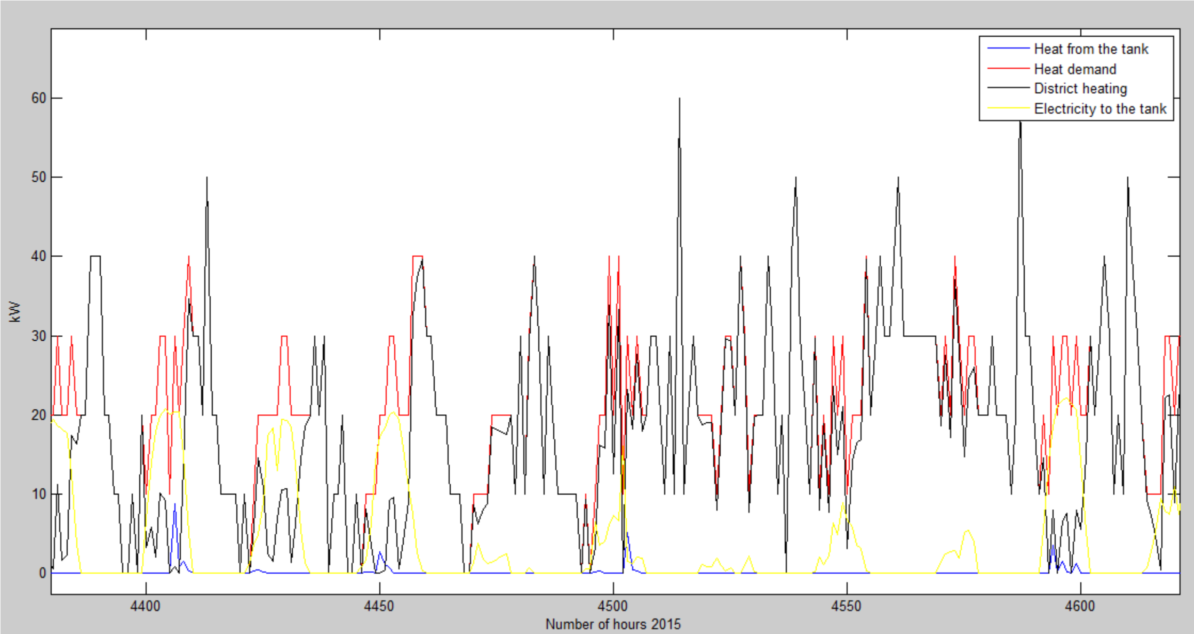

Figure 25: Behavior of the heating system of the alternative system 2 in Sätra 2

As well as for building 1, in Figure 26 for Sätra 2 it can be drawn the temperature evolution in the tank.

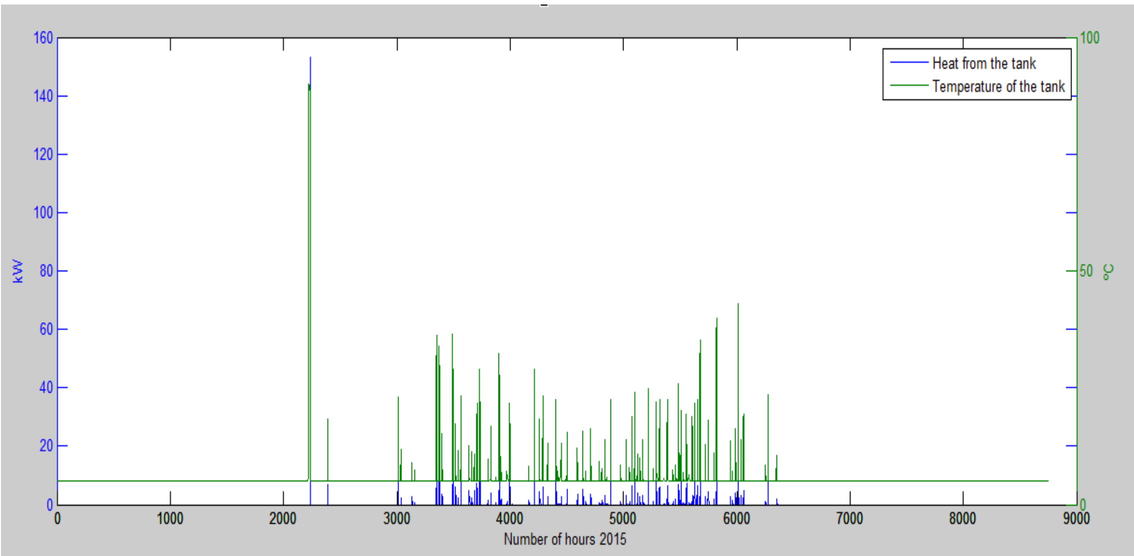

Figure 26: Annual temperature in the hot water accumulator of alternative system 2 for Sätra 2

In addition to the heat cover, it can also be seen in Figure 27 that the solar production in the building is higher than the electricity use, so a big part of the electricity goes to the heating system, but the electricity sold to the grid continues like in Sätra 1 being zero.

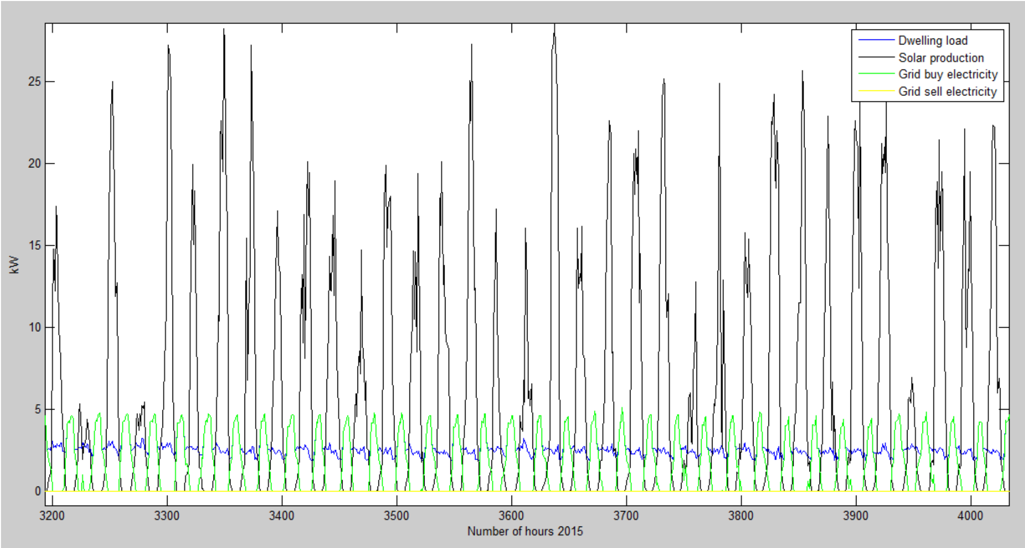

Figure 27: Behavior of the PV system of alternative system 2 in Sätra 2 during some hours of 2015

The self-consumption rate, system winnings and environmental impact for Sätra 2 are shown in Table 17.

Table 17: Self-consumption rate, economic and environmental impact for alternative system 2 in Sätra 2

Sätra 2	Self-consumption rate[%]	Economic savings [SEK]	Environmental impact [CO2 kg/year]
500 liter accumulator	100	45	-860

In system 2, for both dwellings, with the tank of 500 liter the temperature of the tank is higher than 50°C only once. This is due to the large volume of the tank, which was selected because it was a standard tank in the market of the hot water accumulators. Resting the electricity use in the dwellings to the solar production leads to an electricity use for heating that is not so high, so the biggest part is used to satisfy the instant demand of heat in the buildings.

For both buildings the balance of money is positive, so that means that an installation like this in the buildings could make the owners save the amount of the money per year that can be seen in Table 16 and Table 17. It has to be said that the money that can be saved is not higher than 450SEK per year. The savings are still less than the ones that the system without storage can provide in both cases as it can be compared with the values in Table 12 and Table 13. The amount of money, as said before, could be increased if the components that have to be bought for the implementation of the system will decrease, if the electricity price would increase, if the economical subsidies will increase or if the district heating prices would increase.

In all of the cases the self-consumption rate is 100% because the solar production is used always either for the electricity demand, for the heat demand or to increase the temperature of the water in the tank so the electricity does not have to be sold to the electricity grid. The negative point of this system in the dwellings comes from the environmental impact, which is negative in both cases (Table 16 and Table 17).

4.5. Alternative system 3

The only energy demand that this alternative system tries to satisfy is the heat demand of the building (Figure 28). Only when the solar production is higher than the heat demand is when the accumulator increases its temperature to store energy. In the rest of the cases the electricity is used to satisfy the instant demand and if solar production is not enough the rest is purchased to the district heating grid.

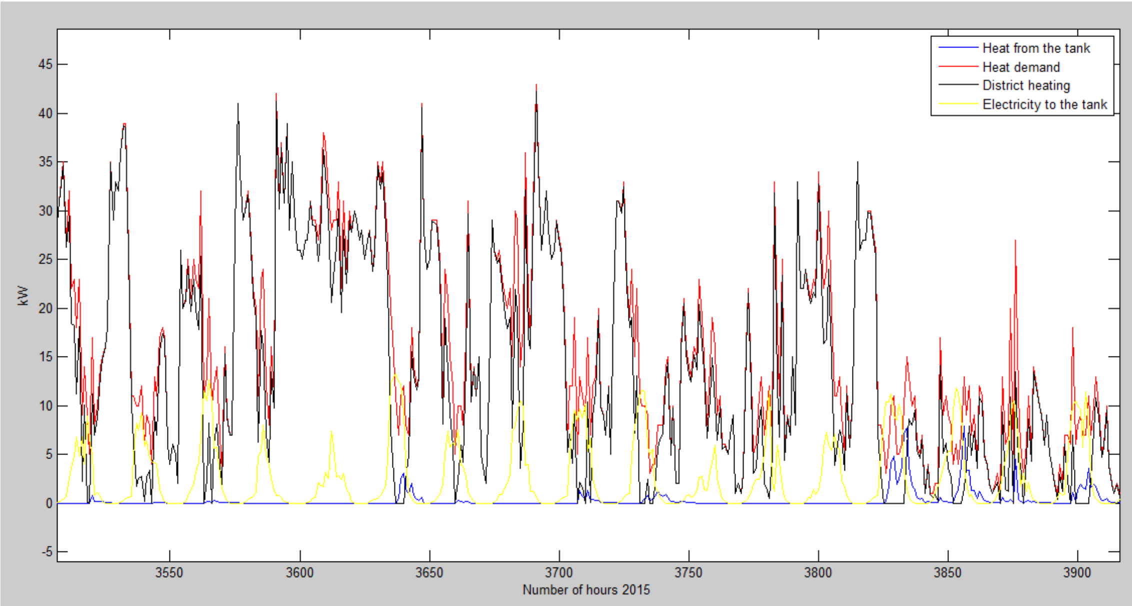

Figure 28: Behavior of the heating system of alternative system 3 in Sätra 1 during some hours of 2015

Since all the electricity produced by PV system is used for heating, the water in the tank reaches higher temperatures because the quantity of spare electricity which should be stored is higher. The maximum temperature in the tank is almost 50ºC (Figure 29) but still is inferior to the designed maximum temperature.

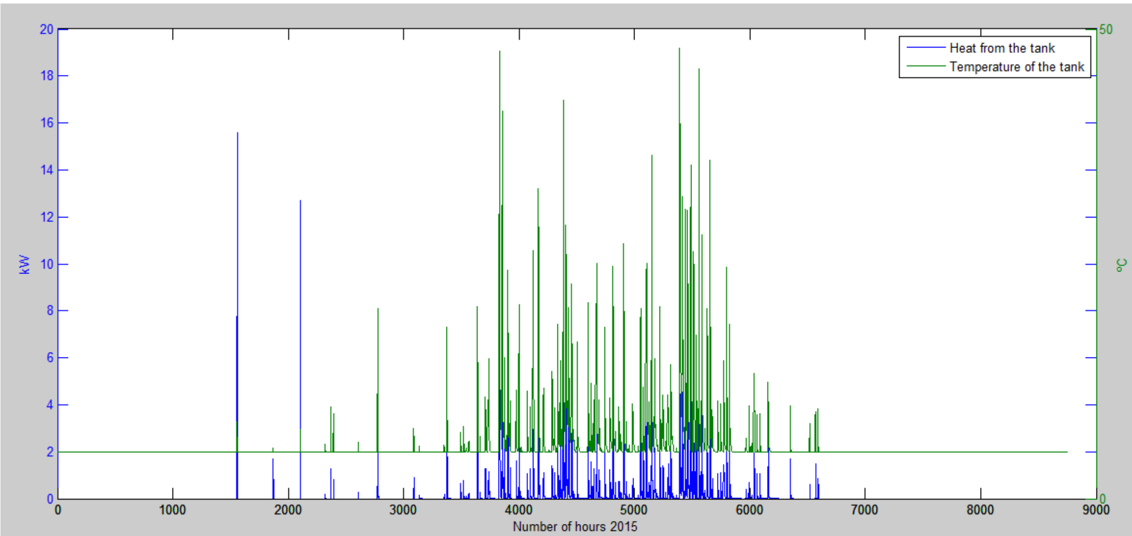

Figure 29 : Annual temperature in the hot water accumulator for alternative system 3 for Sätra 1

Since the temperature as in the previous cases where the tank is used does not get to 90ºC, all the electricity is used for heating and the injected energy to the grid is none, the self-consumption rate is 100%. The economic analysis in this case is negative, each year the owner will lose -1435SEK installing this system.

Table 18:Self-consumption rate,economic and environmental impact for alternative system 3 in Sätra 1

Sätra 1	Self-consumption rate [%]	Economic savings [SEK]	Environmental impact [CO_2 kg/year]
500 litre accumulator	100	-1430	-560

It happens something similar in Sätra 2, where the solar production during lots of hours of the year is not enough to cover the heat demand and the heat has to be purchased from the district heating grid as shown in Figure 30.

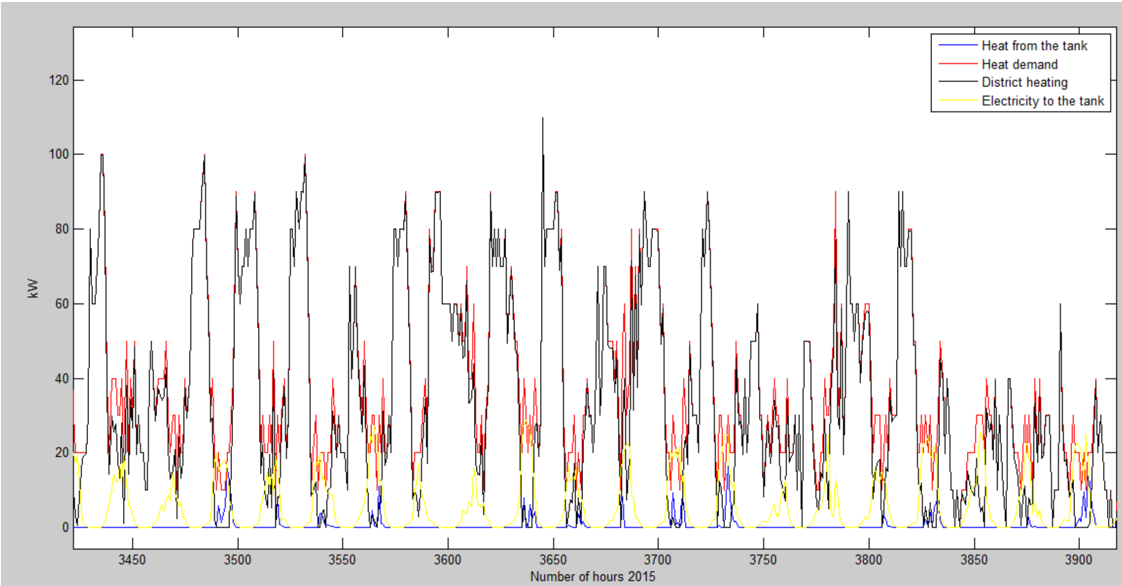

Figure 30: Behavior of the heating system for alternative system 3 in Sätra 2 during some hours of 2015

But unlike in Sätra 1, with the same system but being the solar production and the heat demand different, the temperature during more than one hour of the year 2015 would reach a maximum of 50°C or even in one hour the 90°C(Figure 31).

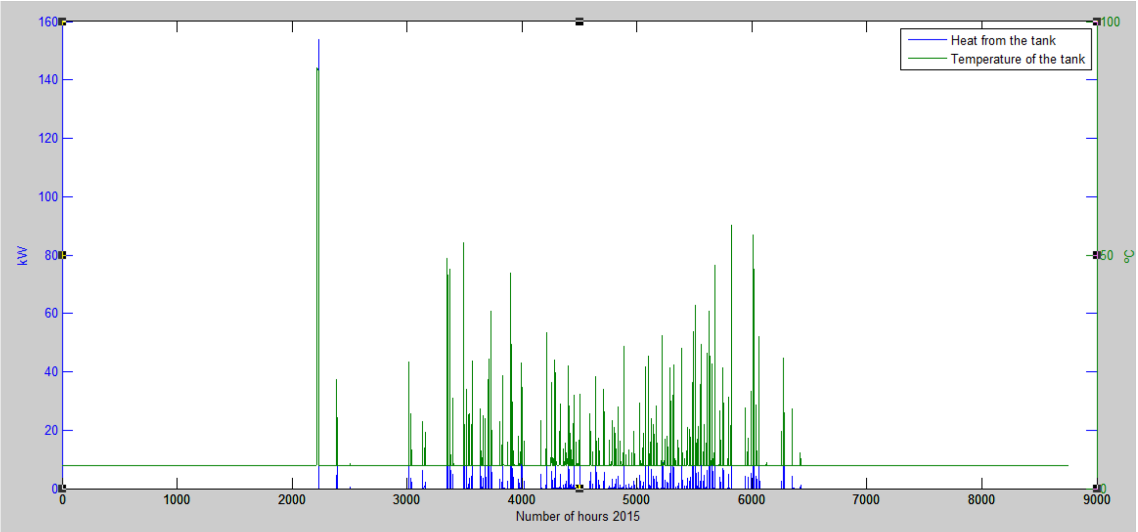

Figure 31: Annual temperature in the hot water accumulator for alternative system 3 for Sätra 2

The economic and environmental analysis for the second dwelling also provides negative results as it can be seen in Table 19.

Table 19: Self-consumption rate, economic and environmental impact for the alternative system 3 in Sätra 2

Sätra 2	Self-consumption rate[%]	Economic savings [SEK]	Environmental impact [CO_2 kg/year]
500 litre accumulator	100	-1630	-1210

5. Discussion

The validation of results has shown that the theoretical production of PVsyst in both dwellings is lower than the one measured in the real system, even though they do not differ a lot. But as it has been said, the location of the measured data and the meteorological data used in PVsyst are not the same. The tilt and the orientation at which the installation has been proposed is not also the same as the one in the real system, so the results can change. Normally, it is more logical to have a little bit higher results in PVsyst than in the reality, as it is presented in some papers [44], but in this case due to what it has been explained about the tilt and the orientation of the solar panels, the results can be valid.

Once the results have been obtained it can be made a comparison between the proposed systems. First of all, it can be concluded that the profitability of none of the systems in nowadays market exceeds 450SEK/year. On the contrary, the PV system without any storage system has annual earnings of 3164SEK for Sätra 1 and 8000 for Sätra 2. The main reason for this results can be attained to the price that it is being paid today for sold electricity. As it has been explained the subsidies that the Swedish government is giving are high and it results in a price for sold electricity of about 920SEK/MWh, which is near the price the consumers pay for electricity. So, if this analysis is done without the subsidies, which would be what it is expected to happen in a near future, the results will vary a lot. The systems will be more profitable with storage.

Moreover, it is expected also to decrease the price of batteries and PV systems. The price of PV system has been decreasing over an over during last years, so the decrease will make the analysis also more profitable with or without batteries.

As it has been proved, battery prices make the analysis to be less than what can be expected of any energy storage system. Batteries do not last so long, so the price per year that the system has to assume for their use is high. Although they are a good way to increase the self-consumption rate they do not provide enough savings unless the battery system size is low.

What it is not expected to change that much is the performance of PbA and LI-ion batteries. As it has been proved, it cannot bring out a clear conclusion of which gives the best results in this kind of dwellings. In each dwelling, to attain a certain self-consumption rate, it is better to use one different. The results of the comparison between the two types depends more in the electricity consumption of the buildings rather than in the performance of the batteries.

So, even tough now the battery analysis is not profitable comparing with the system without storage system, probably in the future it will be.

As for the cases where the hot water accumulator is involved,both of them are in the two dwellings less profitable, or not even profitable to install. The main reason for this is the low price of district heating in Sweden, which makes the accumulator not to be profitable to install. It has to be mentioned that the used accumulator is quite large for the heat consumption this buildings has, so if the volume will be decreased so will be the price of the system and then the profitability will be improved.

On the other hand, environmental evaluation has turned out negative. In all of the cases, as much as the consumption of district heating is decreased, higher is the increase of the kg of CO_2 that are sent to the atmosphere. This fact is due to the CHP electricity production declination. The electricity that is not produced by CHP has to be produced using not renewable energy resources that emit 480Kg CO_2/MWh to the environment, which is more than the fuels used in a CHP plant.

6. Conclusion

It has been proved in this thesis that nowadays it is not profitable in terms of money, and mostly for the environment, to install any storage system in a dwelling with the characteristics of the ones presented. DH and electricity prices are low enough for not making the system profitable. Although if the 3 systems are compared, the one in which the PV production is only used for covering heating demand is the one that provides the most negatives results. In the other 2, the economic results are positive but never better than only installing a PV system without storage.

Moreover, the only reason for which the system without storage system would be profitable today is for the subsidies that the government is giving. Without them, the system would provide, as proven, negatives results which would make the system to provide the owner loses of money every year.

As for the environment, PV systems are good because it is avoided the production of electricity using fuels that harm the environment. The only problem with PV electricity production comes when it is used to decrease the heat demand produced in a CHP plant, because the production of electricity in the plant is reduced. That means that the electricity has to be produced in other plants using probably fuels that cause detriment of the atmosphere.

So as a conclusion, it can be said which changes in the conditions assumed in the analysis would make the storage systems profitable:

- Increase of DH price
- Increase of the Electricity price
- Increase of the Spot price of electricity and governmental subsidies
- Decrease of the yearly prices of the components of the PV system and storage, which means an increase of life expectancy or a decrease of their prices.

On the other side, it has to be mentioned that the analysis of PV system although it does not take into account some important factors as snow, dust, etc., it provides a good approximation to the reality if it is compared with the measures that have been used in the simulation of the 3 alternative systems.

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Appendix I

- Sätra 1 PVsyst analysis: panels in the roof 10°
- Sätra 1 PVsyst analysis: panels in the roof 90°
- Sätra 2 PVsyst analysis: panels in the roof 10°

PVSYST V5.74		18/05/16	Page 1/4

Grid-Connected System: Simulation parameters

Project :	**Dwelling 1**			
Geographical Site	**Gävle**		**Country**	**Sweden**
Situation	Latitude	60.7°N	Longitude	17.2°E
Time defined as	Legal Time	Time zone UT+1	Altitude	8 m
	Albedo	0.20		
Meteo data :	Dwelling 2			

Simulation variant :	**New simulation variant**			
	Simulation date	18/05/16 17h29		

Simulation parameters

Collector Plane Orientation	Tilt	10°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	Linear shadings			

PV Array Characteristics

PV module Si-mono	Model	**96M-420**		
	Manufacturer	Helios Energy Europe		
Number of PV modules	In series	8 modules	In parallel	4 strings
Total number of PV modules	Nb. modules	32	Unit Nom. Power	420 Wp
Array global power	Nominal (STC)	**13.44 kWp**	At operating cond.	11.94 kWp (50°C)
Array operating characteristics (50°C)	U mpp	355 V	I mpp	34 A
Total area	Module area	**82.8 m²**	Cell area	73.4 m²
Inverter	Model	**Sunny Boy SB 2800i**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	224-480 V	Unit Nom. Power	2.60 kW AC
Inverter pack	Number of Inverter	4 units	Total Power	10.40 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	180 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

PVSYST V5.74		18/05/16	Page 2/4

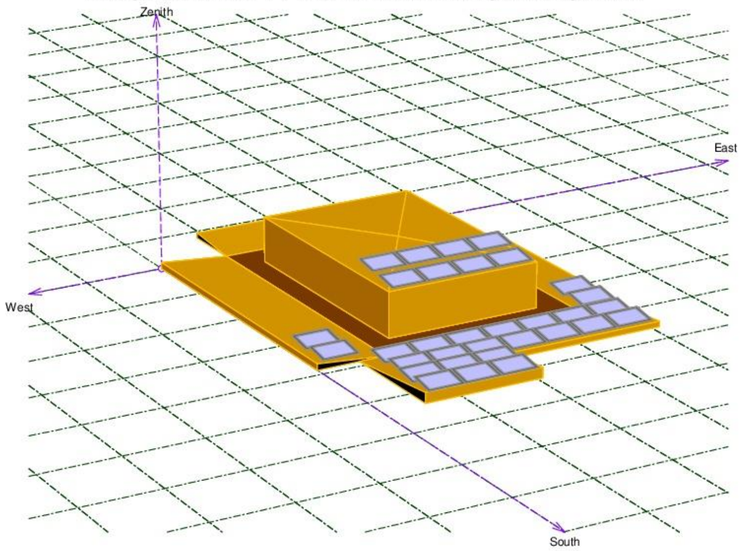
Grid-Connected System: Near shading definition

Project : **Dwelling 1**

Simulation variant : **New simulation variant**

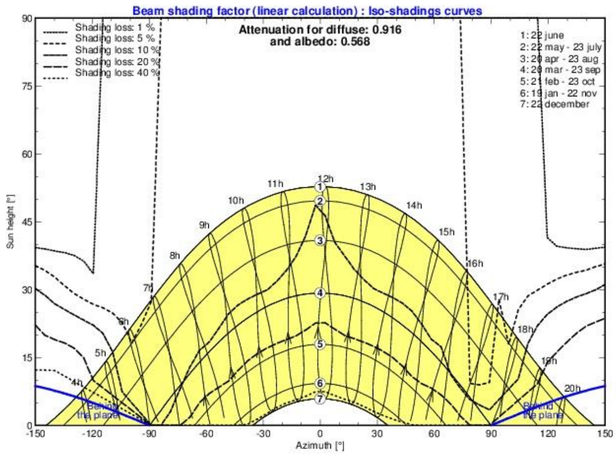
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	32	Pnom total	**13.44 kWp**
Inverter	Model	Sunny Boy SB 2800i	Pnom	2600 W ac
Inverter pack	Nb. of units	4.0	Pnom total	**10.40 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Dwelling 1: Dwelling 1



PVSYST V5.74		18/05/16	Page 3/4

Grid-Connected System: Main results

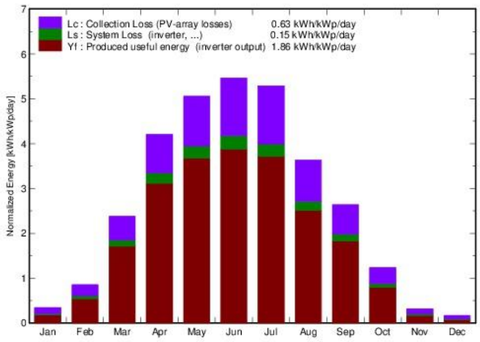
Project : **Dwelling 1**

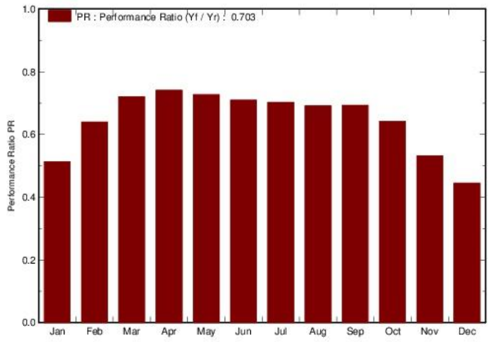
Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	32	Pnom total	**13.44 kWp**
Inverter	Model	Sunny Boy SB 2800i	Pnom	2600 W ac
Inverter pack	Nb. of units	4.0	Pnom total	**10.40 kW ac**
User's needs	Unlimited load (grid)			

Main simulation results

System Production	**Produced Energy**	**9.11 MWh/year**	Specific prod.	678 kWh/kWp/year
	Performance Ratio PR	70.3 %		





New simulation variant

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	7.4	-2.59	10.8	7.9	0.089	0.075	9.93	8.33
February	19.5	-3.04	23.9	19.2	0.231	0.205	11.68	10.38
March	62.5	-0.79	73.7	61.9	0.772	0.714	12.64	11.69
April	115.2	4.61	126.2	110.5	1.350	1.257	12.92	12.03
May	150.2	9.88	156.7	138.4	1.646	1.531	12.68	11.80
June	159.8	13.78	163.9	145.4	1.685	1.564	12.41	11.52
July	159.9	16.75	163.9	144.8	1.664	1.547	12.26	11.40
August	105.6	15.82	112.6	98.8	1.131	1.047	12.14	11.23
September	69.8	11.05	79.2	68.3	0.801	0.738	12.20	11.25
October	31.2	5.85	38.3	30.9	0.367	0.331	11.54	10.43
November	7.9	1.85	9.5	7.6	0.084	0.068	10.59	8.63
December	3.7	-1.31	5.2	3.9	0.040	0.031	9.35	7.23
Year	892.7	6.04	963.8	837.4	9.859	9.109	12.35	11.41

Legends:				
GlobHor	Horizontal global irradiation		EArray	Effective energy at the output of the array
T Amb	Ambient Temperature		E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane		EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings		EffSysR	Effic. Eout system / rough area

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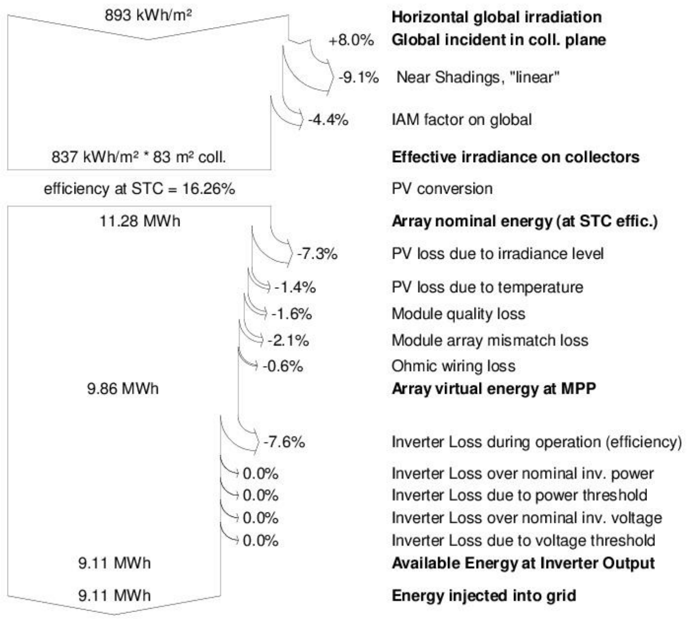
Grid-Connected System: Loss diagram

Project : **Dwelling 1**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	32	Pnom total	**13.44 kWp**
Inverter	Model	Sunny Boy SB 2800i	Pnom	2600 W ac
Inverter pack	Nb. of units	4.0	Pnom total	**10.40 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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Grid-Connected System: Simulation parameters

Project :	**Dwelling 1**			
Geographical Site	**Gävle**		**Country**	**Sweden**
Situation	Latitude	60.7°N	Longitude	17.2°E
Time defined as	Legal Time	Time zone UT+1	Altitude	8 m
	Albedo	0.20		
Meteo data :	Dwelling 1			

Simulation variant :	**New simulation variant**			
	Simulation date	18/05/16 17h35		

Simulation parameters

Collector Plane Orientation		Tilt	90°	Azimuth	0°
Horizon		Free Horizon			
Near Shadings		Linear shadings			

PV Array Characteristics

PV module	Si-mono	Model	**96M-420**		
		Manufacturer	Helios Energy Europe		
Number of PV modules		In series	4 modules	In parallel	1 strings
Total number of PV modules		Nb. modules	4	Unit Nom. Power	420 Wp
Array global power		Nominal (STC)	**1680 Wp**	At operating cond.	1492 Wp (50°C)
Array operating characteristics (50°C)		U mpp	177 V	I mpp	8.4 A
Total area		Module area	**10.4 m²**	Cell area	9.2 m²
Inverter		Model	**Sunny Boy SB 1700**		
		Manufacturer	SMA		
Characteristics		Operating Voltage	139-320 V	Unit Nom. Power	1.55 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	360 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

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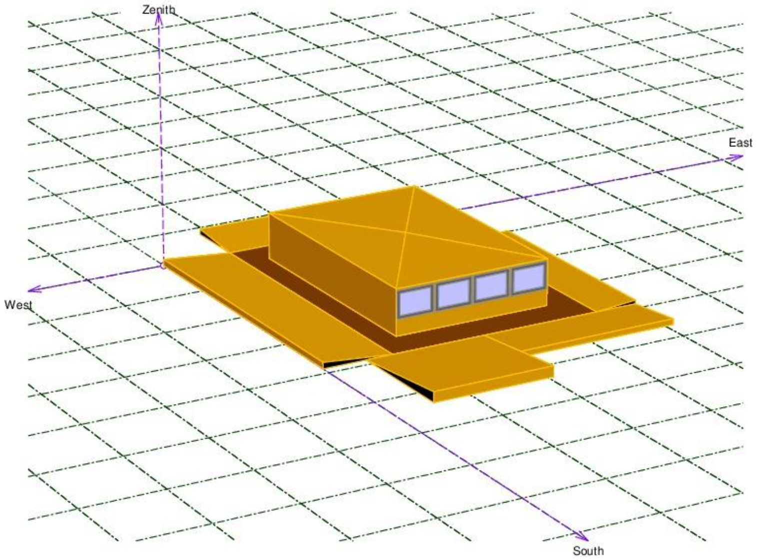
Grid-Connected System: Near shading definition

Project : **Dwelling 1**

Simulation variant : **New simulation variant**

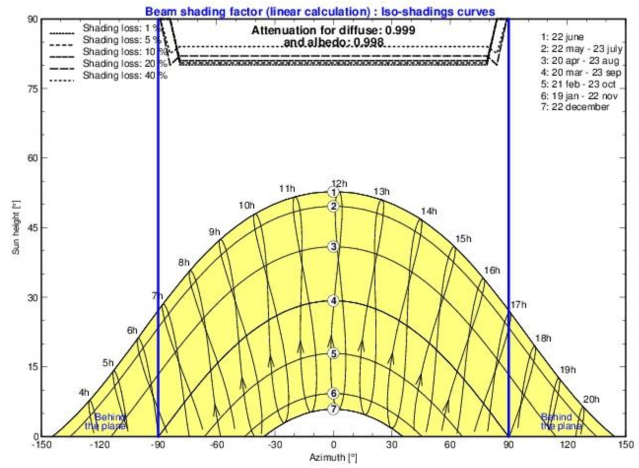
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	90°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	4	Pnom total	**1680 Wp**
Inverter	Model	Sunny Boy SB 1700	Pnom	1550 W ac
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Dwelling 1: Dwelling 1-90



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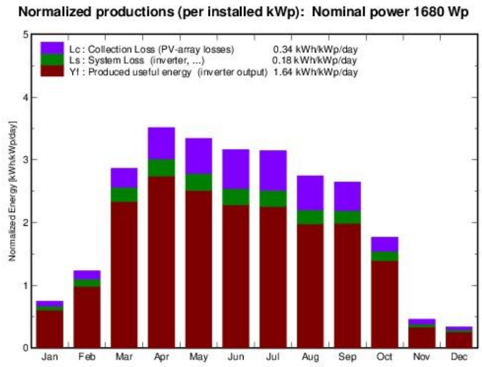
Grid-Connected System: Main results

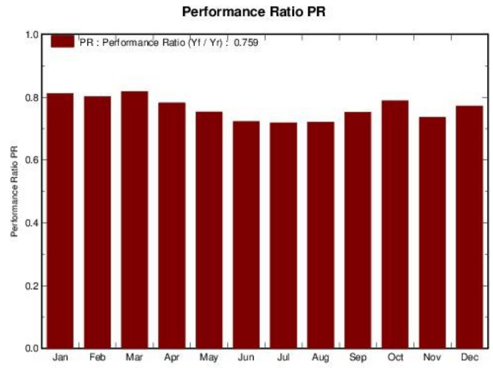
Project : **Dwelling 1**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	90°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	4	Pnom total	**1680 Wp**
Inverter	Model	Sunny Boy SB 1700	Pnom	1550 W ac
User's needs	Unlimited load (grid)			

Main simulation results				
System Production	**Produced Energy**	**1008 kWh/year**	Specific prod.	600 kWh/kWp/year
	Performance Ratio PR	75.9 %		





New simulation variant

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	kWh	kWh	%	%
January	7.4	-2.59	23.2	22.8	35.0	31.6	14.60	13.17
February	19.5	-3.04	34.4	33.6	51.8	46.4	14.53	13.01
March	62.5	-0.79	88.6	85.6	133.7	121.8	14.57	13.27
April	115.2	4.61	105.4	100.4	152.0	138.3	13.93	12.68
May	150.2	9.88	103.5	98.1	144.9	130.8	13.53	12.21
June	159.8	13.78	94.8	89.0	128.2	115.1	13.06	11.72
July	159.9	16.75	97.5	91.8	131.0	117.6	12.98	11.65
August	105.6	15.82	85.1	81.1	114.7	103.0	13.02	11.69
September	69.8	11.05	79.3	76.1	110.6	100.2	13.46	12.20
October	31.2	5.85	54.8	53.4	80.3	72.6	14.16	12.80
November	7.9	1.85	13.6	13.3	19.5	16.9	13.79	11.94
December	3.7	-1.31	10.4	10.2	15.2	13.5	14.18	12.53
Year	892.7	6.04	790.6	755.5	1116.9	1007.7	13.64	12.31

Legends:			
GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
T Amb	Ambient Temperature	E_Grid	Energy injected into grid
GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

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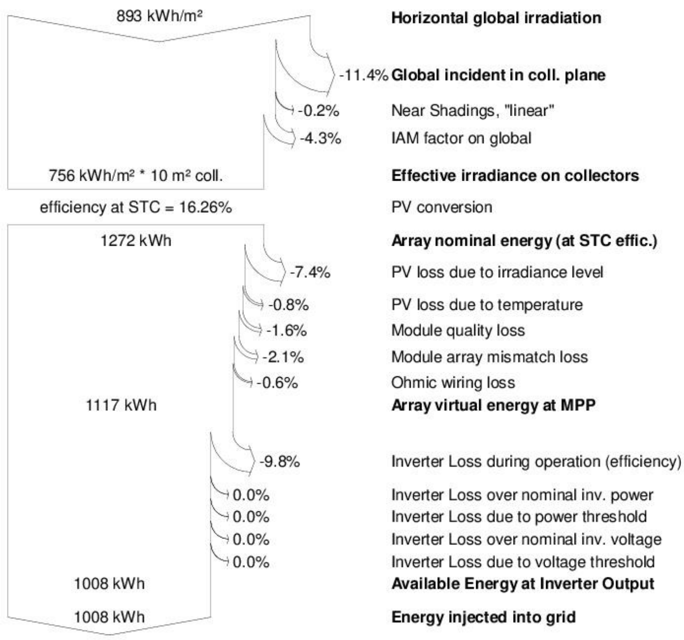
Grid-Connected System: Loss diagram

Project : **Dwelling 1**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	90°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	4	Pnom total	**1680 Wp**
Inverter	Model	Sunny Boy SB 1700	Pnom	1550 W ac
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



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Grid-Connected System: Simulation parameters

Project :	**Dwelling 2**			
Geographical Site	**Gävle**		**Country**	**Sweden**
Situation	Latitude	60.7°N	Longitude	17.2°E
Time defined as	Legal Time	Time zone UT+1	Altitude	8 m
	Albedo	0.20		
Meteo data :	Dwelling 2			

Simulation variant :	**New simulation variant**			
	Simulation date	18/05/16 17h15		

Simulation parameters

Collector Plane Orientation	Tilt	10°	Azimuth	0°
Horizon	Free Horizon			
Near Shadings	Linear shadings			

PV Array Characteristics

PV module Si-mono	Model	**96M-420**		
	Manufacturer	Helios Energy Europe		
Number of PV modules	In series	10 modules	In parallel	8 strings
Total number of PV modules	Nb. modules	80	Unit Nom. Power	420 Wp
Array global power	Nominal (STC)	**33.6 kWp**	At operating cond.	29.84 kWp (50°C)
Array operating characteristics (50°C)	U mpp	443 V	I mpp	67 A
Total area	Module area	**207 m²**	Cell area	184 m²

Inverter	Model	**Sunny Boy SB 4200 TL HC**		
	Manufacturer	SMA		
Characteristics	Operating Voltage	125-600 V	Unit Nom. Power	4.00 kW AC
Inverter pack	Number of Inverter	8 units	Total Power	32.00 kW AC

PV Array loss factors

Thermal Loss factor	Uc (const)	20.0 W/m²K	Uv (wind)	0.0 W/m²K / m/s
=> Nominal Oper. Coll. Temp. (G=800 W/m², Tamb=20°C, Wind=1 m/s.)			NOCT	56 °C
Wiring Ohmic Loss	Global array res.	112 mOhm	Loss Fraction	1.5 % at STC
Module Quality Loss			Loss Fraction	1.5 %
Module Mismatch Losses			Loss Fraction	2.0 % at MPP
Incidence effect, ASHRAE parametrization	IAM =	1 - bo (1/cos i - 1)	bo Parameter	0.05

User's needs : Unlimited load (grid)

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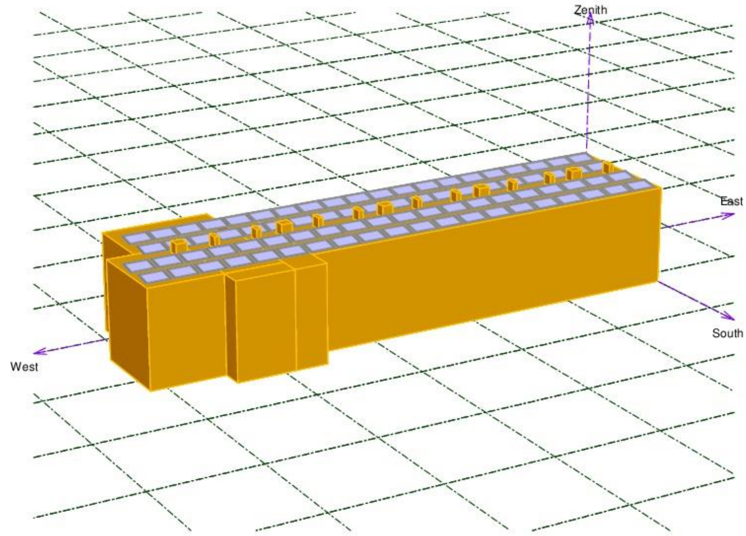
Grid-Connected System: Near shading definition

Project : **Dwelling 2**

Simulation variant : **New simulation variant**

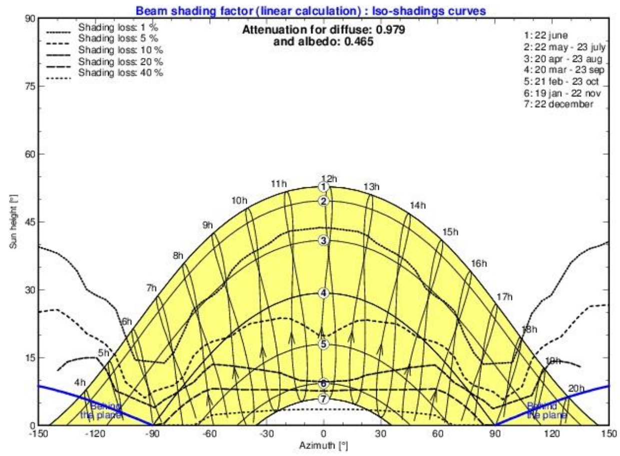
Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	80	Pnom total	**33.6 kWp**
Inverter	Model	Sunny Boy SB 4200 TL HC	Pnom	4000 W ac
Inverter pack	Nb. of units	8.0	Pnom total	**32.0 kW ac**
User's needs	Unlimited load (grid)			

Perspective of the PV-field and surrounding shading scene



Iso-shadings diagram

Dwelling 2: Dwelling 2



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Grid-Connected System: Main results

Project : **Dwelling 2**

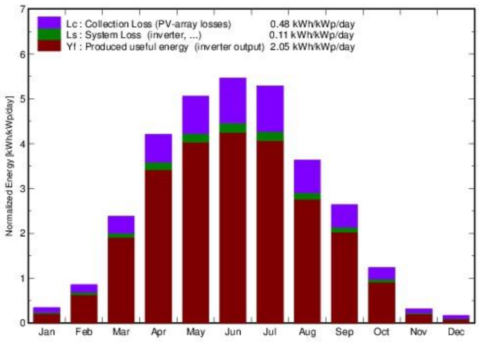
Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	80	Pnom total	**33.6 kWp**
Inverter	Model	Sunny Boy SB 4200 TL HC	Pnom	4000 W ac
Inverter pack	Nb. of units	8.0	Pnom total	**32.0 kW ac**
User's needs	Unlimited load (grid)			

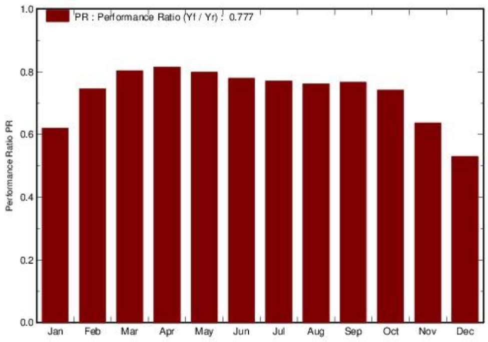
Main simulation results

System Production	**Produced Energy**	**25.16 MWh/year**	Specific prod.	749 kWh/kWp/year
	Performance Ratio PR	77.7 %		

Normalized productions (per installed kWp): Nominal power 33.6 kWp



Performance Ratio PR



New simulation variant

Balances and main results

	GlobHor	T Amb	GlobInc	GlobEff	EArray	E_Grid	EffArrR	EffSysR
	kWh/m²	°C	kWh/m²	kWh/m²	MWh	MWh	%	%
January	7.4	-2.59	10.8	8.8	0.253	0.225	11.30	10.05
February	19.5	-3.04	23.9	21.3	0.646	0.598	13.06	12.09
March	62.5	-0.79	73.7	67.1	2.095	1.990	13.72	13.03
April	115.2	4.61	126.2	118.6	3.617	3.453	13.84	13.22
May	150.2	9.88	156.7	148.3	4.403	4.202	13.57	12.95
June	159.8	13.78	163.9	155.7	4.498	4.287	13.25	12.63
July	159.9	16.75	163.9	155.0	4.446	4.240	13.10	12.49
August	105.6	15.82	112.6	105.9	3.029	2.879	13.00	12.35
September	69.8	11.05	79.2	73.4	2.152	2.040	13.12	12.44
October	31.2	5.85	38.3	34.2	1.020	0.954	12.84	12.02
November	7.9	1.85	9.5	8.4	0.235	0.204	11.88	10.33
December	3.7	-1.31	5.2	4.2	0.110	0.092	10.31	8.60
Year	892.7	6.04	963.8	900.9	26.504	25.164	13.28	12.61

Legends:				
	GlobHor	Horizontal global irradiation	EArray	Effective energy at the output of the array
	T Amb	Ambient Temperature	E_Grid	Energy injected into grid
	GlobInc	Global incident in coll. plane	EffArrR	Effic. Eout array / rough area
	GlobEff	Effective Global, corr. for IAM and shadings	EffSysR	Effic. Eout system / rough area

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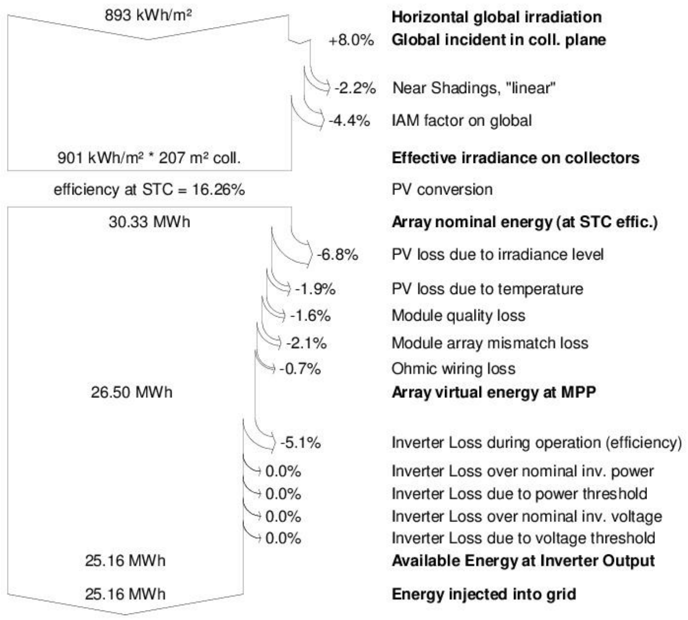
Grid-Connected System: Loss diagram

Project : **Dwelling 2**

Simulation variant : **New simulation variant**

Main system parameters	System type	**Grid-Connected**		
Near Shadings	Linear shadings			
PV Field Orientation	tilt	10°	azimuth	0°
PV modules	Model	96M-420	Pnom	420 Wp
PV Array	Nb. of modules	80	Pnom total	**33.6 kWp**
Inverter	Model	Sunny Boy SB 4200 TL HC	Pnom	4000 W ac
Inverter pack	Nb. of units	8.0	Pnom total	**32.0 kW ac**
User's needs	Unlimited load (grid)			

Loss diagram over the whole year



Appendix II

Alternative system 1

```
%% Battery and solar production calculation Jokelvagen with Pb battery
system
home
clear all
close all

%DATA
load('Jokelvagen2015.mat') %Grastenvagen2015  %Energy(kWh)
load('use.mat')
load('a2014.mat')

%Generation Bjorn House kW(1 hour)
Load=zeros(8760,1);
h=0;
for i=1:8760
    if i<7213
        Load(i)=use(length(use)-i+1);
    end
    if i>=7213
        Load(i)=a2014(length(a2014)-h);
        h=h+1;
    end
end

%Battery size
C_Pb=20; %AH
Voltage_Pb=24;%V
Battery_sizePb=0;%Energy(kWh)


%CONSTANTS PbA
state_charge_range_Pb=0.5;
Maximum_state_charge_Pb=0.9;
Minimum_state_charge_Pb=0.4;
Maximum_current_charge_Pb=0.2*Battery_sizePb;%A
Maximum_current_discharge_Pb=0.4*Battery_sizePb;%A

%Solar production
Solar_production=zeros(length(Jokelvagen2015),1);
Production_house=zeros(length(Jokelvagen2015),1);

for i=1:length(Load)
    Production_house(i)=Load(i);
end

for i=1:length(Jokelvagen2015)
    if Production_house(i)<0
        Solar_production(i)=0;
    end
    if Production_house(i)>0
    Solar_production(i)=Production_house(i)*6;
    end
end

%Battery evolution
```

```
Battery_state=zeros(length(Jokelvagen2015),1);
Battery_state(1)=0;
Energy_Battery=zeros(length(Jokelvagen2015),1);
Energy_Battery(1)=0;
Grid_buy=zeros(length(Jokelvagen2015),1);
Grid_buy(1)=0;
Grid_sell=zeros(length(Jokelvagen2015),1);
Grid_sell(1)=0;
Difference=zeros(length(Jokelvagen2015),1);
Difference(1)=0;
Difference_current=zeros(length(Jokelvagen2015),1);
Difference_current(1)=0;
Current_Pb=zeros(length(Jokelvagen2015),1);
Current_Pb(1)=0;
Battery_SOC=zeros(length(Jokelvagen2015),1);
Battery_SOC(1)=0;

for i=2:length(Jokelvagen2015)
    Energy_Battery(i)=Solar_production(i)-Jokelvagen2015(i);
    Battery_state(i)=Battery_state(i-1)+Energy_Battery(i); %kWh
    Grid_sell(i)=0;
    Grid_buy(i)=0;
    Difference(i)=0;

   %Current control
    if Energy_Battery(i)>0 %Charge
        Current_Pb(i)=Energy_Battery(i)/Voltage_Pb;
        if Current_Pb(i)>Maximum_current_charge_Pb
           Difference_current(i)=Energy_Battery(i);
           Energy_Battery(i)=Maximum_current_charge_Pb*Voltage_Pb;
           Battery_state(i)=Battery_state(i-1)+Energy_Battery(i);
           Grid_sell(i)=Difference_current(i)-Energy_Battery(i);
        end
        if (Battery_state(i)/(Battery_sizePb))>Maximum_state_charge_Pb
        Difference(i)=Energy_Battery(i);
        Battery_state(i)=Battery_sizePb*Maximum_state_charge_Pb;
        Energy_Battery(i)=Battery_state(i)-Battery_state(i-1);
        Grid_sell(i)=Grid_sell(i)+Difference(i)-Energy_Battery(i);
        end
    end
    if Energy_Battery(i)<0 %Discharge
        Current_Pb(i)=(-Energy_Battery(i))/Voltage_Pb;
        if Current_Pb(i)>Maximum_current_discharge_Pb
          Difference_current(i)=Energy_Battery(i);
           Energy_Battery(i)=(-Maximum_current_discharge_Pb)*Voltage_Pb;
           Battery_state(i)=Battery_state(i-1)+Energy_Battery(i);
          Grid_buy(i)=Energy_Battery(i)-Difference_current(i);
        end
        if (Battery_state(i)/Battery_sizePb)<Minimum_state_charge_Pb
        Difference(i)=Energy_Battery(i);
        Battery_state(i)=Battery_sizePb*Minimum_state_charge_Pb;
        Energy_Battery(i)=Battery_state(i)-Battery_state(i-1);
        Grid_buy(i)=Grid_buy(i)+Energy_Battery(i)-Difference(i);
        end
    end
    Battery_SOC(i)=(Battery_state(i)/Battery_sizePb)*100;
end

Self_consumption_Pb=1-(sum(Grid_sell)/(sum(Solar_production)))

figure
```

```
plot(Jokelvagen2015(:))
hold on
plot(Solar_production(:),'black')
%plot(Battery_state(:),'r')
plot(Energy_Battery(:),'r')
plot(Grid_buy(:),'g')
plot(Grid_sell(:),'y')
legend('Dwelling load','Solar production','Energy battery','Grid buy
electricity','Grid sell electricity')
xlabel('Number of hours 2015')
ylabel('kW')

figure
plot(Battery_SOC)
figure
plot(Battery_state)
%% Desfase energergetico(SOC)
Energy_change=zeros(length(Jokelvagen2015),1);

for i=1:(length(Jokelvagen2015))
        Energy_change(i)=Battery_SOC(i);
end
%% Vida util baterías

%Cálculo ciclos de baterías

ciclos2=0;
maximos2=min(Energy_change(:));


for i=2:(length(Energy_change)-1)
    rampa=Energy_change(i-1)-Energy_change(i);
    rampa1=Energy_change(i)-Energy_change(i+1);
    if rampa>0
        if rampa1<0
            ciclos2=ciclos2+1;
            maximos2(end+1)=Energy_change(i);
        end
        if rampa1==0
            ciclos2=ciclos2+1;
            maximos2(end+1)=Energy_change(i);
        end
    end

end


%Histrogramas de ciclos de baterías
x=1:1:100;
num=hist(maximos2,x);
figure
hist(maximos2,x)
hold on
xlabel('% DoD')
ylabel('Number of cycles')

years=1500/ciclos2;

%% Prices
```

```
%Batteryprice=11.77*140*Battery_sizePb;
Electricityprice=(1*sum(Jokelvagen2015));     %SEK/MWh
%Discount1=0.6*sum(Grid_sell);
%Discount2=200*sum(Grid_sell)/1000;
%Discount3=0.05*sum(Grid_sell);
PVsystem=15*6*2.6*1000; %SEK


Instalation=(PVsystem/25)-(sum(Grid_sell)*0.27496)+(sum(Grid_buy)*1);
Total1=Electricityprice;
Profitability=Total1-Instalation
```

Alternative system 2 and 3

```
%% Battery and solar production calculation Jokelvagen with Pb battery
system
home
clear all
close all

%DATA
load('Jokelvagen2015.mat')  %Jokelvagen2015 %Energy(kWh)
load('use.mat')
load('a2014.mat')
load('HeatJokelvagen2015.mat')

%Generation Bjorn House kW(1 hour)
Load=zeros(8760,1);
h=0;
for i=1:8760
    if i<7213
        Load(i)=use(length(use)-i+1);
    end
    if i>=7213
        Load(i)=a2014(length(a2014)-h);
        h=h+1;
    end
end

%Solar production
Solar_production=zeros(length(Jokelvagen2015),1);
Production_house=zeros(length(Jokelvagen2015),1);

for i=1:length(Load)
    Production_house(i)=Load(i);
end

for i=1:length(Jokelvagen2015)
    if Production_house(i)<0
        Solar_production(i)=0;
    end
    if Production_house(i)>0
    Solar_production(i)=Production_house(i)*6;
    end
end
```

```
%Battery evolution
Grid_buy_electricity=zeros(length(Jokelvagen2015),1);
Grid_buy_electricity(1)=0;
Grid_sell=zeros(length(Jokelvagen2015),1);
Grid_sell(1)=0;
Electricitytotank=zeros(length(Jokelvagen2015),1);
Electricitytotank(i)=0;

for i=2:length(Jokelvagen2015)
    Grid_sell(i)=Solar_production(i)-Jokelvagen2015(i);
    if Grid_sell(i)>0
       Grid_buy_electricity(i)=0;
    end
    if Grid_sell(i)<0
       Grid_buy_electricity(i)=-Grid_sell(i);
       Grid_sell(i)=0;
    end
    Electricitytotank(i)=Grid_sell(i);
end

Self_consumption=1-(sum(Grid_sell(:,1))/(sum(Solar_production(:,1))))



%% Modeling the hot water tank

Tmin=5; %K
Tmax=90; %K
Tsurr=20; %K
Tout=65;
Cp=1.16; %4.1813; %kJ/kgK
U=0.33; %W/m2K
V=500; %litre o m3
r=0.67/2; %m
Vm3=V*0.001; %m3
h=Vm3/(pi()*(r^2))
A=(2*pi()*(r^2))+(2*pi()*r*h);

Ttank=zeros(length(HeatJokelvagen2015),1);
Ttank(1)=5;
Q_loss=zeros(length(HeatJokelvagen2015),1);%the same as the one in the
tank %K
Q_loss(1)=0;
m=zeros(length(HeatJokelvagen2015),1);
m(1)=0;
massflowhouse=zeros(length(HeatJokelvagen2015),1);
massflowhouse(i)=0;
QPv=zeros(length(HeatJokelvagen2015),1);
QPv(i)=0;
QTank=zeros(length(HeatJokelvagen2015),1);
QTank(i)=0;
QDH=zeros(length(HeatJokelvagen2015),1);
QDH(i)=0;
QexcessTank=zeros(length(HeatJokelvagen2015),1);
QexcessTank(i)=0;


for i=2:8760
    HeatJokelvagen2015(i)=HeatJokelvagen2015(i)*1000; %kWh
    massflowhouse(i)=(HeatJokelvagen2015(i)/(Cp*(Tout-Tmin)));
```

```
    QPv(i)=Grid_sell(i);
    Q_loss(i)=U*A*(Ttank(i-1)-Tsurr)/1000;
    if Ttank(i-1)<Tsurr
        Q_loss(i)=0;
    end
    if Ttank(i-1)>Tmin
        QTank(i)=(Ttank(i-1)-Tmin)*massflowhouse(i)*Cp;
    end
    if Ttank(i-1)==Tmin
        QTank(i)=0;
    end
    QDH(i)=HeatJokelvagen2015(i)-QPv(i)-QTank(i);
    if  QDH(i)<0
        QexcessTank(i)=-QDH(i);
        QDH(i)=0;
    end
    if QDH(i)>0
        QexcessTank(i)=0;
        Grid_sell(i)=0;
    end

    if QexcessTank(i)==0
        Ttank(i)=Ttank(i-1)-(Q_loss(i)*1000/(V*Cp))-
(QTank(i)*1000/(V*Cp));
    end
    if QexcessTank(i)>0
        Ttank(i)=Ttank(i-1)-
(Q_loss(i)*1000/(V*Cp))+(QexcessTank(i)*1000/(V*Cp))-
(QTank(i)*1000/(V*Cp));
        Grid_sell(i)=0;
    end
    if Ttank(i)>Tmax
        Grid_sell(i)=massflowhouse(i)*(Ttank(i)-Tmax)*Cp;
        Ttank(i)=Tmax;
        QTank(i)=massflowhouse(i)*(Tmax-Ttank(i-1))*Cp;
    end
    if Ttank(i)<Tmin
        Grid_sell(i)=0;
        QDH(i)=QDH(i)+(massflowhouse(i)*(Tmin-Ttank(i))*Cp);
        Ttank(i)=Tmin;
        QTank(i)=massflowhouse(i)*(Ttank(i-1)-Tmin)*Cp;
    end

 end

Self_consumptionTank=1-(sum(Grid_sell(:,1))/(sum(Solar_production(:,1))))
figure
plot(QTank(:,1))
hold on
plot(HeatJokelvagen2015(:,1),'r')
plot(QDH(:),'black')
plot(Electricitytotank(:),'y')
legend('Heat from the tank','Heat demand','District heating','Electricity
to the tank')
xlabel('Number of hours 2015')
ylabel('kW')

w=1:8760;
figure
[ax, h1, h2]=plotyy(w, QTank, w, Ttank)
legend('Heat from the tank','Temperature of the tank')
```

```
xlabel('Number of hours 2015')
set(get(ax(1),'Ylabel'),'String','kW')
set(get(ax(2),'Ylabel'),'String','°C')

figure
plot(Jokelvagen2015(:))
hold on
plot(Solar_production(:,1),'black')
plot(Grid_buy_electricity(:,1),'g')
plot(Grid_sell(:,1),'y')
legend('Dwelling load','Solar production','Grid buy electricity','Grid
sell electricity')
xlabel('Number of hours 2015')
ylabel('kW')


%% Prices

Electricityprice=(1*sum(Jokelvagen2015));    %SEK/MWh
Discount1=0.6*sum(Electricitytotank);
Discount2=200*sum(Electricitytotank)/1000;
Discount3=0.05*sum(Electricitytotank);
PVsystem=15*6*2.6*1000; %SEK
%Tankprice=28200;

%Tankprice=39000
%Tankprice=51250
years=25;
Districtheatingprice=0.77*sum(HeatJokelvagen2015);

Instalation=(PVsystem/25)-(sum(Electricitytotank)*0.27496)-Discount1-
Discount2-Discount3+(sum(Grid_buy_electricity)*1);
%(Tankprice/years)%(%(sum(QDH)*0.77)
Total1=Electricityprice; % +Districtheatingprice;
Profitability=Total1-Instalation
```