UNIVERSITETET I AGDER

Analysis of Electrical Loads and Strategies for Increasing Self-Consumption with BIPV

Case study : Skarpnes Zero-Energy House

by

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This Master's Thesis is carried out as part of the education at the University of Agder and is therefore approved as a part of this education. However, this does not imply that the University answers for the methods that are used or conclusions drawn.

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Abstract

At Skarpnes village (Southern Norway), the houses as zero energy buildings (ZEB) are installed with Building Integrated Photovoltaic (BIPV) systems, and these houses are not containing smart control of equipments. The aim of such buildings is that the amount of electrical energy produced is the same as that consumed in the buildings on an annual basis. In this thesis, the main objective is to analyse the methods for increasing self -consumption in BIPV, by minimizing the cost of purchasing electricity from the grid at time with no PV production, and maximizing the utilization of solar PV generated power, which reduces the power sold back to the grid. To achieve this, two methods for increasing self-consumption, namely demand side management (DSM) and energy storage using domestic hot water (DHW) tank were analyzed. Maximizing self-consumption of residential PV systems is profitable, because the sale cost of exported power to the grid is lower than that of importing power from the grid. To achieve high self- consumption, shiftable loads (e.g. heat pump) are controlled so that solar PV energy utilization especially at time with high solar irradiation can be maximized. The results show that, load shifting play an important role in minimizing the cost of imported energy, for example in May, by storing the excess PV production through DHW tank to be used in the evening or morning the following day. By considrering some selected clear days in six months, this excess PV energy boosted water from 40 ^{0} C to 90 ^{o} C, (corresponding to the set limits for minimum and maximum temperature) without assistance from the grid distribution network. Supply and demand cover factors were used to determine when the loads in houses are covered by PV production or not. Based on the available dataset, it has been found that in December 2015 and May 2016, 3.3 % and 56.7 % of demand respectively is covered by solar PV. Loss of load probability (LOLP) is used to analyze the time where load demand is not covered by PV production at desired reliability level. The results of this research are important in implementation of DSM techniques for economic analysis in BIPV systems. Also, the use of excess PV energy storage through DHW tank minimizes the energy exchange between BIPV and the grid. The results of this thesis will contribute further to the investigation of self- consumption analysis in the BIPV systems, by maximizing energy utilization in the BIPV systems.

Keywords: *BIPV, PV production, electric loads, self-consumption, cover factors, Load-shifting, heat pump, domestic hot water storage.*

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LIST OF ABBREVIATIONS

BIPV: Building-integrated photovoltaics

CP: Circulation pump

COP: Coefficient of performance

DLC: Direct load control

DSM: Demand side management

HP: Heat pump

HVAC: heating, ventilation and air-conditioning

ILC: Indirect load control

LOLP: Loss of load probability

nZEB: Nearly (Net) zero energy building

PV: Photovoltaic

RCN: Research Council of Norway

SC: Self- consumption

γD: Demand cover factor

γS: Supply cover factor

Chapter 1. INTRODUCTION

This chapter gives the reader a fundamental understanding of the background and motivation for the thesis, problem statement, objectives of thesis and thesis outline. The key assumptions and limitations are also highlighted.

1.1. Background and Motivation

Nowadays, domestic appliances are some of the modern electrical loads without which life cannot be imagined. With continuous increase in electrical loads, peak power demand has caused undesirable effects to the reliability and stability of an electric power system during the past few decades. The increase in peak demands has also put the transmission and distribution network lines on risk of failure and outages due to excessive stress caused by overloading. Electrical energy cannot be stored cheaply in great quantities. Therefore, supply and demand must be balanced simultaneously. To ensure sustainability of power supply with grid- connected system, demand side management (DSM) techniques provide a variety of measures to reduce energy consumption from the grid and maximize the on-site energy generation, which leads to more manageable demand [1]. DSM is an important in smart grid with nZEB that allows consumers to make decisions regarding energy consumption, and helps energy users to shape the load profile and to reduce peak load demand [2], this also results in cost saving for building owner [3].

At Skarpnes Zero Energy Village (Skarpnes Boligfelt) outside Arendal, Skanska has built five 'near-zero energy buildings'(nZEB), i.e. houses that are equipped with PV systems on the roof and modern equipment for heating and ventilation, to enable an annual zero energy budget. These five houses have also been equipped with instrumentation to closely monitor the electrical energy production and consumption in the households, as well as other parameters related to indoor climate and efficient energy control. The village is the basis for several research projects, including "Electricity Usage in Smart Village Skarpnes" which is funded by the Research Council of Norway (RCN) and run by the local utility owner Agder Energi Nett in collaboration with the University of Agder, the research institute Teknova and the power electronics and conversion company Eltek. The main goal of the RCN project at Skarpnes village is to investigate the characteristics and influence of power peaks of the electrical loads and how these may be mitigated to reduce the demands on the grid and maintain always high power quality. A sub-goal is to investigate the characteristics of PV production and how it influences the power exchange with the grid. It is very important to analyze the solar PV in grid- connected systems and its applications for an optimal economical and energetic operations, like Skarpnes zero energy village, where nZEB concept must be achieved. This is achieved with the increase in self- consumption of on-site solar PV production. Load shifting is widely applied as the most effective load management technique. It takes advantage of time independence of loads and shifts the high load energy consumption from period without PV production to the period with available PV production.

Technical appliances with a high consumption of electrical energy and an independent use regarding time could be integrated into a DSM system with load shifting for having a good plane of HP demand. The customer's acceptance is an important factor since he must agree to a shift of his electrical devices if there is no lack of comfort [4]. Therefore, load shift (e.g. heat pump) must match with customer heat demand sufficiency all times, which is accomplished with help of domestic heat water storage for delivering heat at the time HP is shifted at high PV production.

1.2. Problem statement

PV energy production depends on the periods of the year and the hours of the day. Domestic loads vary with time of use during the day, where during the morning and evening the power consumption increases with no much PV power production. High power demand of electrical loads like heating, ventilation and air-conditioning (HVAC) equipments is a challenge for houses owner due to higher cost of electrical energy, also it affects the power system of grid network due to the fluctuations in demand and can cause the power outage in the network. The quantity of power utilisation from solar PV in BIPV system can be evaluated by the amount of PV energy self-consumed during a given period. The cost of buying electricity from the grid is higher than that of selling from solar PV to the grid. Thus, maximizing the PV power utilization is important in reduction of this cost. Thus, it is important to identify shiftable loads for increasing self-consumption. The excess solar PV production instead of exporting it, it can be used for domestic hot water (DHW) tank to be used for the following day for increasing self- consumption in BIPV.

1.3. Goals and Objectives

The main objectives of this thesis are to analyse the self- consumption of PV power production and the loads in corresponding houses with load management. Peak power demand for household loads affects the electricity cost due to high import power from the grid, which happens at time where power production from solar PV is not sufficient to cover the whole demand. The following objectives are highlighted during this thesis:

- Evaluate average and maximum power production and consumption (time duration and when it occurs) for each house.
- Discuss the strategies for increasing self- consumption.
- Developing a load shifting model and for reducing the cost of energy from and grid.
- Excess solar PV energy storage using DHW tank.
- Quantify the match between PV production and electrical consumption.

1.4. Key Assumptions and Limitations

In Skarpnes village, two houses of different azimuthal orientation named H1 and H2 will be investigated with the solar PV production on their rooftops. During this thesis, there was consideration of electrical energy supplied to heat pump to produce heat, which in turn, supplies heat to the domestic hot water(DHW) storage. For demand side management, heat pump shifting is done for days (clear days) where solar PV is great than heat pump energy consumption. Also, ventilation, fan convector and circulation pump are analyzed. The system to be considered is grid-connected without electrical energy storage by help of batteries.

1.5. Thesis Outline

This thesis is organized into six chapters. In chapter one, there is an introduction to the background of this thesis work, the problem statement regarding the case study, goals and objectives of this thesis, and the limitation of the work. In chapter two, there is a theoretical background for some relevant topics related to solar PV production, energy consumption, demand side management by focusing on HP pump shifting, and heating systems. In chapter three, there is a geographical description of the houses H1 and H2 where data were collected. There is also presentation of the solar panel specification which are mounted on the rooftop of these houses. Then, the methods used for data collection and analysis of results are presented in this chapter. Chapter four discusses the important formulae to be used for cost minimization with load shifting. It shows also the algorithm for load shifting of heat pump referred to the availability of solar PV production. Then, there is modelling of heating system with calculation of heat produced from heat pump to the domestic hot water tank. Chapter five shows the results of HVAC energy consumption, HP shifting, the cost of energy without and after HP shifting, the storage system of heat in DHW tank using the excess of PV energy instead of exporting it into the grid. It quantifies also the cover factors in H2 with HVAC equipments in six months, and cover factor with total electrical loads in the both H1 and H2. The last chapter six presents the conclusion regarding this thesis, and it gives important suggestions and remarks for future work.

Chapter 2. LITERATURE REVIEW

In this chapter, theoretical reviews are described for more understanding of thesis objectives. Solar PV production and electrical loads consumption are compared for evaluating the level of self-consumption in the house. Also, strategies for increasing self- consumption with DSM and energy storage with help of DHW tank are described. For analyzing matching between energy production and consumption, demand and supply cover factor are used.

2.1. Theoretical background

The energy consumption of in BIPV typically peaks in the morning and evening, and the solar PV production depends on the local weather and seasons with system characteristics of installed PV modules [5]. The utilisation of on-site renewable energy sources in BIPV systems is leading to a mismatch barrier between on-site renewable energy production and the household load demand. Power mismatching occurs when the quantity of on-site energy production differs from that of the energy consumption [6]. When PV production is higher during the day it can exceed power demand especially during summer, and it could be better to store the excess of energy produced during daytimes, but storage in batteries is very expensive and requires high investment cost. In case this storage system is not yet implemented, the excess of electricity generated is fed back to the grid network which compensate the use of energy during the night where there is no PV production [7]. The actual possible storage system in the village is done as thermal storage, where the domestic hot water (DHW) tank get heat from heat pump.

2.1.1. Residential loads with solar PV production

Solar photovoltaic panels (PV) installed on the roofs of domestic houses generate electricity from sunlight, which is important for reducing electrical power consumption from the grid [8]. The example is shown in Figure 1, where for an average solar home in Honolulu, 56 percent of solar electricity is sold back into the grid [9]. From Figure 1, there is matching between PV production and consumption at the point between 7 and 8 am; it happens also at the point between 17-18 hour in evening for the same day. For other times, there is load mismatching with buying or selling electrical power to or from the grid. Solar energy in Norway, especially at Skarpnes zero energy village, during winter when a large demand of heating equipments is required, the irradiance received is at its lowest value due to the Earths position relative to the Sun. A good matching of

PV generation to the domestic demand is important, as it decreases the exchange with the distribution grid and maximizes the utilization of on-site generation. General, the ability of PV to match peak demand increases its value. Load matching in each house is highly variable depending upon the power produced and power consumed. The degree of matching in individual households depends on activity patterns that influence the appearance of the daily load curve [10].

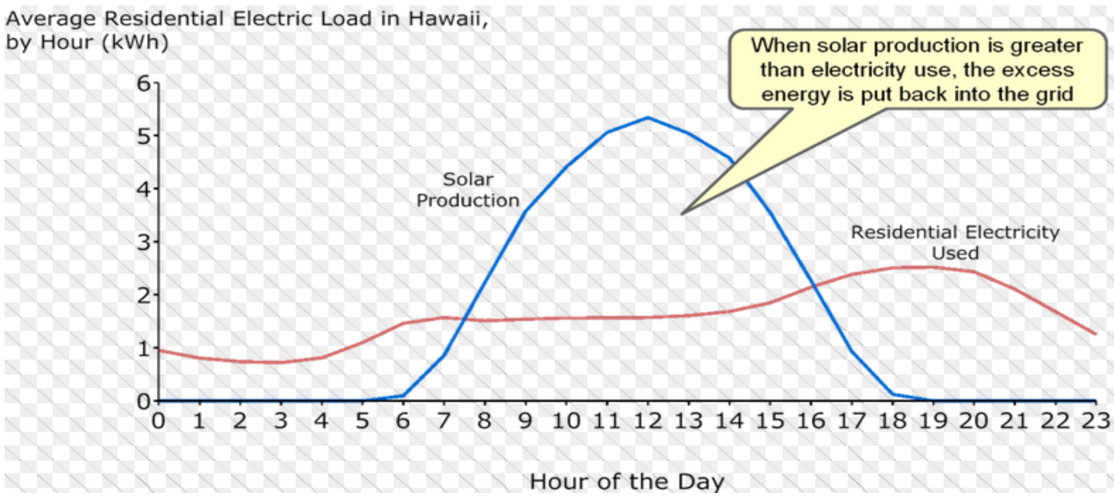

Figure 1: Average annual residential load and PV production for Honolulu [9]

Due to the load mismatch, some amount of PV electricity may be exported to the grid because the PV field is oversized or the electrical demand is temporarily small; the surplus would be stored or consumed with help of DSM by introducing a programmable load shift strategies, because the selling price of electricity to the grid is generally less than purchase price from the grid. Adversely, higher energy consumption, which does not match the available PV generation, requires to be supplemented by the grid electricity. The presence of the load mismatch due to the improper habits in using the electrical appliances can cause the occurrence of disadvantageously purchasing electricity from the grid and/or squandering the unexploited PV energy. If only a very small part of the PV generation is used to supply the household appliances, benefits will not compensate disbursements. When almost all PV electricity is used by the household, the economic benefits with self-consumption can be very convenient [11].

2.1.2. Residential power management and appliance classification

The installation of a PV plant can have a significant impact on the energy behavior of users. The energy management problem can be expressed as the minimization of energy cost function. Thus, it is possible to monitor electrical consumptions of each appliance in the house [12]. Home appliances are classified into three main categories [13]:

Non-shiftable appliances: They have fixed power requirement and operation period; the optimization will ensure continuous supply of power, for example Televisions or Refrigerators.

Power-shiftable appliances: They can be operated using less power when the load is more. So, scheduling is done to operate them with respect to their power consumption. e.g. Bulbs, heaters.

Time-shiftable appliances: These appliances can be switched to work at the time when load is less. Hence these called as time shiftable. e.g. washing machines, heat pump.

2.2.Grid- connected system for matching production and consumption

Grid-connected PV systems are the most popular solar electric system on the market today. A grid-connected system consists of five main components: (1) a PV array, (2) an inverter, (3) the main service panel or breaker box, (4) safety disconnects and (5) meters. The PV array produces DC power (voltage, current), which is commonly used for many electrical appliances [14]. Figure 2 shows a simplified PV grid connected system. There are two basic types of inverters; line-commutated and self-commutated string [15]. SMA inverters, which are used in Skarpnes village are line-commutated inverters which are used to ensure a very low harmonic distortion and a power factor very closed to unit.

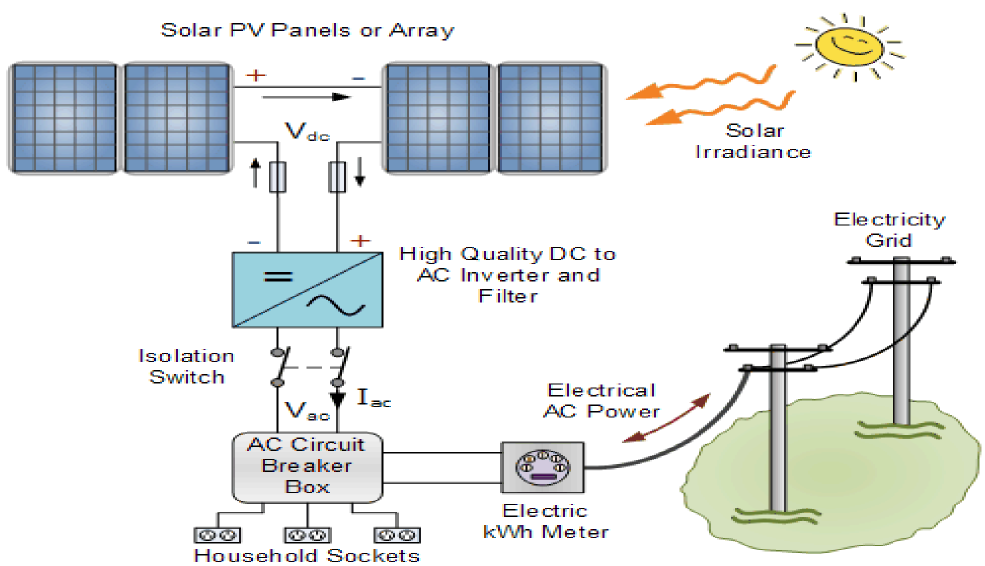

Figure 2: Simplified PV grid connected system [16]

In a grid-connected system, if the buildings use more electricity than their solar PV feed into the grid during a given month, the building owners pay only for the difference between the used power and the produced one by help of net metering (recording in- out power flow) [17]. Electrical smart metering is an important parameter in grid- connected system because they used to register electricity consumption every hour, and automatically send information about the consumption to energy company, which is Agder Energi Nett for the case of Skarpnes village. The smart meter opens for digital and smart power management in the house. With this technology, it becomes possible to discover and resolve faults in the power grid faster, and this results in a more reliable power supply. This is the reason why, the Norwegian Water Resources and Energy Directorate (NVE) have decided that all electricity consumers in Norway shall have smart electricity meters installed by 1st of January 2019 [18]. From the grid connected system with PV- solar panels installed on the rooftop of building, the nearly zero energy building can be achieved with a system which produces an equal amount to the consumption on an annual basis [19].

2.3. Zero energy balance system

The Net Zero energy building, (Net ZEB) has become a prominent wording to describe the building energy efficient and renewable energy utilization to reach a balanced energy budget over a yearly cycle. The sketch shown in Figure 3 gives an overview of relevant terminology addressing the energy use in buildings and the connection between buildings and energy grids for achieving nZEB. The annual import/export balance is used in the present case. The balance is calculated between energy delivered or imported into the building (E_{Im}) and the energy exported from the building (E_{Ex}) to the grid, as seen in equation (2.1).

$$E_{net} = E_{Ex} - E_{Im} \tag{2.1}$$

This energy is calculated by taking the total sum over the year for all energy generated and consumed within the given house in the village [20]. A net zero energy balance is reached if E net (kWh) is close to zero, and positive net energy balance means more exported than delivered, commonly termed a plus house.

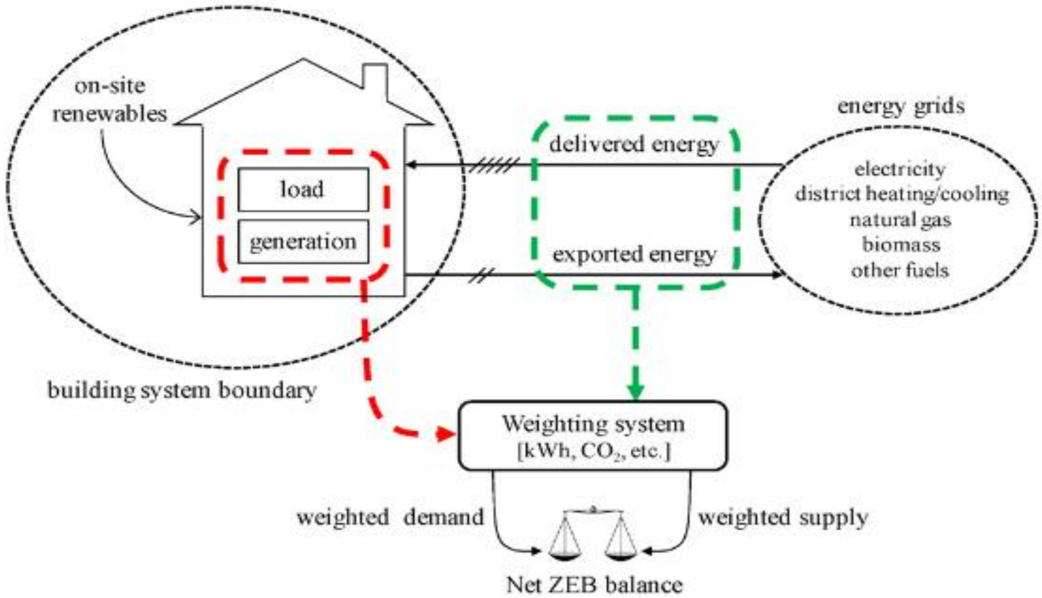

Figure 3: Connection between buildings and energy grids showing relevant terminology [20].

The key role of Net ZEB is based on the approach of reducing the amount of delivered energy and generating credits by feeding energy into grids. The Directive of the European Union Parliament on the energy performance of buildings requires all new buildings to be nearly zero-energy by the end of 2020 and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings [21].

2.4.Self-consumption of PV electricity in residential buildings

Self-consumption (SC) in BIPV system can be defined as the fraction of on-site renewable energy generated which is used to power domestic loads, rather than being exported to the grid [22]. Mechanisms promoting SC of PV electricity are based on the idea that PV electricity will be used first for local consumption and that all this electricity should not be injected into the grid [23]. The *Figure 4* shows the size of self- consumption compared to the power injected into the grid and that consumed from the grid.

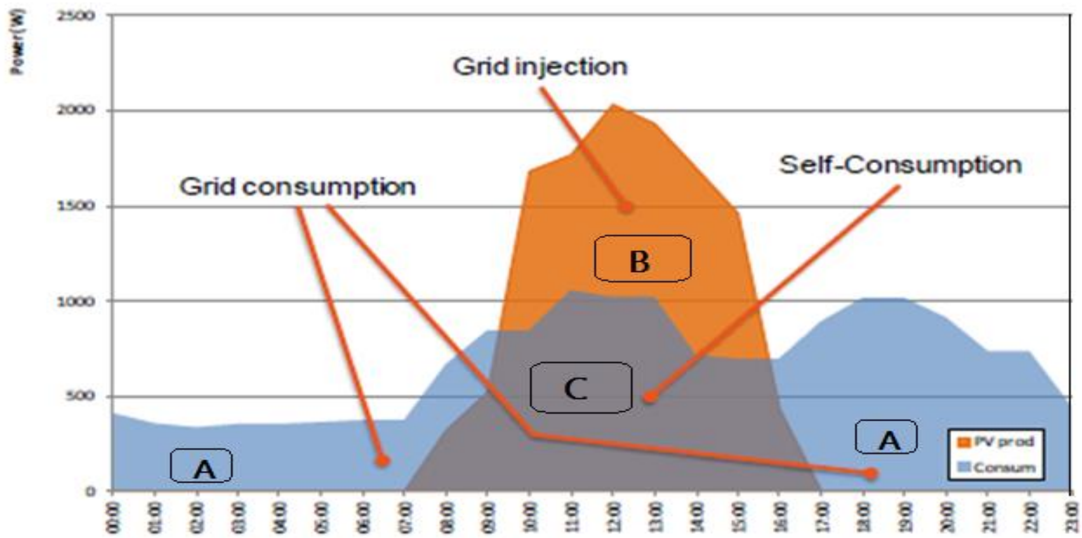

Figure 4: Comparison of production and consumption profiles (with modification) [23]

Most of the power production takes place when residents are not at home. Thus, demand response represents the practice of managing electricity demand in a way that peak energy use is shifted to off-peak periods enabling higher rates of self-consumption or, more generally, the adaption of demand to grid issues. With electricity storage and demand response, rates of SC can be raised, and benefits in terms of mitigation of network costs due to the integration of PV could be achieved [24]. In the next years, PV systems will not be designed just to generate the amount of electricity as high as possible, but even to limit electricity exportation from the building to the grid and allow the user to achieve high degree of electricity self-consumption [25].

During this thesis, modelling of self-consumption is done in terms of the supply cover factor, while self-sufficiency the same as demand cover factor which are described in section 2.10. The Figure 4 shows a schematic outline of the power profiles of on-site PV generation and power consumption. The areas A and B are the total net electricity demand and generation, respectively. Here, the overlapping part in area C is the PV power that is utilized directly within the building, referred as self- consumption [26]. From Figure 4, the SC can be defined using equation (2.2).

$$SC = \frac{C}{B+C} \tag{2.2}$$

The self- sufficiency (SS) is defined as the degree to which the on-site generation is sufficient to fill the energy needs of the building, and can be defined using equation (2.3) using *Figure 4* data.

$$SS = \frac{C}{A+B} \tag{2.3}$$

2.5. Important factors affecting self-consumption

When evaluating and interpreting the PV self-consumption, it is important to be aware of how a couple of factors affect the results:

-Relative sizes of PV power generation and power demand. Self-consumption, as defined above, is normalized by the total power generation, and self-sufficiency by the total power demand. Therefore, increasing the PV generation relative to the demand will always decrease the self-consumption while self-sufficiency will be increased or remain unchanged.

-Time resolution**.** In many practical situations, the self-consumption of a building is determined from discrete data series of average power generation and demand, typically hourly values. A general conclusion seems to be that for individual buildings, sub-hourly data are needed, especially to capture the behavior of high peak powers [26].

Typically, electricity production and consumption are registered and presented on an hourly basis or longer. A low time resolution (large time step) may lead to an overestimation of the self-consumption since fluctuations of the power production and power consumption are levelled by averaging the values [27]. The important fluctuations on short time scales (1-min or 10-min) may be overlooked when using data averaged over longer time intervals (1-h). In energy and building simulations, 1 hour is a commonly used time-step [10]. Moreover, there are many events where the time scale is considerably shorter, e.g. in minutes or even in seconds. One example is the power production of a photovoltaic (PV) system during a scattered cloudy day [28]. At Skarpnes zero energy village, the time resolution is accounted initially on 1-minute basis from Hidacswebview, and it is converted into 15-minute and 1-hour time-resolution. In this thesis, these different time resolutions are evaluated and compared.

2.6. Options for improved self-consumption

There are two methods used for improved self-consumption, namely energy storage and load management. These techniques can either be used separately or combined. Load management is hereafter included in the broader concept of demand side management (DSM) [26]. In DSM, load shifting and peak clipping are modelled with objective functions subjected to specific constraints.

2.7. Demand side management

The scope of the DSM programs is the planning, development and implementing of programs whose objective is to shape actively the daily household load profiles of customers to realize or achieve better overall system utilization [29]. DSM defined here as actions taken to influence the way consumers use electricity to achieve energy savings and higher efficiency in energy use of residential consumers is increasingly viable with the use of highly efficient electrical appliances that can be remotely controlled [30]. The goal of DSM is to reduce electricity demand, and to increase the efficiency of the system by bringing both demand and supply to the best possible low value [31]. DSM has been regarded as the "Holy Grail" of efficient power generation and it can also be classified into the following two terminologies.

•**Energy efficiency** (EE): programs which are designed to reduce electricity consumption throughout the year by focusing on reducing energy consumption and overall energy demand.
•**Demand Response** (DR): It can be defined as the changes in electricity usage by end- use customers from their normal consumption patterns in response to changes in the price of electricity overtime. It is using programs which are automatic with a processing unit having the right to moderate or turn-off certain appliances (e.g. air-conditioners, pool pumps, washing machines, etc.) for a short time- period at customer sites [32].

The heat pumps are included in the DSM model to plane the residual load curve because the heat pumps consumption is expected to be very high in comparison to the remaining domestic loads. The only thing the customer requires is to have his individual heat demand always covered [4]. The control strategies using DSM for HP are based on the facts that, heat pump could be operated during onsite-excess production hours to store heat in domestic hot water (DHW) tank, and standard controls to merely enforce heat pump switching during excess production has shown limitation in reaching improving self-consumption. In such controls, a contrast in profiles of the two entities exists. On one side, the heat pump in such control works independent of onsite production and operates at full loads to meet the loads that are set by comfort control whereas on the other side, the onsite solar PV production has a strong variability in profile and increasing along the day with highest peak somewhere at mid-day [33].

2.7.1. Architecture and components of DSM

DSM frameworks are designed to optimally manage the electric resources of users through a specific architecture. The following are the basic components of the DSM framework:

•**Local generators**: local energy plants generate electric energy that can be either used locally or injected into the grid, and in this thesis, solar PV mounted on the rooftops of houses are the local generators.

•**Smart devices**: electric appliances that are capable to monitor themselves, thus providing data, such as their energy consumption, and that can be remotely controlled. Those are shiftable loads in the house, where heat pump is selected in this thesis due to its higher variations in power consumption.

•**Sensors**: used to monitor several data within the house, temperature and light. Power meter sensors can be used to monitor and control these appliances, so that appliance can be shifted.

•**Energy storage systems**: are storage devices that allow the DSM system to be flexible in managing electric resources.

•**Smart grid domains**: the distribution, operation, market, service provider and customer domains of the smart grid. A utility company, which is part of the market domain, supplies electric energy to users from whom it receives payments with respect to energy tariffs [2].

2.7.2. Demand side management techniques

DSM program is a program used to control the load profile indirectly to achieve the utility objectives. These objectives are:

- ✓ To have the load factor as close as possible to 1.0
- ✓ To have the peak load within the proper margin.

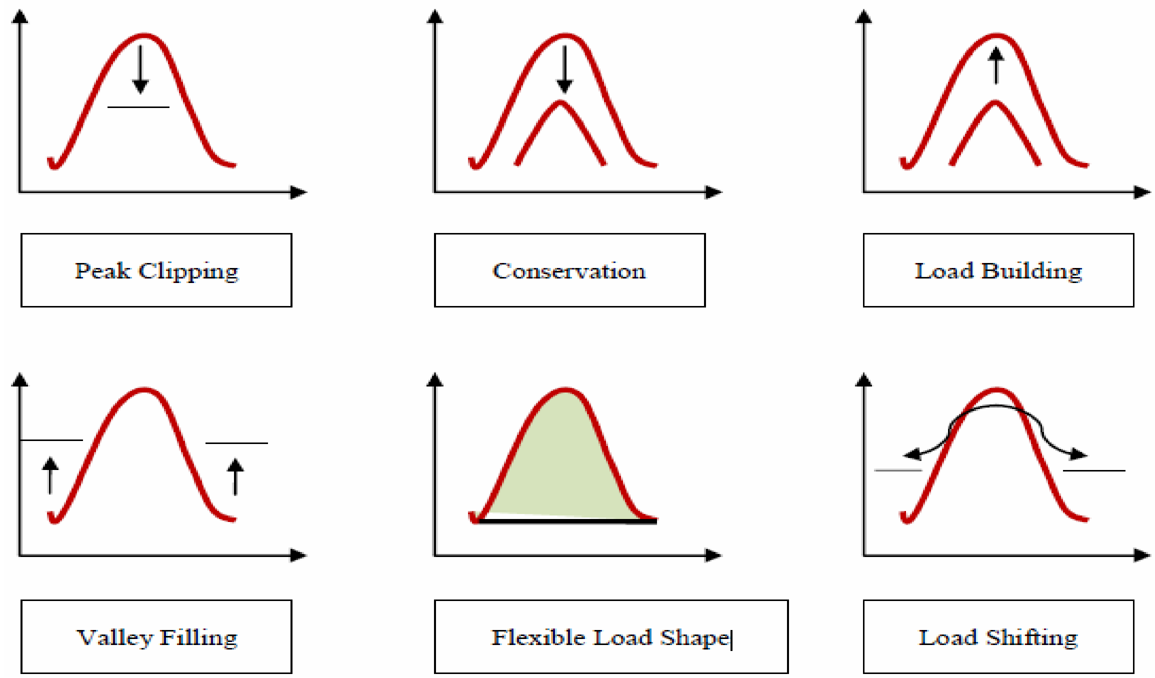

Figure 5: Demand Side Management Techniques with load shape objectives [34]

The load shapes which indicate the daily or seasonal electricity demands of industrial, commercial or residential consumers between peak and off peak times can be altered by means of six broad methods: peak clipping, valley filling, Load shifting, Strategic conservation, Strategic load growth and Flexible load shape [35] as seen in Figure 5.

Load shifting: is widely applied as the most effective load management technique. It takes advantage of time independence of loads and Shifts the peak period loads to off-peak hours. For the new load shifted, the net effect is a decrease in peak demand, but no change in the total energy consumption [29]. The effect of a load shifting in a residential PV scenario is shown in Figure 6, where the red line is the PV production, green line is the original household consumption profile, blue line is the consumption profile after the shift. The principle of load shifting is that the power before load shift is the same as that after shifting.

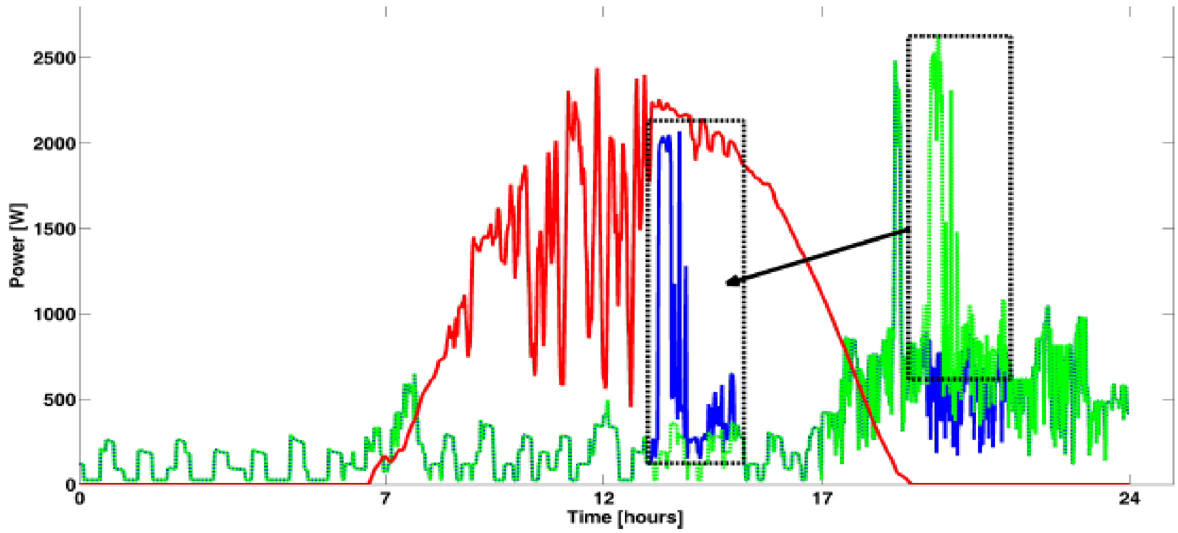

Figure 6: Load shifting technique [12].

Basically, the power consumption is much more in the morning and evening than during the day where there is maximum solar PV power generation, which requires to import power from the grid, while in mid-day, there is excess of solar PV production to be exported to the grid, thus, applying DSM with load shifting is can be used to increase the self- consumption.

Peak Clipping: This is used to decrease the demand during the peak load periods. Also, these loads can't be shifted to the off- peak periods. This could be due to lack of installed capacity during these periods. This program could be achieved be indirectly forcing the consumers to decrease their loads on their supply points [29]. Generally, this method is used by utilities which don't have enough power generation to meet the peak load. The main objective of peak clipping method is to reduce the operating costs by avoiding the use of expensive peak power plants [36].

Energy Conservation: This program is used when it is required to decrease the energy consumption all over the load period. It can be achieved by using high efficiency components [29].

Load Building: This program is used when it is required to increase the energy consumption. This could be very beneficial in case of surplus capacity. This is because the average cost per KWh will decrease [29].

Flexible Load Shape: is mainly related to reliability of smart grid can reduce a consumer load demand if needed. The customer must then produce his own electricity or use other energy sources to meet his demands [35].

Valley Filling: In this program, the main objective is to increase the demand during the off-peak periods while having the same load peak. This could be achieved by encouraging the consumers to increase their demand [29].

The first two techniques (A and B) of DSM are proposed to be applied on the residential loads in this thesis since, they are considered as new resources that can help the utility to meet the increasing in self- consumption [36].

2.7.3. Implementation of DSM Techniques

Referring to [29] and [34], the scope of implementing DSM techniques are classified into two main categories, direct and indirect load control:

1. Direct load control(DLC): This is a method by which the utility can modify customers load pattern. It can be applied by switching off the power supply on specific category of customers at specific time interval, or force the customers not to use a specific type of electrical load at specific time interval. From [37], when households allow DLC, consumer loads can be: (i) scheduled, (ii) interrupted, and (iii) sequenced.

(i) Scheduling: Appliances can be scheduled for off-peak periods. Not only on a day to day basis, but also on an hourly basis.

(ii) Interruption: During high load periods, appliances can be interrupted to reduce consumption. Appliances will resume when the load returns to off-peak periods, e.g. dishwashers, etc.

(iii) Sequencing: Appliances with multiple interval usage, e.g. cooling or heating appliances, can be sequenced to reduce peak building and create a more continuous demand load.

2. Indirect load control (ILC): it is the optimal way by which the utility can change the customers load pattern by using special methods such as: i) Time of use rates, ii) Thermal energy storage iii) Efficient tariff system, iv) Electrification technologies and v) Efficient end use technologies. For example, using ILC method, an electronic messaging service which alerts consumer of high loads and prices, or real-time electricity price displays, to persuade consumers to reduce their consumption by turning “off” non-essential appliances.

2.7.4. Demand Side Management Applications

The main target for the end user is to reduce the amount of the electricity bill without any contraction with the production policy or quality of the product. While the target for the utility is to improve the load factor and increase the spinning reserve of the system. Load factor (L.F) is defined as ratio of average energy consumption over a period to peak energy consumption in that period [38] and the system L.F belongs between 0 and 1. The two proposed programs must achieve the target of the utility and end user taking into consideration the constraints imposed on both utility and end users [34]. Therefore, the objective function is formulated either to improve system performance by increasing load factor and enhance customer service quality or to control the use of the supply side resources subject to end user demand. The mathematical formulation of DSM techniques as optimization problem where the optimization problem is generally determined by clarifying the following questions [34], [29]:

1. What does the model seek to determine?
2. What are the objectives (goals) needed to be achieved to determine the best solution?
3. What are the variables of the problem?
4. What constraints must be imposed on variables to simulate properly actual variables?

The objective function is formulated either to control the use of the supply side resources subject to end user demand for power and energy without loss of production or comfort, or to improve system performance by increasing load factor and enhance the customer service quality. Two kinds for the objective function are contributed, either to maximize the system load factor for the utility, or to minimize the total cost of the bill for the customer [29]. By reducing consumption and shifting loads during periods when the system is constrained results in less system losses (both production and transportation losses), lower system balancing costs and so increase system efficiency. Furthermore, DSM programs can reduce electricity prices as a shift of demand during peak periods could reduce the need for higher marginal cost generation power plants to operate [37].

2.7.5. Constraints and objective functions of the DSM optimization problem

To make the optimization model easier to follow and understand, constraints are grouped into five categories, as represented in Figure 7. There are electric devices, local energy generators (in this case is solar PV), energy storage systems (not yet installed in Skarpnes village), energy balancing and electric energy market (price). Firstly, constraints on electric devices are introduced to model the electric appliances of residential customers. Specifically, three different kinds of devices are considered: fixed devices, whose usage cannot be modified, shiftable devices, which can only be shifted in time without altering their load profile, and elastic devices, which are fully adjustable, both in terms of usage time and instantaneous power consumption [39].

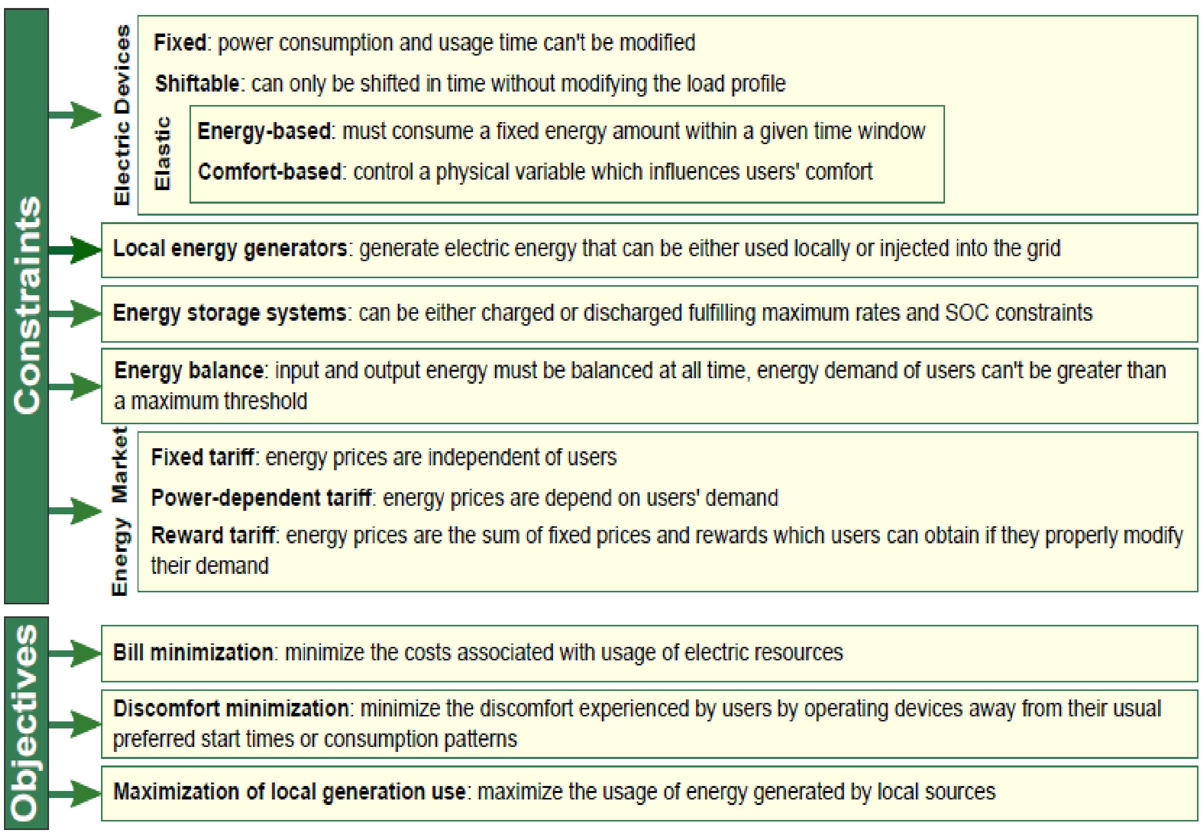

Figure 7: Constraints and objective functions of the DSM optimization problem [39]

Local generators and storage systems are described to constrain the net- generation of renewable energy sources (RES) and the charge/discharge rates and state of charge of the batteries. The energy balancing constraints, are defined to realistically model the interaction of consumers with the grid. Finally, the constraints on the electricity market are used to define the energy tariffs, regarding the cost of exportation and importation of energy [39]. Constraints and objective functions of the DSM optimization problem with load shifting are described in chapter four.

2.8. Heat pump terminologies in domestic housing for heat storage

Heat pumps are also appropriate measures for demand side management in smart grids because they can convert (sustainably generated) electrical energy into thermal energy, which can be used in the built environment later for space heating/ cooling or hot- water storage. A heat pump consumption in BIPV is high and can double the electrical use of an average household in existing buildings [40].

2.8.1. Heat pump components

The heat pump is a complete heat pump installation for heating and hot water. Certain models have an integrated water heater. Using the tap water stratification technology, more effective heat transfer and efficient layering of the water in the water tank is achieved. The heat pump is equipped with control equipment, which is operated using a control panel. Heat is distributed throughout the house via a water-borne heating system. The heat pump supplies as much of the heat demand as possible before auxiliary heating is engaged and assists. The heat pump consists of five basic units shown in *Figure 8* [41].

Figure 8: Heat pump components [41]

1. Heat pump unit with compressor, heat exchanger, circulation pumps for brine and heating systems, valves and safety equipment.

2. Water heater
3. Exchange valve or shunt valve that the heated water either passes through to the heating system or to the water heater depending on whether heating or hot water is to be produced.
4. Auxiliary heater with an electrical heater installed on the heating system's supply line.
5. Control equipment [41].

Compared with a system based solely on direct electric heating, heat pump systems have typically an annual energy saving in the range of 50 – 80 %. *Figure 9* shows a highly-simplified sketch of a heat pump system for heating and cooling of buildings. HP can use different heat sources, where ambient air, ground source and seawater are the most interesting. Ambient air is the most common heat source for heat pump in smaller residential buildings in Norway. For heat pump systems in large non-residential buildings, ground source and seawater are the most common heat sources [42].

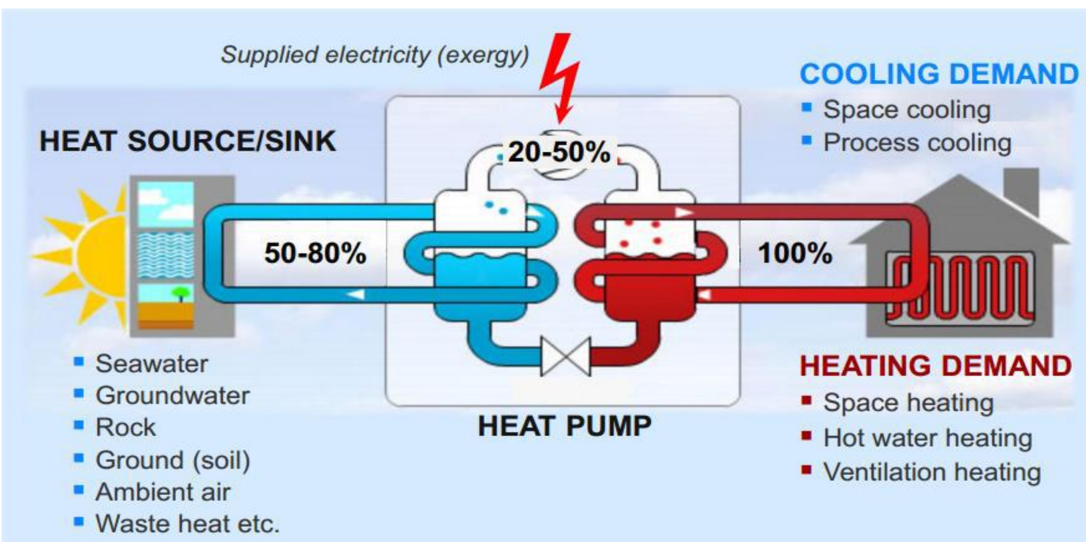

Figure 9: Principle sketch of a simple heat pump, source/sink and heating/ cooling system [42].

During this thesis based on the data available at Skarpnes, the ground heat pump is used to deliver building heating and domestic hot water. Refer to [43], to increase the self-consumption of buildings, there must have certain flexibility regarding to energy demand. Such flexibility must consider thermal comfort. Measurement data gained from a small, well-insulated multi-family dwelling shows that, the self-consumption of electricity generated on site by (PV) was approximately 28 % between September 2011 and April 2012 during daytime hours from 10 am to 4 pm each day. During the remaining hours of the day, approximately 27 % of the overall electricity consumption could be attributed to the heat pump. Therefore, the most promising regarding shifting loads into daytime hours can be used for increasing self-consumption. Therefore, the run-time of the heat pump was constrained to 10 am through 7 pm starting February 2013. This resulted in a shift of approximately 1MWh from night-time to daytime hours. The overall self-consumption was thus increased from 21 % (winter 2011/2012) to 34 % (winter 2013/2014). Modelling, diagram with more explanation are developed in chapter four and the resulting values compared to this case are found in chapter five.

At Skarpnes, the ground source heat pumps will be drilled for each single-detached dwelling. The apartments will share pumps. The ground source heat pumps will have a constant temperature throughout the year (7-8 degrees Celsius) and will be used for both heating of building and water as well as for cooling the building during the hot season [44].

2.8.2. Working principle of heat pump

A heat pump is a device in which a refrigerant is circulated that undergoes phase transitions; from liquid to gas (evaporation) and from gaseous to liquid (condensation) [40]. External energy (most of the time electrical) is therefore needed as input for the compression [45]. A heat pump generates sustainable heat with the help of electrical energy, thus, the advantages and disadvantages of heat pump can be found in [46] and [47]. The heat generated from heat pump (heat supply) is delivered to the domestic hot water (DHW) tank, which in turns, supply hot water to the building. The smaller the temperature difference between source and delivery system (the so-called ‘temperature lift’ of the heat pump), the higher the yield coefficient of performance (COP), of the heat pump [40]. The COP is defined as the ratio of the useful heat over the work input. A classic electric heater has a ratio of 1 [45].

Nowadays, Norway is one of the few countries where electricity is the main heating source. The main heating source for about 73 % of the households is based on electricity, either by electric space heaters (48 %), electric floor heating (7%), air-air heat pumps (21 %) or central heating with electricity [47], and refer to one case in Netherlands, it is expected that solar PV can supplement about 35% of the annual electric consumption of the heat pump [40]. The study of heat pump system is helpful in domestic load analysis at Skarpnes. The type of HP installed at Skarpnes village of "IVT Premium Line® HQ "model is shown in Appendix- A.

2.8.3. Daily profile of heat pump electricity demand

Referring to [48], four periods of 14 days each were studied in detail with respect to daily patterns of consumption. The 4 periods were distributed over different seasons during 2010 (March 18th – 31st, July 11th – 24th, October 10th – 23rd, December 1st – 14$^{th.}$ Figure 10 gives the daily average demand of the heat pumps expressed in half-hourly intervals. In all four seasons two maxima can clearly be seen, at around midnight and around 8-9 a.m.

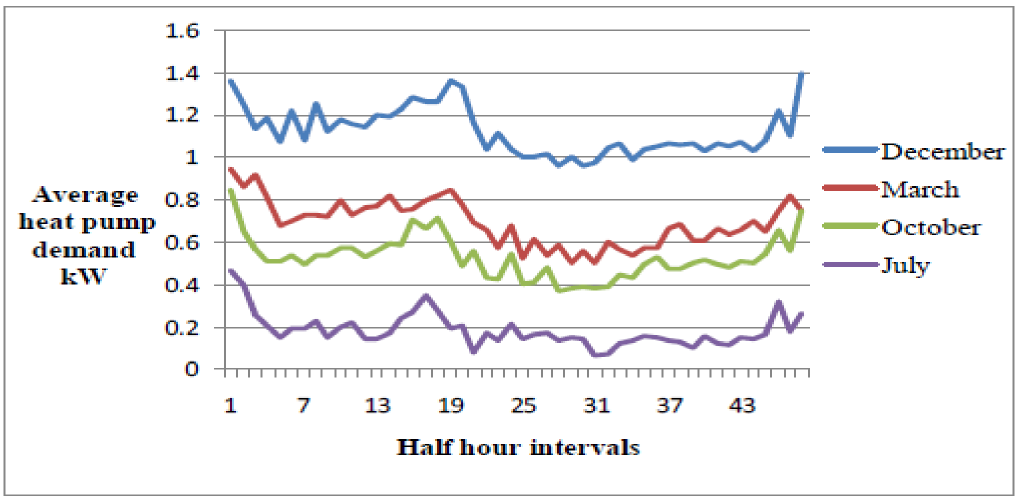

Figure 10: Daily profile of heat pump electricity demand by seasons for a given case [48]

The shape of the daily profile shown in Figure 10 is essentially driven by two factors, the external ambient temperature and the times when heating of DHW tank takes place. Heat pump manufacturers and installers generally recommend that space heating should operate continuously, with a control mechanism that seeks to maintain a constant room temperature by varying the temperature of the circulating water in the radiator system so that the heat transfer from the radiators to the rooms matches the losses to the external environment. This leads to an electrical load proportional to the difference between room and external ambient temperatures [48]. From Figure 10, daily profile of heat pump electricity demand varies depending up on the seasons, where power demand increases from July to December. During this thesis, the circulation pump is maintained in action continuously, whereas heat pump necessary to supply DHW tank is controlled, depending up on the availability of solar PV energy production.

The domestic hot water utilization is between 17 and 39% of household energy demand; consequently, domestic hot water tanks represent a potentially significant source of energy storage to accommodate the large and intermittent demands of instantaneous power that occur throughout the day in a typical dwelling. The transition towards renewable energy sources has led to an increased focus on the potential application of demand side management strategies for electric domestic hot water systems [49].

2.8.4. Domestic hot water storage tank

PV electricity can be stored as heat to be used for domestic needs, for example a water tank to be used when the heat demand is high. The thermally stratified tanks are characterized by gradually stratified layers of water volumes at different temperatures, designed to minimize the mixing of the volumes. When water is used as the storage medium, it naturally becomes stratified because of its higher density at lower temperatures: the cold water remains at the bottom, the hot water moves to the top, and the intermediate region is called the thermocline as shown in Figure 11 [50]. When observing the temperature distribution as function of height (x) in a real tank, one concept used to characterize the level of stratification within a storage is to quantify the temperature gradient (dT/dx) and thickness of the thermocline (intermediate region) that separates the hot and cold regions within the storage [51]. The water's thermal stratification is affected by several aspects, such as the size and shape of the tank (the ratio of its height to its diameter), the location and geometry of the inlets and outlets, and the temperatures and flow rates during charging and discharging [50].

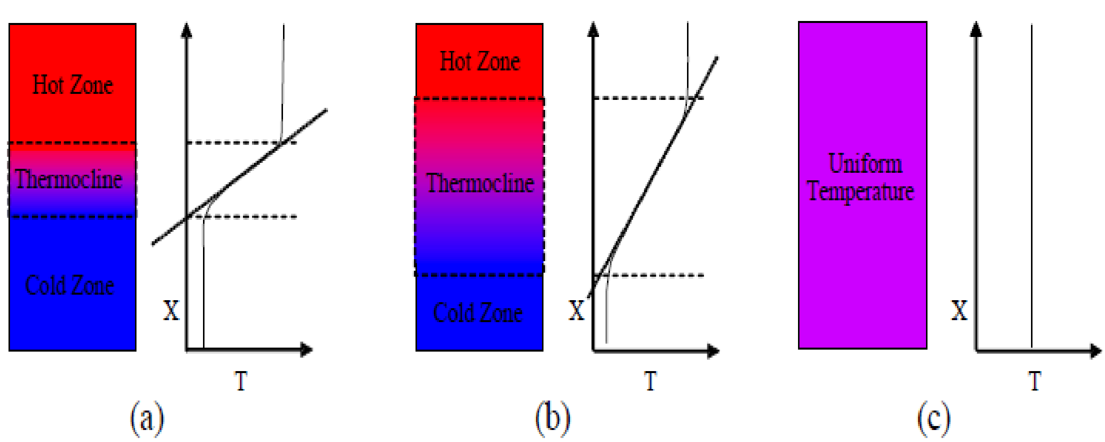

Figure 11: Different levels of stratification in a storage tank with equivalent stored energy [51]

For different levels of stratification within a storage tank, the three storage tanks containing equivalent energy are illustrated in Figure 11 . In Figure 11 (a) the temperature gradient between the hot and cold regions of the storage is observed to be large and the thickness of the thermocline small. In Figure 11 (b) the temperature gradient is smaller and the thickness of the thermocline is larger than the storage shown in Figure 11 (a). In effect, the storage shown in Figure 11 (a) is more highly stratified than the storage shown in Figure 11(b). Finally, in Figure 11 (c), the storage is at a uniform temperature and is observed to be unstratified.

DHW should be delivered without increased risk for bacterial growth. The highest risk of Legionella proliferation is in temperature range 35-45°C, i.e. exactly the temperatures of DHW used for tapping [52]. Usually, there is no growth above 55°C, and a temperature of over 60°C has a bactericidal effect [53]. The maximum temperature is 90 °C, and this is also precaution measures for the case study of Skarpnes, where the domestic hot water tank is heated once a week to prevent Legionella.

The heat capacity of a water tank containing 90 ^{o} C hot water at an ambient temperature of 21 ^{o} C is 87.2 Wh/kg as compared to electricity storage densities for Li-ion batteries of 140 Wh/kg. Comparing to electricity storage batteries, hot water tanks provide a cheaper means of energy storage [54]. The stratification in the storage tank mainly depends on how the energy is added to and extracted from the storage. This includes the value of the inlet and outlet flow rates and their temperatures and positions [50].

2.8.5. Domestic hot water components and application

A domestic hot water tank is made up of the following main components:

• An insulated cylindrical hot water storage tank usually is made of stainless steel.

• An electric heating element located at the bottom of the tank.

• A cold-water inlet and a hot water outlet.

• A tempering valve that regulates the water temperature at the usage outlets.

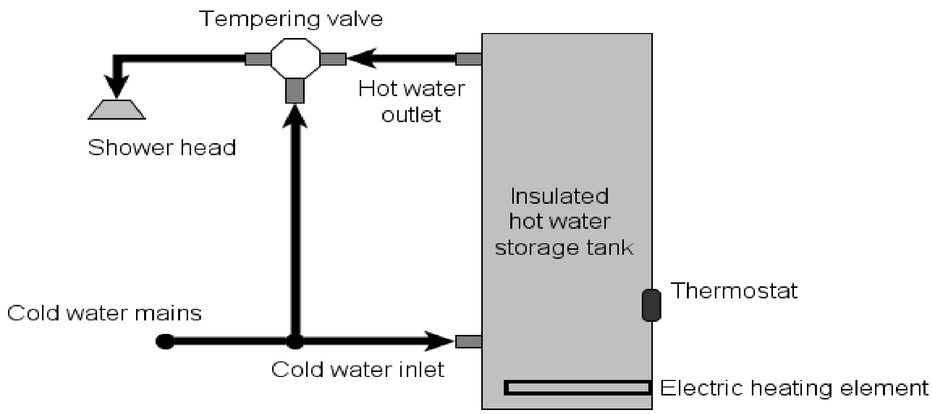

Figure 12: Simplified block diagram of DHW for showering [55]

During a shower, the cold water at mains pressure flows into the bottom part of the storage tank, while hot water flows through the outlet at the top of the tank and enters the tempering valve. The tempering valve regulates the water temperature at its outlet to a preset value by mixing the right amount of hot (from hot water storage tank) and cold water (from mains supply). A thermostatic element immersed in the mixed water contracts or expands to move a piston that regulates the flow of hot and cold water entering the valve [55].

2.9.Electrical energy storage system for self- consumption improvement

Another option for increasing self- consumption is introducing small storage units as buffers between the PV system and the distribution grid. When the PV system overproduces power, the battery stores energy up to the battery capacity. Figure 13 shows grid- connected solar PV systems with battery storage. At net demand, the battery unloads energy with a good efficiency [56].

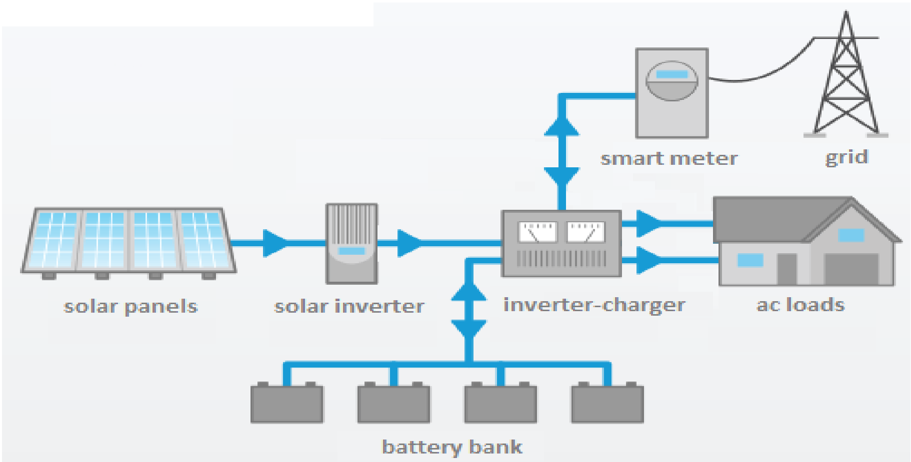

Figure 13: Grid connected solar PV systems with battery storage [57]

Today, the cost of a battery storage system is high, which is one important drawback [58]. There are a few different battery technologies available on the market suitable for residential electricity storage, for example lead-acid, lithium-ion (Li-ion), Sodium-Sulphur (N_aS), Nickel–cadmium (N_iC_d) and Nickel metal hydride (N_iMH). From these batteries, lead-acid is the most mature storage technique but lithium-ion batteries have the greatest potential for future development and optimization due to high storage efficiency as well as high energy density [26].

In this thesis, the li-ion battery is recommended for future study in electrical storage system because of its advantages in the combination of performance capability, safety, lifespan and costs over other types of batteries, and Table 1 shows the comparison of characteristics between Lead acid and Lithium ion battery types. Compared with other types of battery used in battery storage for PV systems, the charge and discharge curve of li-ion battery is nearly flat, and this means less voltage variation will appear in the system [8].

Table 1: Characteristics of Lead acid and Lithium ion battery types [59]

Characteristics	Lead acid	Lithium ion
Energy Density (Wh/L)	54-95	250-360
Specific energy (Wh/kg)	30-40	110-175
Depth of discharge (DOD)	50%	80%
Temp range of Charge	-40°c – 27 °c	-20°c – 55 °c
Efficiency	75%	97%
Replacement timeframe (year)	1.5-2	5-7
Maintenance costs	SLA = 2% VRLA=10%	None
Battery Cost ($/kWh)	120 (3,840baht)	600 (19,200baht)

The electricity demand of households has been growing rapidly for the last decades [31]. This requires the large distribution network for electric supply, which results in an increase in infrastructure cost, and the important strategy to manage loads in BIPV with grid- connected system is to shift the power demands (not covered by the solar PV power) to the time with higher

PV generation (clear day time). In terms of energy saving with help of batteries, peak generated energy can be used later to cover the load demand when there is no solar PV generation [31]. Figure 14 shows the demand energy from the grid with battery saving for load and PV matching where the excess solar PV generated is stored in batteries.

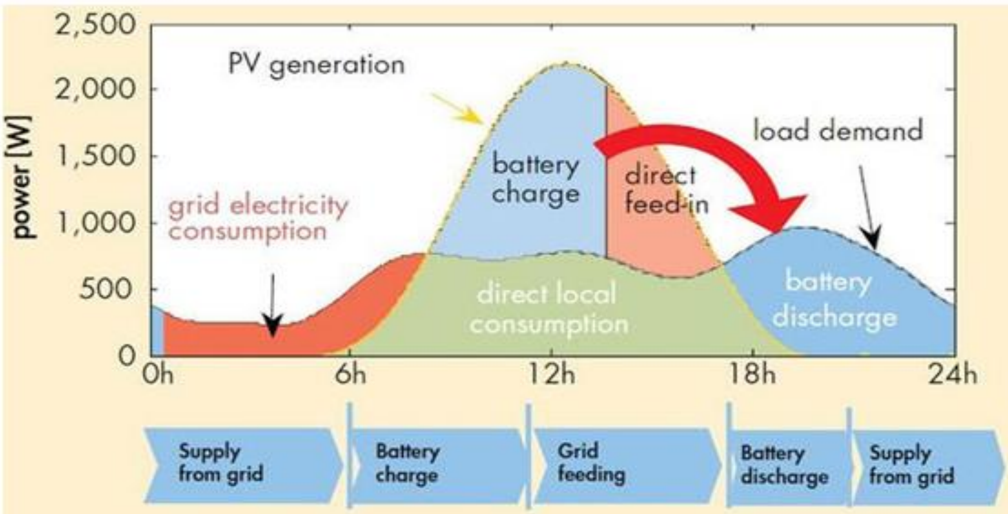

Figure 14: Energy demand from the grid with battery saving for load and PV matching [31]

When using energy storage, it is important not to count losses related to it as self-consumption. Since management of energy storage, i.e. charging, storing energy and discharging, always leads to losses, it is more efficient to use the generated PV electricity instantly if possible, instead of storing it for later use. This aspect is important to be considered, since energy storage is likely to be used as method of increasing the self-consumption in future building development [60]. The management of energy storage systems (ESSs) in BIPV requires an electrical setup which comprises smart meters, smart sockets, for realizing the load-shift of different appliances, and a main controller to realize load management [61]. Considering the single PV/ESS (energy storage systems) and the demand of the house where it is connected the control works as follows:

•the ESS is charged when there is power surplus between the PV production and the demand;
•the ESS is discharged when the demand exceeds the generation;
•otherwise, the ESS is in idle mode. Each customer controls independently its PV/ESS [62].

Therefore, with storage system the solar PV self-consumption is increased, thereby purchase of electricity can be avoided and the energy costs are decreased.

2.10. Load matching indicators

The load matching indicators describe the degree of matching of on-site energy generation to local energy demand, and thus they can also indicate the building expected interaction with the energy infrastructure, i.e. the amount of imported and exported energy [63]. These indicators show the capacity of solar PV power plant to cover or not the household loads and the building-grid exchange variation for a specified time within a given period.

2.10.1. Demand and supply cover factor

Cover factor (electrical cover factor) is defined to quantify the mismatch or non-simultaneity between local demand and production of a certain energy flow. It identifies the ratio to which the local supply is covered by local demand (or self-consumption) and vice versa (or self-generation) [64]. Within this context, the demand cover factors γD (or load cover factor) and supply cover factor γS provide information about demand and supply between building and the grid. Referring to the Figure 15, the net energy consumption is the difference between PV production, and electrical energy from the grid. Therefore, γD is defined as 'the ratio to which the energy of the load is covered by the BIPV supply', and γS is defined as 'the ratio to which the BIPV supply is covered by the energy demand' respectively [5]. During this thesis, the storage and system losses are ignored in calculation of cover factors and the parameters to be considered are mentioned in Figure 15, which are considered as those for houses H1 and H2 in the Skarpnes case study. Also, this figure gives an overview of the energy flows and terminologies used in this case study. From this figure, P_S is the BIPV supply power i.e. here from the photovoltaic system to the loads and P_D the power demand by domestic loads.

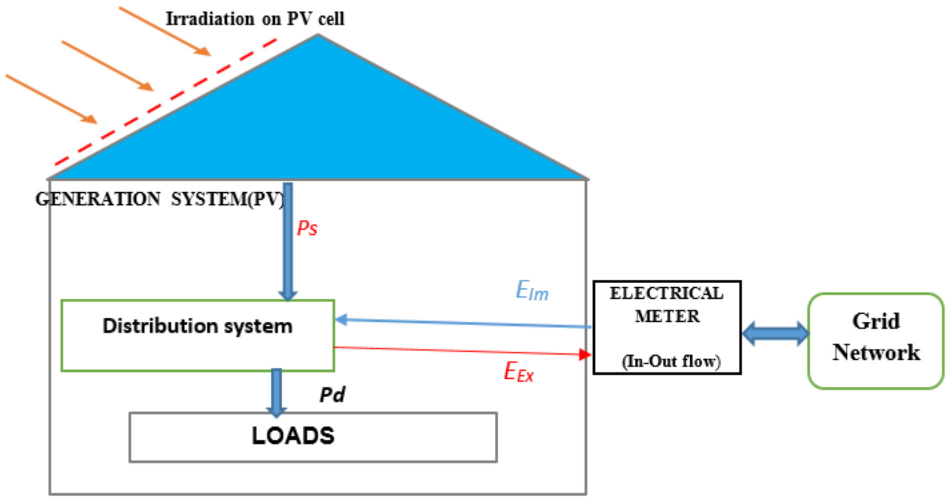

Figure 15: Schematic view of the electrical energy flows with BIPV system.

The principle of energy balance suggests that the sum of energy supplied by solar PV (Ps) with that imported from the grid(P_{Im}) should be equal the sum of energy consumed by the loads(P_d) and that exported (P_{Ex}) to the grid as shown in equation (2.7) in terms of energy.

$$E_{PV} + E_{\mathrm{Im}} = E_{Ld} + E_{EX} \tag{2.7}$$

The cover factors for a period [t1, t2] are defined in equation (2.8) and equation (2.9). However, these two equations do not yet include the possible storage (either electrical or thermal energy) systems of locally solar PV produced electricity, and the system losses are not considered.

$$\gamma_s{}^E = \frac{\int_{t1}^{t2} \min\{P_d, P_S\} dt}{\int_{t1}^{t2} P_S dt} \tag{2.8}$$

$$\gamma_D{}^E = \frac{\int_{t1}^{t2} \min\{P_d, P_S\} dt}{\int_{t1}^{t2} P_d dt} \tag{2.9}$$

The term min {P_S, P_d} represents the part of the power demand covered by the supply power or the part of the supply power covered by the power demand [5]. The γD, represents the percentage of electricity consumption covered by on-site generation, and [65].

2.10.2. Loss of Load Probability

Loss of load occurs when the system load exceeds the generating capacity available for use and is used to analyze the generation and demand system reliability. Loss of Load Probability (LOLP) is a projected value of how much time, in the long run, the load on a power system is expected to be greater than the capacity of the available generating resources. It can be further explained as, for the BIPV, the probability of the system load exceeding the available on-site generating capacity [66], and thus, how often energy must be supplied from the grid [63]. The LOLP can be calculated using equation (2.10) [63]. The LOLP can be also defined in terms of import and export by considering the net difference between the energy imported from the grid to that exported to the grid during a given period.

$$LOLP = \frac{Time_{Pd>Ps}}{T} \tag{2.10}$$

where; T: Time resolution for a given period;

Chapter 3. DATA COLLECTION AND METHODS

In this chapter, the Skarpnes zero energy village is described with its geographical orientation and system details. The specifications of the solar PV panels mounted on the rooftops of houses are shown. The methodology used to collect data and to analyze results are presented.

3.1. Description of Skarpnes Zero Energy Village

The Smart Village Skarpnes (58.43°N, 8.72°E) is located close to the city of Arendal in south of Norway. The Skarpnes buildings lie on a sunny hill on the west side of Nidelva in Arendal and was at the time of installation the largest zero net energy housing project in the Nordic countries, developed by the building contractor- Skanska [44]. Five buildings in this village have solar panels on the roof, which provide electricity to these buildings. In addition, five of the houses are built as nZEB with BIPV systems on the roof, where all technical solutions have been carefully designed to minimize the annual energy consumption [67].

During this study, only two houses H1 and H2, where one is oriented towards South-Est and other is oriented towards South- West are to be taken into consideration. Figure 16 shows the orientation of houses in Skarpnes village while Figure 17 shows one of the houses with solar PV on the rooftop.

Figure 16: The orientation of house in Skarpnes village

Figure 17: View of a typical house in Skarpnes, with solar PV on the rooftop

The tilt angle of the BIPV solar panels is 32^0 .H2 is oriented towards the South-East while H1 is oriented towards South -West . As these BIPV systems are fixed with different orientations, they receive peak solar irradiation at slightly different times, means that, PV power production occurs differently between these two houses. During this work, the heat pump as electrical load is supplied by electricity from either solar PV or grid distribution network depending upon the season of the year and hours of a day. Figure 18 shows the main components of heating system with HP, which will be useful in modelling of hot water temperature from domestic hot water tank. In this figure, the source of cold water is not shown for modelling simplification. The houses at Skarpnes is using ground source (brine- to-water) heat pump system, which harnesses natural heat or ground heat source (Q_{GHS}) from underground by pumping brine through it. The HP is receiving electrical energy (P_{el}) from PV system during high irradiation (clear day) or from the grid distribution network. This HP increases the Q_{GHS} into Q_{HP}, which is then applied to the domestic hot water storage tank (Q_{st} of DHW) for delivering hot water to be used for example in shower. This Q_{HP} is also supplied to building heating storage (Q_{st} of BH) to deliver heat (Q_{BH}) for building heating with help of heat exchanger.

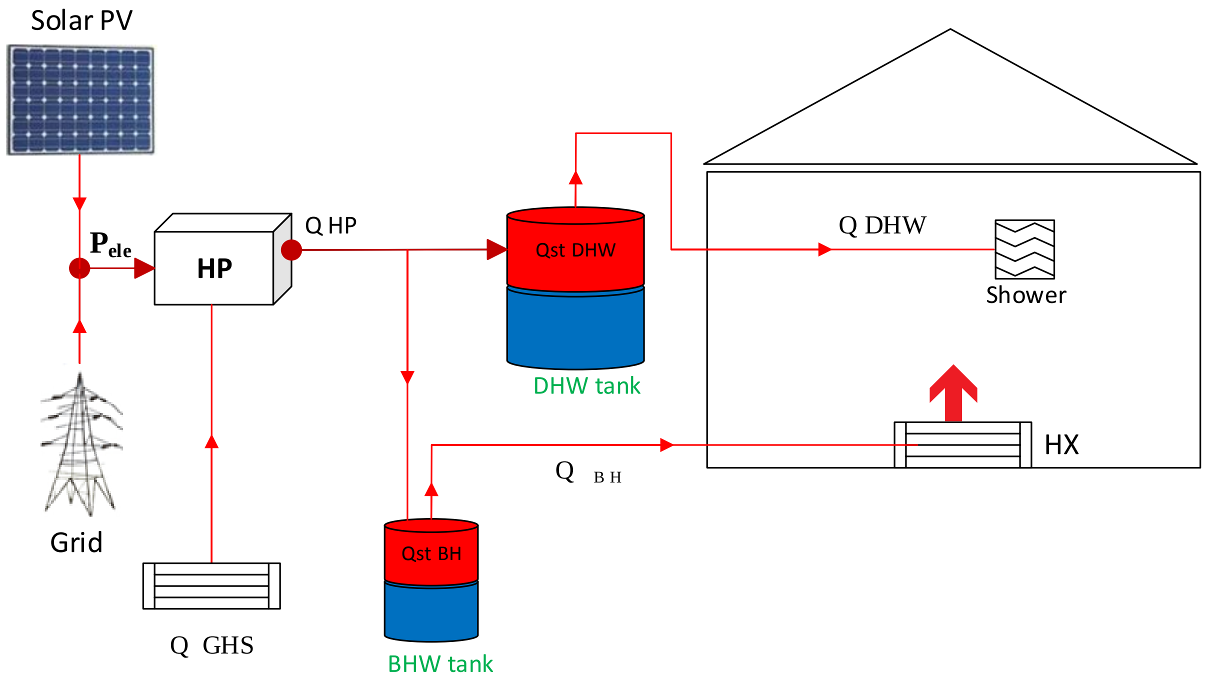

Figure 18: Heating system in the residential heating system

By linking the thermal and electrical networks of a house, heat pumps in combination with thermal storage offer significant advantages over costlier and more complex electrical storage methods (like batteries) [68].

3.2. Specifications of PV system for each building and data for heating system

The solar panels used at Skarpnes were provided by SunPower 230(E18). Utilizing 72 all back-contact solar cells, the SunPower 230 delivers a total panel conversion efficiency of 18.5%. Figure 19 (left) shows the comparison of solar panel efficiency used in Skarpnes village is compared with other types of panels.

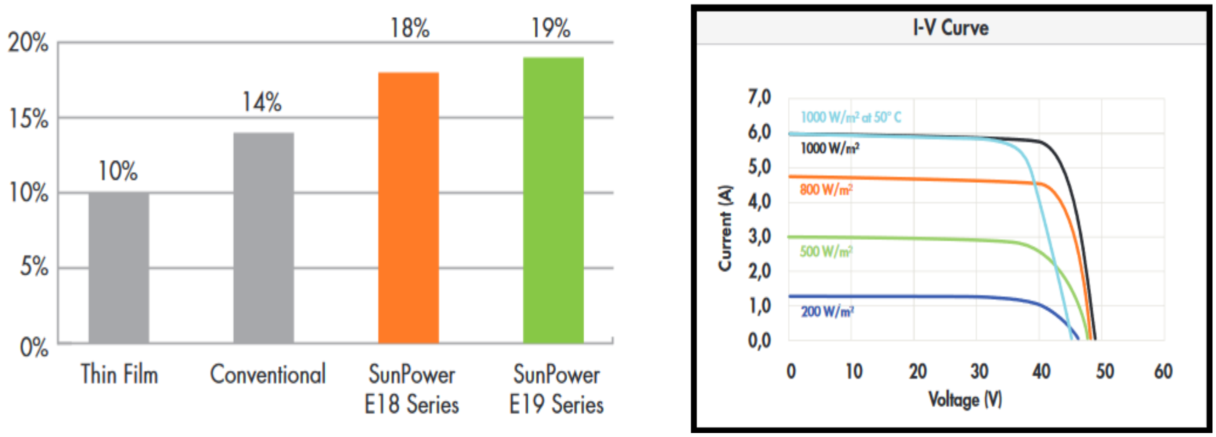

Figure 19: SunPower's efficiency (left) and I-V characteristics (right) of PV module at Skarpnes [69]

Specifications of PV system for each building are as the following:

- PV system has been built with 32 panels with single inverter.
- PV panel model: Sunpower E18/230 Solar Panel, model SOLRIF-SPR-230NE-BLK-D
- Total PV area per house: 32 x 1.244 m2 = 39.8 m2
- Total installed PV power per house: 32 x 230 wp = 7360 wp
- PV roof tilt angle: 32 degrees
- Inverter type: SMA Tripower 7000TL20

Figure 19 (right) shows the I-V characteristics of the solar panel module used at Skarpnes. The panel's voltage-temperature coefficient and low-light performance are listed as attributes that provide high energy yield per peak power watt [69]. The electrical characteristics of the SunPower solar panel used at Skarpnes zero energy village is found in Appendix- A, Table A. Technical data for heating system with heat pump can found in Appendix- B in Figure B.

3.3. Research methods and data analysis

During this thesis, data are collected in Skarpnes zero energy village for two houses named H1 and H2, including household load profiles with PV production. The data to be analyzed are from Hidacswebview SQL server database, taken from ABB electrical power meters (instruments counting in and out flow of energy) and an SMA inverter. The data are available in 1-minute resolution, and are converted into 15- minutes and 1-hour time resolution for further analysis. Then, results are simulated and analysed using excel spreadsheets and MATLAB, and the choice of datasets is based on available data, which are limited to six months for H2 and three months for H1. For daily load and PV analysis, six clear days (4^{th} December, 1^{st}January 2016, 3^{rd} February 2016, 25^{th} March 2016, 1^{st} April 2016 and 25^{th} May) in the house (H2) are considered.

The loads in the houses are identified as shiftable (i.e. heat pump) and no shiftable loads. The MATLAB code developed is used in load shifting methods, which is used to minimize the use of power from the grid by increasing the self- consumption from solar PV generation. Due to the variation in electrical load demand with respect to time solar PV production, DSM is used to shift some specific loads at the time with higher PV production for reducing demand from the grid. It is economical to maximize the use of PV produced on- site because the selling cost of energy from the BIPV to the grid in Norway (C_P =0.3 NOK/kWh taken as average) [70] is less than the purchasing cost of energy from the grid to the house (C_N = 0.8 NOK/kWh taken as average) [47]. This shows that by using the self-produced PV power, which is done by increasing self-consumption, there will be a profit.

In this thesis, the potential applications of heat pump in households connected to a thermal storage are analyzed as they hold a high impact on the overall energy system. The optimal operation and how the storage sizing influences the temperature system performance in DHW tank are investigated, whereby increasing the size of the tank, the time required to heat water up to the maximum allowable temperature is increased. Modelling of DHW and BHW tank, which get heat from HP, are used to store the excess PV energy instead of sending it back to the grid. This excess PV energy is assumed in this work to heat water tank from lower temperature limit of 40 ^{0} C to an upper temperature limit of 90 ^{0} C, which is used for domestic hot water heating and for building heating. The time to heat this water is determined for the selected volumes of storage tanks. The analysis of the matching energy production and consumption in this work is done with help of demand and supply cover factors and loss of load probability (LOLP).

3.4.PV production with domestic loads

During this thesis, two types of loads are considered separately; HVAC (where heat pump is used for shiftable loads) and total electrical loads. Figure 20 and Figure 22 show the total solar PV power production and the total HVAC loads respectively during the month of May 2016 for both H1 and H2. Thus, it is important to analyze the self-consumed energy in different time-resolutions, and apply the control strategies for increasing the self- consumption with PV in corresponding houses.

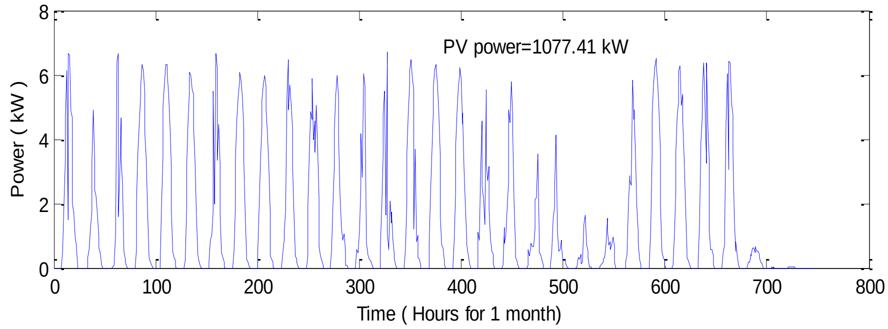

Figure 20: Total PV production, H2, May 2016

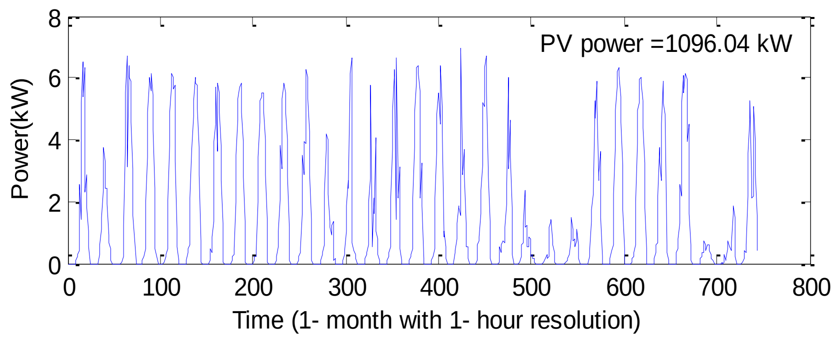

Figure 21: Total PV production, H1, May 2016

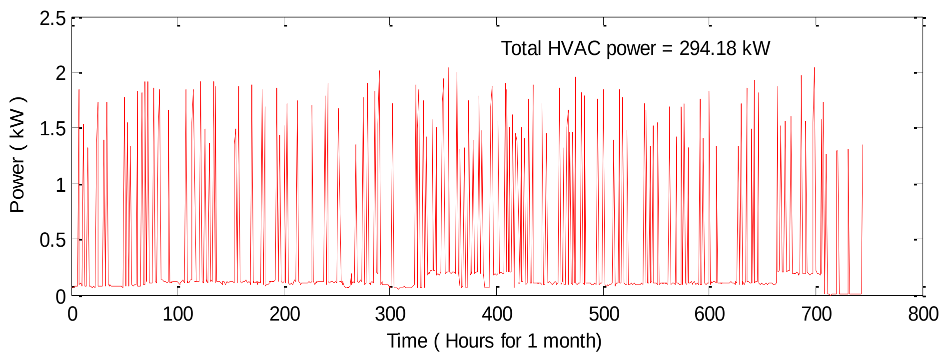

Figure 22: Total HVAC power consumption, H2, May 2016

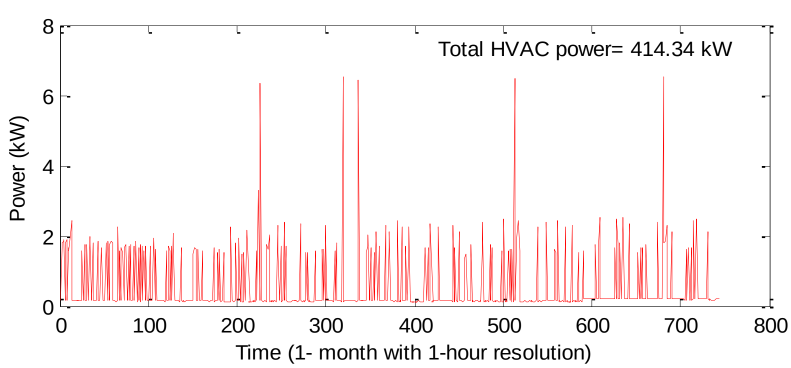

Figure 23: Total HVAC power consumption, H1, May 2016

For the house H2 in May 2016, the total PV production is 1077.41 kW, while the total HVAC consumption is 294.18 kW, which implies that only 27.3 % of PV production is consumed by the loads, while 72.7 % of production is exported to the grid. For the house H1, as shown in Figure 21 and Figure 23, 38.8% of PV production is consumed by the HVAC loads, while 62.2 % of production is exported to the grid. During May for both houses, more energy is export to the grid. To increase the self- consumption in BIPV system, this excess energy can be stored either electrically by help of batteries or thermally by help of domestic hot water (DHW) storage tank. Likewise, load shifting with HP can be used to increase the self-consumption in BIPV. Therefore, the results about strategies to increase self-consumption are developed in chapter five.

Chapter 4. MODELLING AND OPTIMIZATION METHODS

The goal of optimization is to find the values of a model's variables that generate the best value for the objective function, subject to any limiting conditions(constraints) to the variables [29]. The objective is a function which is required to be minimized while meeting the constraints [3]. Appling DSM at Skarpnes village, the objective function is to minimize the cost of selling power to the grid, by increasing self-consumption with reduction in the high load demand. With higher demand or supply in comparison to other, it results in more import or export to or from the grid (higher exchange with the grid). In this chapter, the circuit diagram of heating system in the house is illustrated. Therefore, modelling of the heat flow from HP to hot water storage is done for determining the hot temperature in both domestic hot water tank and in building hot water tank.

4.1.Minimization of the Residential Electricity cost

Let the variable C, be defined to represent the cost of electricity for a given period (week, month or year). In this method, the cost to be minimized is the difference between the cost of imported energy and the profit of exported energy as shown in equation (4.1). The cost of import energy (C_{Imp}) exists at time the power demand is greater than PV production, while the cost of export (C_{Exp}) happens when PV power production is greater than power demand during the time of a day.

Objective function

$$MinC = Min(C_{\mathrm{Im}\,p} - C_{Exp}) \tag{4.1}$$

with: $$C_{\mathrm{Im}\,p} = \sum_{j=1}^{N} \left[\left(P_{L(j)} - P_{PV(j)} \right) * t_{(j)} * C_N \right] \quad \text{(for } P_{L(j)} \geq P_{PV(j)}\text{)} \tag{4.2}$$

$$C_{Exp} = \sum_{j=1}^{N} \left[\left(P_{PV(j)} - P_{L(j)} \right) * t_{(j)} * C_P \right] \quad \text{(for } P_{L(j)} \leq P_{PV(j)}\text{)} \tag{4.3}$$

where;

C_{Imp}: is the cost of imported energy from grid, (NOK)

C_{Exp}: is the total profit of selling electricity to the grid, (NOK)

$P_{L\,(j)}$: is power consumed by load in time interval j, (kW)

$P_{PV\,(j)}$: is the solar PV power produced in time interval j, (kW)

C_N: is the normal cost of buying electricity from the grid to the house

C_P: is the profit or selling cost electricity from PV to the grid

$t_{(j)}$: Time resolution conversion

Constraints

Refer to equation (4.1), this optimization reduces the domestic electricity bill, and the shiftable devices should operate at average low cost. Hence, in optimizing the appliance schedule plan, the time with solar PV energy greater than load energy is considered. The optimization problem is then formulated by adding equation (4.1) with the inequality and equality constraints on the load consumption as in equation (4.4) and (4.5) [3].

Inequality constraint: $$\sum_{j=1}^{N} E_{T(j)} \leq \sum_{j=1}^{N} E_{M(j)} \tag{4.4}$$

Equality constraint: $$E_{New(i)} = E_{Old(i)} \tag{4.5}$$

where;

E_T (j): is the total energy consumption in time interval j expressed in kWh;

$E_{M(j)}$: is the maximum energy consumed in time interval j expressed in kWh

$E_{New(i)}$: is the energy consumed for load (i) after shifting

$E_{Old(i)}$: is the energy consumed for load (i) before load shifting

In this work, the energy consumption to be considered is for HP which is considered as shiftable load. The equality constraint clarifies that the energy consumption before load shifting is the same as that after shifting and the only change is the time at which energy is used.

4.2. DSM with load shifting algorithm for import and export analysis

This work is developing an algorithm for managing the energy consumption of home appliances regarding to the solar PV production. The focus of this work is to control selected load or appliance for maintaining its power consumption below or equal to that of PV production during the daytime.

The algorithm for DMS with load shifting is shown in Figure 24. The HVAC loads in this algorithm are heat pump(HP), circulation pump(CP), ventilation(Ventil) and fan convector(FC), and the demand for these loads is to be compared with power supply (P Supply) from solar PV.

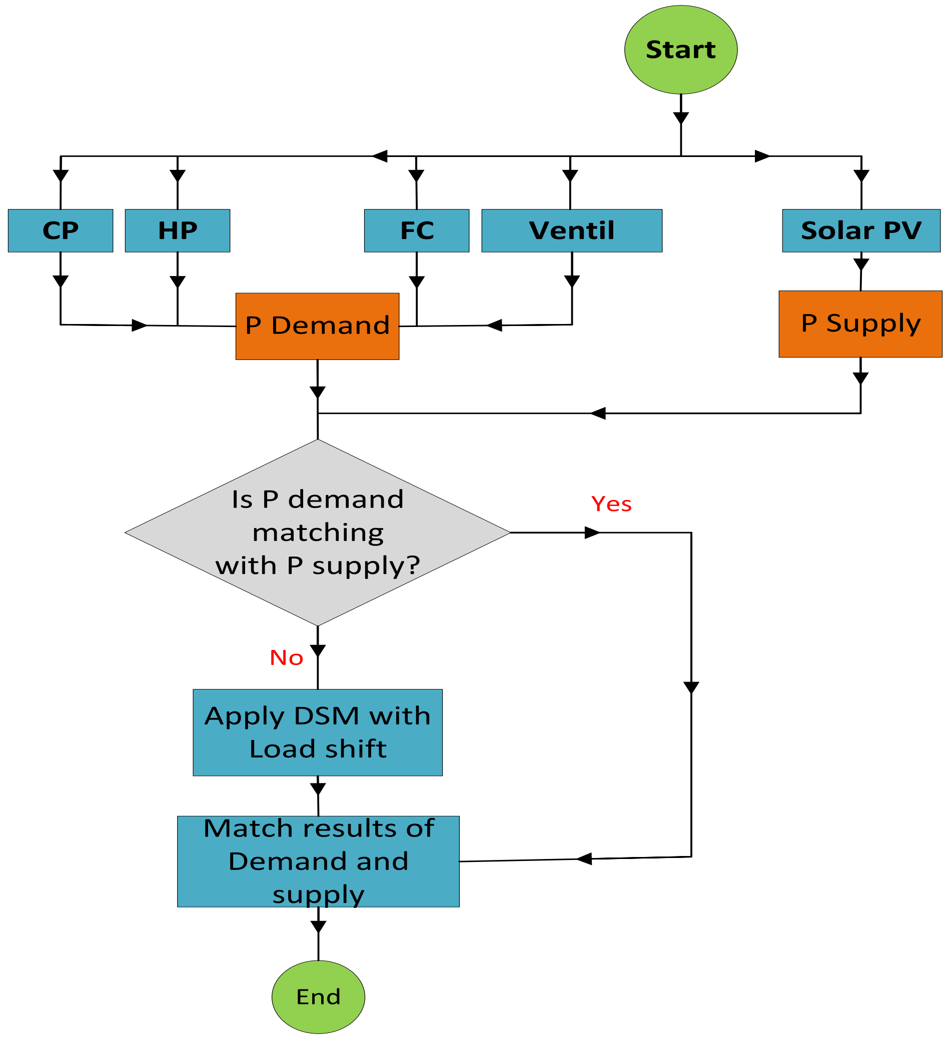

Figure 24: DSM with load shifting algorithm

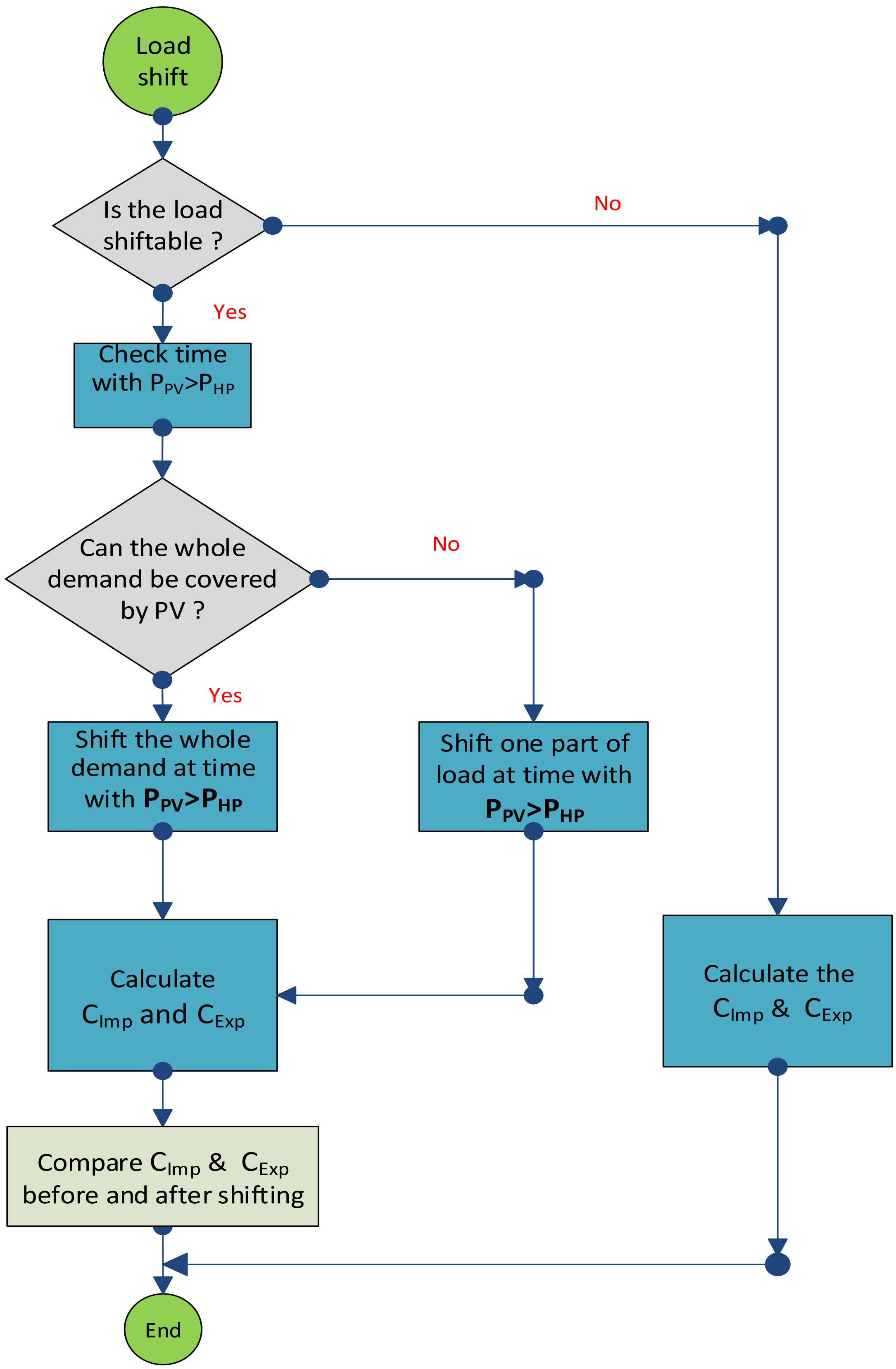

Figure 25: Load shifting algorithm for minimizing import and export power to or from grid

The detailed algorithm for load shifting is shown in Figure 25. The algorithm starts by checking the properties of load demand profiles, whether is shiftable or not (here the shiftable load is heat pump). Then, it comes to know if the load profile during the day can be covered by corresponding solar PV production or not. In this shifting, the principle point is to shift the load at time with PV production greater than the heat pump demand ($P_{PV}>P_{HP}$), and check the resultant reduction in cost of purchasing power (cost of import power) from the grid (C_{Imp}), and cost of selling power (profit of export power) to the grid (C_{Exp}).

4.3. Maximizing the overall system load factor

The load factor(LF) is explained in section 2.7.4. With a perfect (ideal) load management, the value of LF becomes 1, means that there is no variation in power consumption, thus, the average consumption is the same as the its maximum for the whole period. So, equation (4.6) is used to calculate the average consumption(P_{Av}), while equation (4.7) is used for maximizing system L.F.

$$P_{Av} = \left[\sum_{i=1}^{M} \sum_{j=1}^{J} P(i,j) \times t(j) \right] / \sum_{j=1}^{J} t(j) \tag{4.6}$$

$$MaxL..F = \left\{ \left[\sum_{i=1}^{M} \sum_{j=1}^{J} P(i,j) \times t(j) \right] / \sum_{j=1}^{J} t(j) \right\} / \sum_{j=1}^{J} P_{M(j)} \tag{4.7}$$

4.4. Modelling of heat flow in the building with heat pump and DHW tank

In this system, the heat pump supplies heat to the domestic heat storage (DHW) tank for domestic hot water demand (shower), and building heating storage (BHW) tank for space (building) heating. This HP is consuming electrical energy from either grid system or solar PV depending upon the availability of solar PV power, and on this diagram, the electrical supply to the HP is not shown. In case this HP is not providing sufficient heat demand to the system, an electric heating element (extra) is used to boost the heat from HP to meet the heat requirement. Figure 26 illustrates the circuit diagram of two hot water storage tanks, heat pump and heating system used in the buildings. The domestic hot water storage (DHW) at Skarpnes is specifically designed to force the effect of difference in mass between cold and hot water to prepare a hot area on upper part of the tank. The origin of this diagram can found in Appendix- B in Figure A with heating system for domestic hot water tank and building heating. For DHW tank, this hot area is used to provide the domestic hot water to be used for showering, while that for BHW tank is used for building heating. The actual

DHW tank is having the capacity of 185 litres, while BHW tank is 40 litres, both to be heated by heat pump. The cold water supplied to the DHW tank is from the district drinking water which is operating as open system.

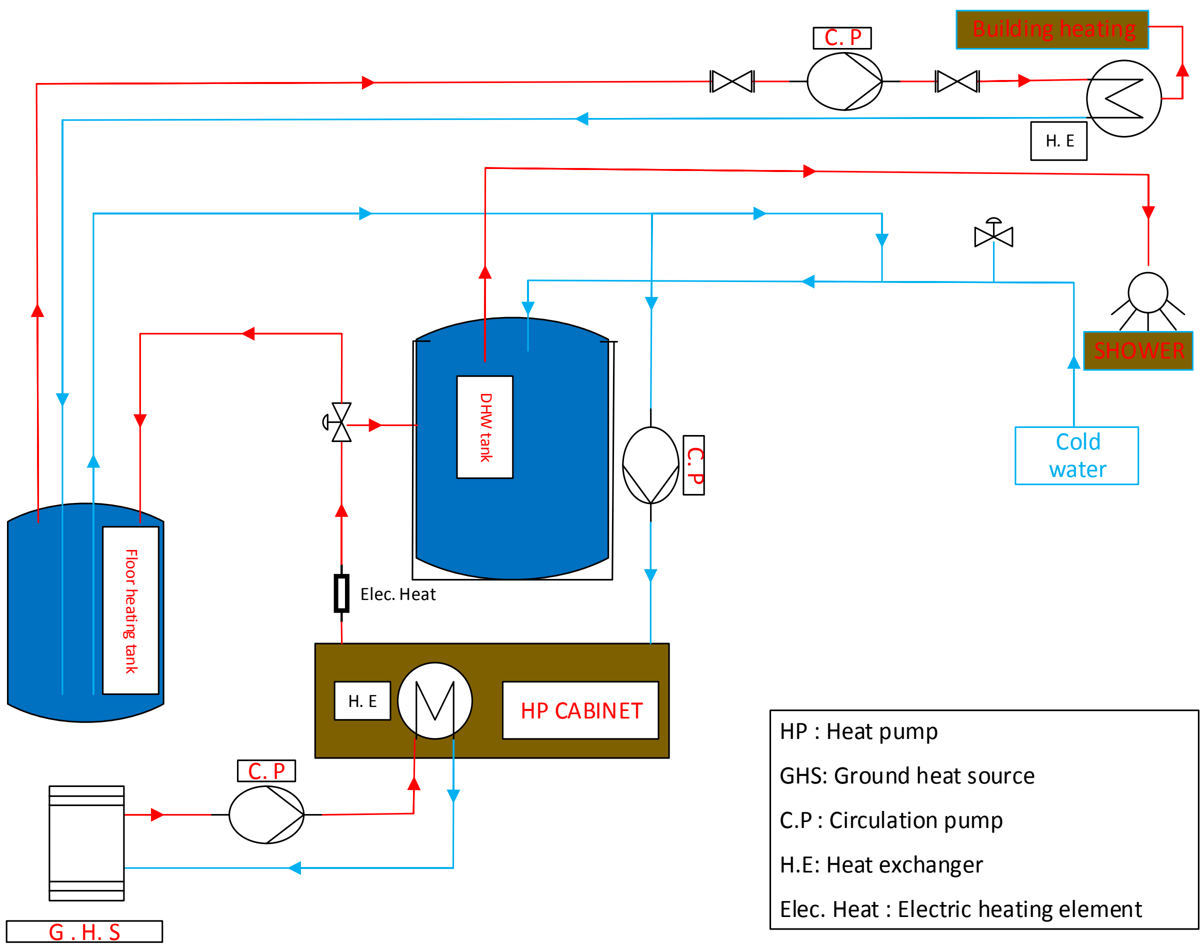

Figure 26: Circuit diagram of hot water storage tanks, heat pump and heating system in the house

Heat exchangers (H.E) in this figure are used to facilitate the exchange of heat between two fluids (hot and cold) that are at different temperature while keeping them from mixing with each other. The hours required to heat water in tank at maximum temperature of 90 ^{o}C have been determined with four types of tank volume as models and the actual volume of tank used at Skarpnes village, with minimum temperature of 40 ^{o}C. This will show that, as the volume for the DHW tank increases, the time required to get water in tank heated at 90 ^{o}C increases also as shown in chapter five. The stored energy is depending on the domestic hot water needed in house and space heating demand and this is achieved through the nominal power of the compressor electrical power demand. Refer to Figure 18 and use the parameters for heating system, the coefficient of performance(COP) of HP is calculated using equation (4.8).

$$COP = \frac{Q_{HP}}{P_{Ele}} \quad \text{and} \quad QHP=COP*P_{Ele} \tag{4.8}$$

where; $$P_{Ele} = Q_{HP} - Q_{GHS} \tag{4.9}$$

P_{Ele} = Electrical energy from either grid or PV
Q_{GHS} = heat extracted from the ground

The COP for the HP is measured as 2.2 based on the analysis after the first year of operation [71]. Heat storage modelling is done by considering the heat from HP supplied to hot water storages for both shower and building heating. During modelling and simulation, the heat storage is assumed as lossless. Also, the heat loss in pipe from HP to hot water storage is not considered. Thus, thermal energy storage (Q_{ST}) can be used to help balance between heat generated by HP and heat demand for domestic hot water, Q_{ST} (DHW) and for building heating, Q_{ST} (BH) as shown in equation (4.10).

$$Q_{HP} = Q_{ST}(DHW) + Q_{ST}(BH) \tag{4.10}$$

Therefore, for simplification, in one case, the heat transfer from the HP is assumed to be the same as that for DHW storage tank, while for other case, the heat transfer from the heat pump (Q_{HP}) is considered as equal to that for building heating. Thus, the heat transfer rate for hot water used in shower (Q_{BH}) and that for building heating (Q_{DHW})can be calculated using equation (4.11), and (4.12) respectively.

$$Q_{DHW} = \dot{m}_{DHW} * C_p * \Delta T \tag{4.11}$$

$$Q_{BH} = \dot{m}_{BH} * C_p * \Delta T \tag{4.12}$$

where;

Cp: is heat capacity, (kJ/kg ^{o}C)

$\dot{m}$: is the mass flow to the DHW tank or to BH tank, (kg/s)

ΔT: is the temperature difference (T_{hot}- T_{cold}), (^oC)

Q: Heat transfer rate, (kW)

Chapter 5. RESULTS AND DISCUSSIONS

In this chapter, shiftable (heat pump) and non- shiftable (ventilation, circulation pump and fan convector) loads are identified and analysed. For shiftable loads, heat pump has been selected because it is one kind of controllable load. Thus, the heat pump demand can be shifted with higher flexibility compared to other HVAC loads. Then, the profit of exporting energy to the grid and the cost of importing energy from the grid during six months in house (H2) are analysed for better understanding the benefit of load shifting. Also with help of energy storage, excess PV were used for heating water up to 90 ^{o}C in domestic hot water tank. It is also important to evaluate demand and supply cover factor before and after load shifting for selected clear days in 6-months for H2. The loss of load probability (LOLP) was also discussed in this chapter.

5.1. Analysis of HVAC loads and solar PV energy

Table 2 shows the values for solar PV energy with specified HVAC electrical loads, heat pump(HP), ventilation, circulation pump(CP) and fan convector (FC) in House H2 during the period of 6 months recorded using 1- resolution.

Table 2: Total HVAC loads with PV from Dec 2015 to May 2016, H2

Month	PV (kWh)	HP (kWh)	Ventilation (kWh)	CP (kWh)	FC (kWh)	Total HVAC loads	Net Import	Net Export
Dec-15	76.38	286.02	109.00	30.81	7.87	433.71	357.32	-
Jan-16	35.56	296.67	86.75	25.72	7.22	416.36	380.81	-
Feb-16	417.47	419.14	62.58	34.30	7.39	523.41	105.94	-
Mar-16	538.32	374.68	62.08	34.68	6.78	478.22	-	60.10
Apr-16	841.93	284.38	35.28	30.17	4.47	354.31	-	487.63
May-16	2174.15	460.12	98.77	48.85	5.10	612.83	-	1561.32

Considering data from Table 2, this shows that, the solar PV is not enough to cover the energy required for HVAC loads in this house from Dec 2015 to February 2016, while total household loads from March to May are covered by solar PV.

The HP is requiring more energy than the sum of other non- shiftable loads, which means that, optimization could be considered to stabilize and match energy system especially for shiftable load. Shifting the peak period for HP power consumption to off-peak hours, by considering the time from PV production off-peak hours of the day to peak production hours for maximizing the cost savings because the cost of purchasing electricity from the grid is greater than that of selling the excess electricity back to the grid.

Referring to table B in Appendix- A, the peak energy for HP (31.5 Wh) and ventilation (30.7 Wh) is high compared to circulation pump and fan convector (1.6 Wh and 2.0 Wh respectively). The time at which the peak demand occurs are found in table B in Appendix- A. As expected, table B show that, most of household loads peak in the morning and evening, while peak solar PV occurs in mid-day, and this difference in peak requires energy exchange between the solar PV on the roof of building and the grid energy, to satisfy the load demand. By comparing HP with ventilation in January 2016, the peak and average energy consumption of HP is more than three times compared to that of ventilation.

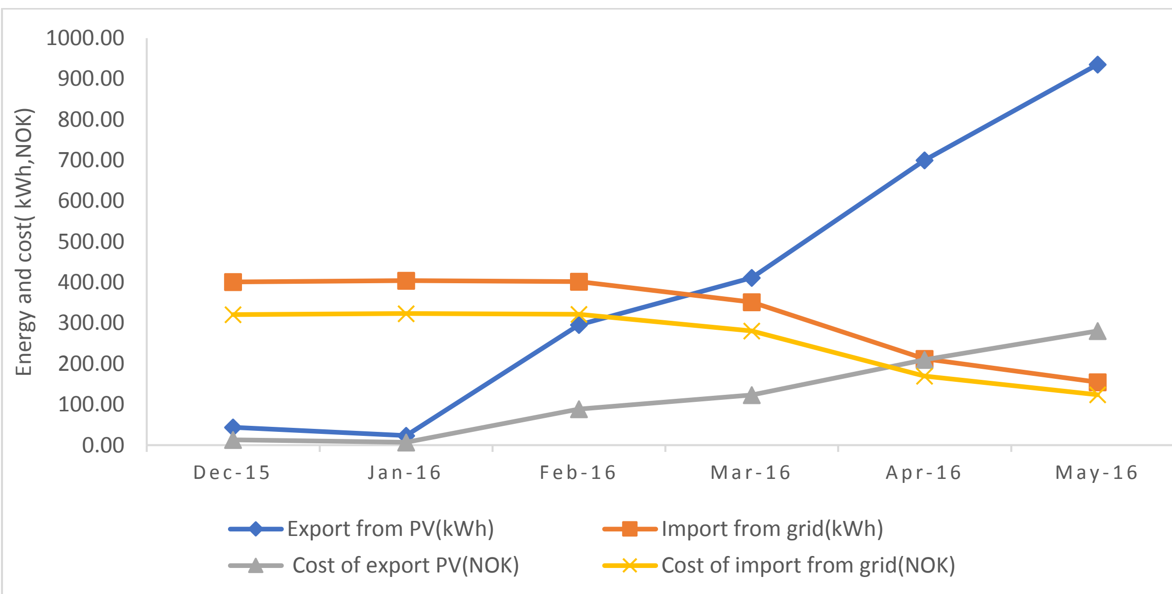

Figure 27: Energy import and export, and associated cost of import(purchase) and export(sale), for 6-months in H2

Figure 27 shows the change in import and export energy with corresponding cost for H2 over a period of six months. From December to May, the energy exported increases and profit increases, while and the energy imported decreases with decrease in imported energy cost. Thus, much interest is to maximize the use of solar PV generated than selling it to the grid. Table D from Appendix -A shows the corresponding values in each month.

5.2. Heat pump consumption with solar PV production

For maximizing the on- site PV energy utilization with HP, the peak demands are shifted to low demand, considering especially the time with high local PV production during the day [40], and this will increase the self- consumption. From this Figure *28*, by considering the month of May with 1- minute resolution, the maximum PV production is 7.2 kW, while that for the HP power consumption is 1.9 kW. For this month of May, if HP demand is only supplied by solar PV, it can use 21.2 % of total PV production and other 78.8% of PV production is exported to the grid or can be used by other loads in the house as well. In this month, there is more power exported to the grid, and to maximize the utilization of this energy, HP demand must be shifted to the time with low demand corresponding to high PV production.

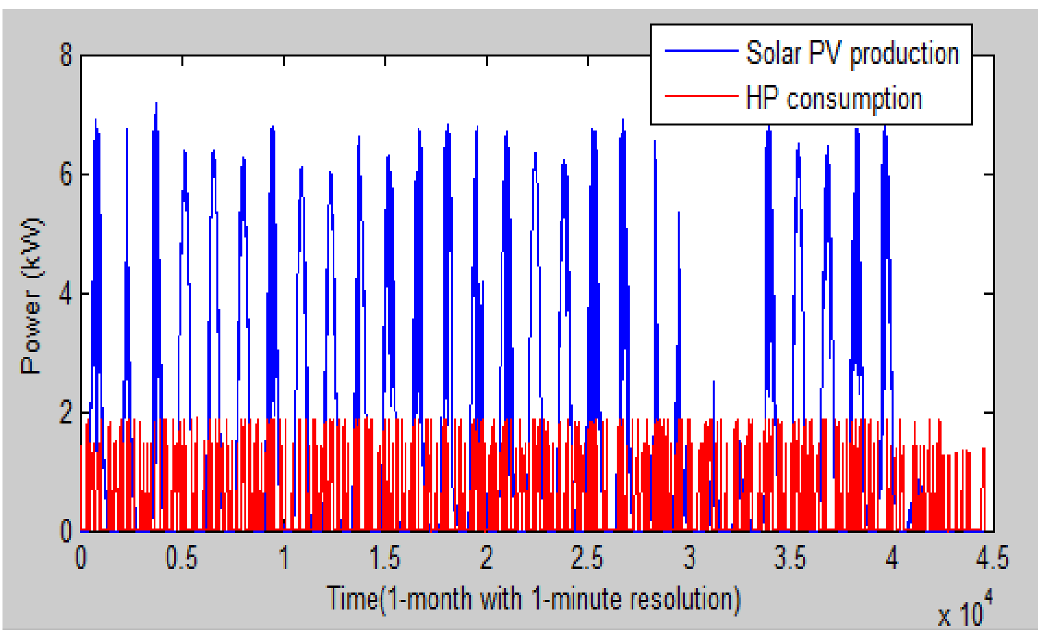

Figure 28: Power consumption of solar PV and heat pump, H2, May 2016

Refer to *Figure 29*, this day in May has PV generation of 3011.5 kW with HP demand of 485.2 kW, which means that the HP is consuming 16.1% of solar PV production. Without load shifting, there is a grid- BIPV power exchange and the HP requires 190.4 kW from the grid during the period without enough PV production, while solar PV export 2716.7 kW to the grid during the day with high irradiance. The maximum solar PV production is 6.4 kW, while that for HP consumption is 1.9kW.

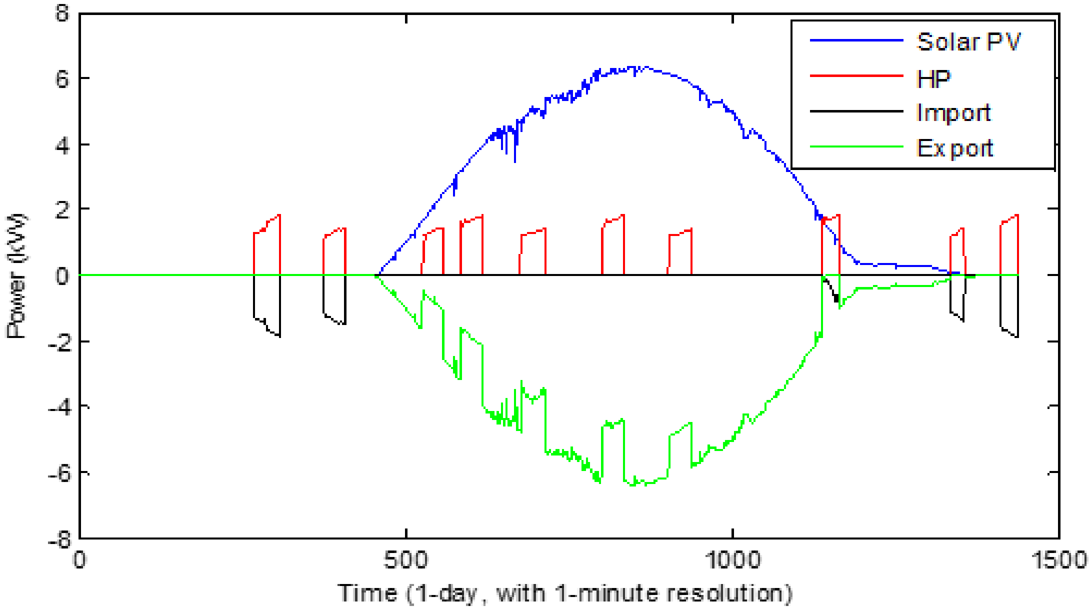

Figure 29: Solar PV, import and export power without load (HP) shifting, H2, 4-May16

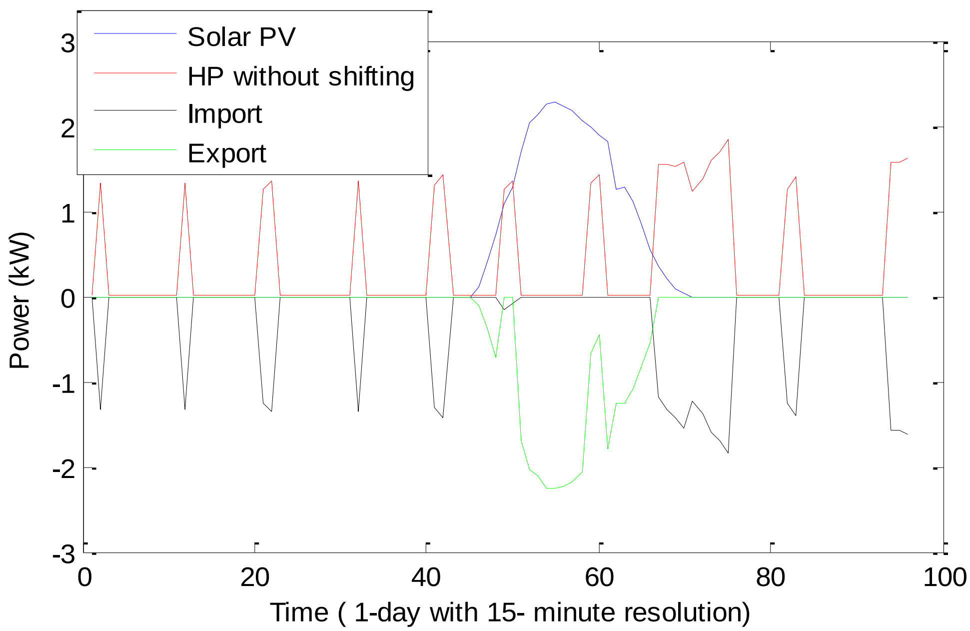

Figure 30: Solar PV, import and export power without load (HP) shifting, H2, 9-Dec-15

Figure 30 shows the solar PV, HP, import and export power without HP shifting for one clear day in December. Here, the total demand is not covered by the solar PV but from 11:15 to 16:15 the BIPV is exporting a net power of 25.9 kW to the grid, whereby importing a net power of 30.6 kW during a time with not enough solar PV. With load shifting, it is economical to decrease this grid- BIPV power exchange.

5.3.Analysis of non- shiftable loads

In this thesis, non- shiftable loads (Ventil, CP, FC) have lower power consumption compared to the heat pump. From Figure 31 (H2, May) and Figure 32 (H2, December), ventilation shows higher variations in power consumption compared to CP and FC. The average power of ventilation (0.147 kw) is more than ten times that of fan convector (0.011 kw), while that of circulation is 0.041kw.

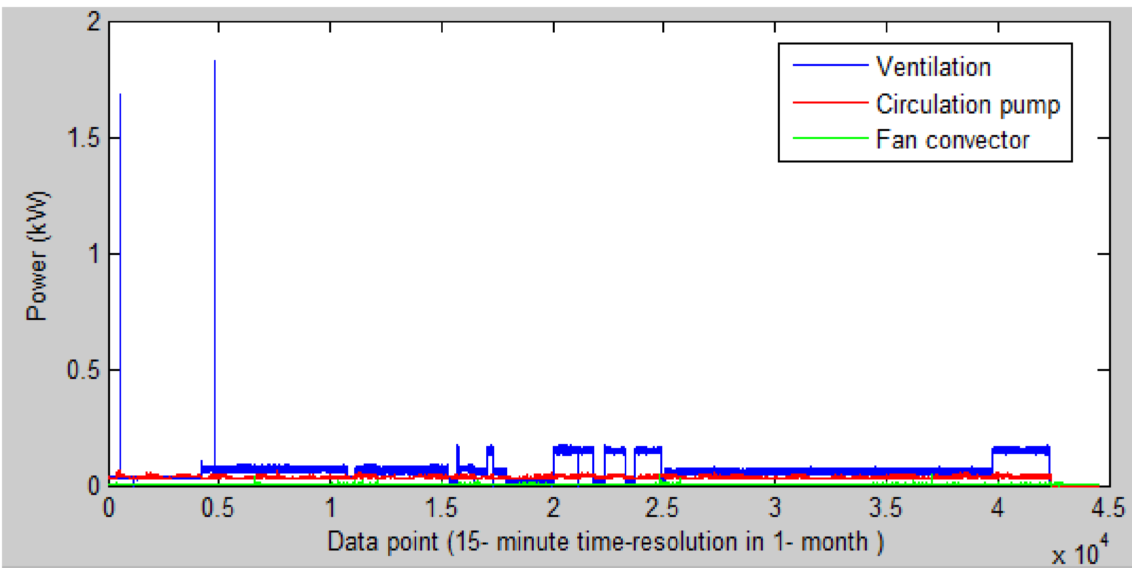

Figure 31: Power consumption of non -shiftable HVAC loads, May2016, H2

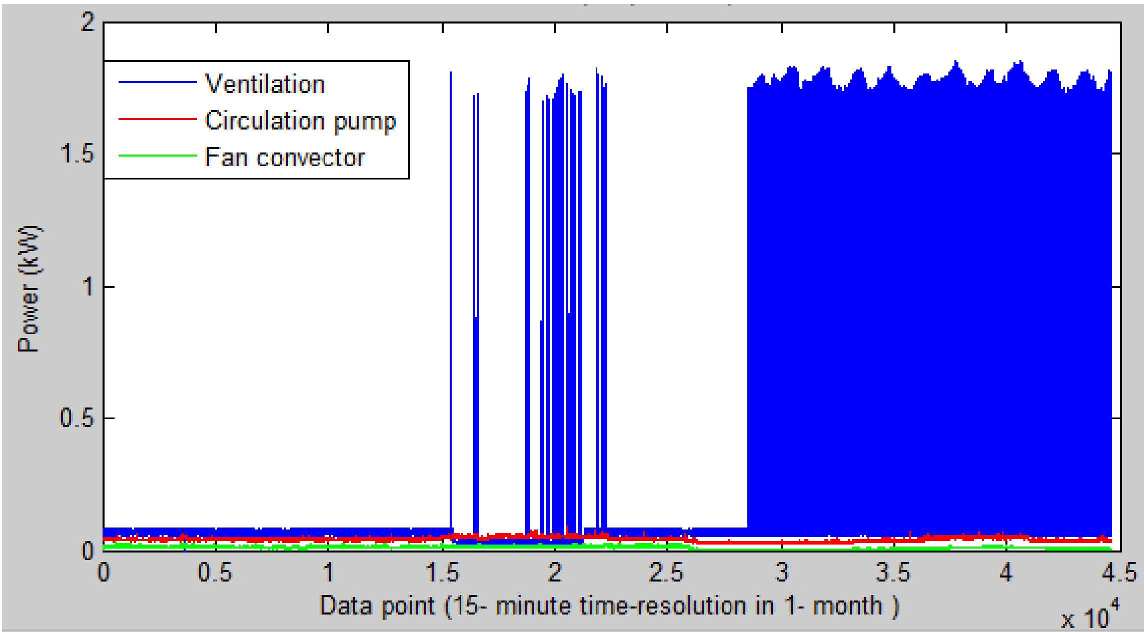

Figure 32: Power consumption of non -shiftable HVAC loads, Dec 2015, H2

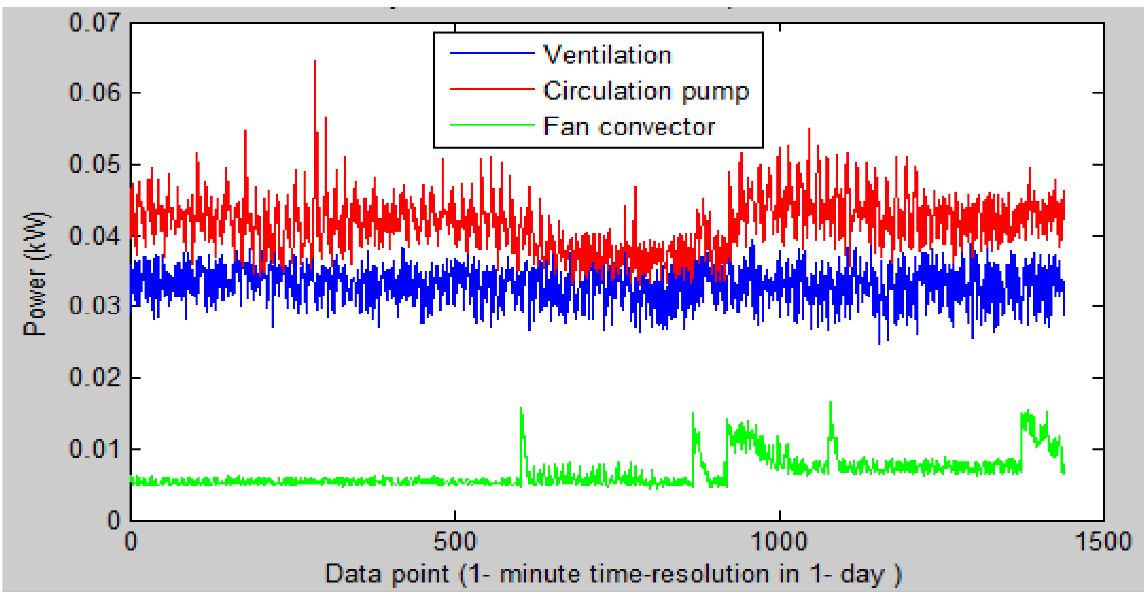

Figure 33: Power consumption of non -shiftable HVAC loads, weekend day, 9 Apr 2016, H2

These non-shiftable loads implement the BIPV system's power constraint on the household appliances that are fixed and cannot be shifted and power consumption with these loads is not varying regularly like that of shiftable loads which are switched ON and OFF in a constant interval of time. For example, by comparing load profile of ventilation from *Figure 31* to *Figure 33* using different time- resolutions (1- minute and 15- minute), there is irregularity in power demand, which implies that it is not possible to control this load in terms of load shifting. It also reports that the energy cost of the non- shiftable loads is changing according to the time of use of these equipments.

5.4. Energy cost for heat pump and solar PV

Figure 34 illustrates an example of excess solar PV energy production (supposed to be exported) and excess heat pump energy consumption (supposed to be covered by the grid) and the corresponding costs in H2, for a clear day of 12th Apr 2016. During this day, for PV production of 45.7 kWh, there is 41.87 kWh to be sent to the grid and sold at price of 12.56 NOK. In this day, when PV production is less than HP demand, HP requires 5.37 kWh at cost of 4.29 NOK. By maximizing the utilization of this PV energy using load shifting method, the whole demand is covered by solar PV and no energy needed from the grid. Here, excess PV (exported) is calculated by considering the time where the load (heat pump) is using less energy compared to that generated by solar PV, while excess HP(imported) is when the heat pump is not covered by the on -site PV energy production and requires additional energy from the grid to cover its demand.

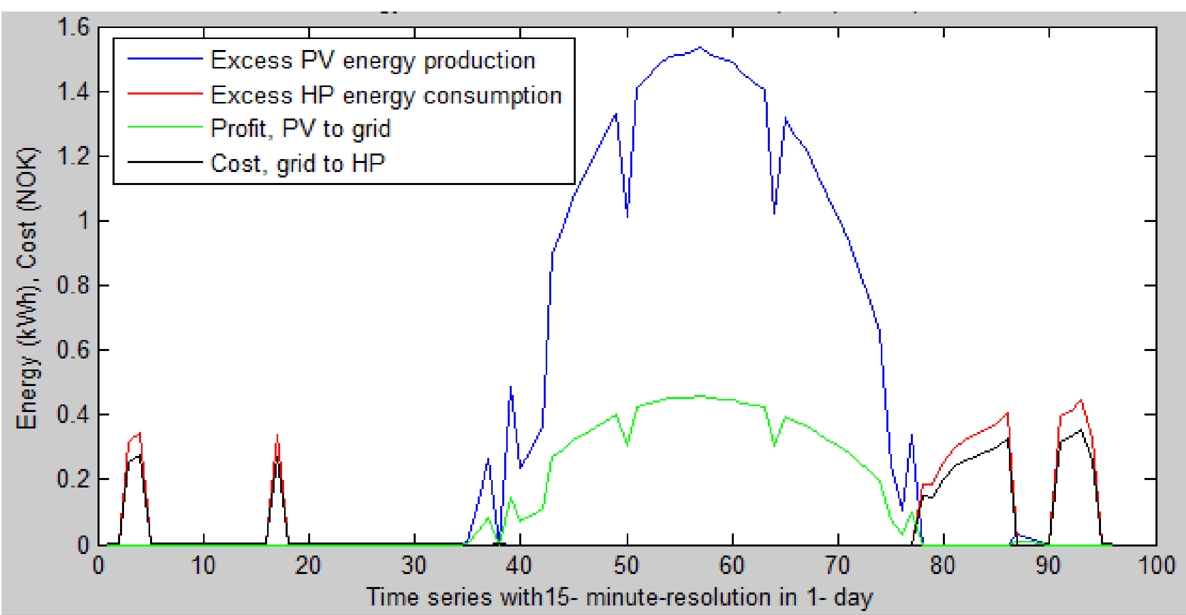

Figure 34: Excess PV energy (exported) excess HP energy (imported) and associated profit and cost for solar PV production and HP consumption without shifting, H2, (12 Apr 2016)

From Appendix -A Figure J shows the monthly value of excess PV and HP energy and associated profit and cost for H2, Dec 15- May 16(calculated from 15- minute- resolution data).To avoid this unbalance of energy tariff for purchased and sold electricity, load shifting (for selected months May and April) is used to maximize the use of this solar PV production instead of selling it back to the grid.

5.5. Load shifting analysis

By using scripts developed in MATLAB according to the method described in chapter 4, HP demand is shifted to the time with higher solar irradiance, meaning higher PV energy production so that the energy generated during this time is stored by help of domestic hot water storage, which can be used at time without solar irradiation (morning and night). In this section, the impact of load shifting with HP is discussed with corresponding reduction in energy cost.

5.5.1. Heat pump load shifting

During load shifting, the building users must agree to a shift of his electrical devices if there is no lack of comfort in electrical energy demand like building heating or domestic hot water demand. So, HP shift must match with building user heat demand sufficiency all times. With help of DHW storage, the heat demand can be covered either by the heat storage tank or by direct use of electricity (from grid or solar PV). Figure 35 (left) shows the HP demand with solar PV production before applying load shifting method for 1 clear day in May. The result for HP shifted at time with high solar energy production is shown in Figure 35 (right). In this shifting, the HP is switched on at time with solar PV energy production greater than HP demand continuously and is stopped when fulfilling the daily heat requirement with the energy being the same as that before shifting.

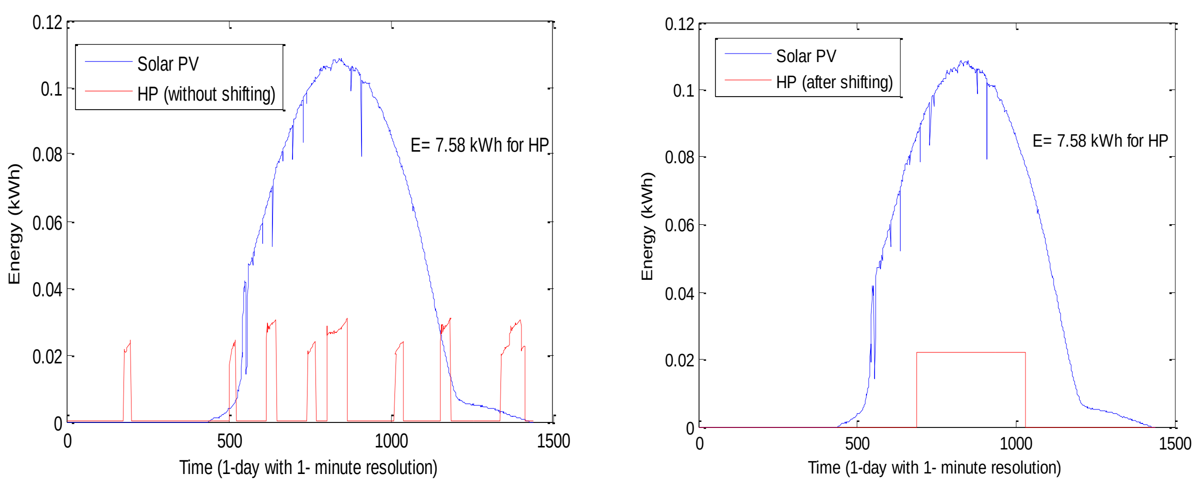

Figure 35: HP without shifting(left) and HP shifted(right), H2, 25-May16

Here, the total HP demand is fully covered by the solar PV power production and no power imported from the grid is required for its operation, which is the advantage of load shifting. In both cases (left and right) from Figure 35, the total solar PV is 51.44 kWh, while that for HP is 7.58 kWh before and after shifting. With shifting, the HP is running continuously from 11 am to 6 pm, meaning 7 hours of working instead of running it for the whole day (24 hours). During this time, the whole heat generated cannot be used, this heat is used for DHW tank heating, which could be used at time with no solar PV generation, and this is discussed more in section 5.8.

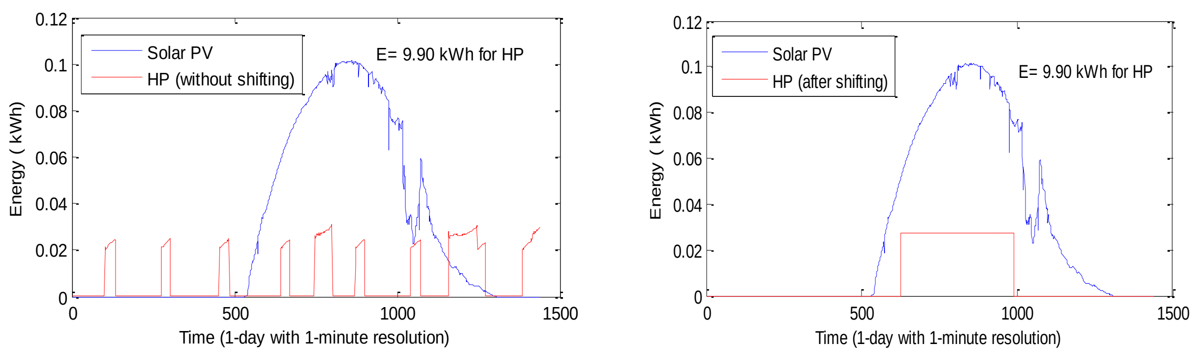

Figure 36: HP without shifting(left) and HP shifted (right), H2,1- April 2016

Figure 36 shows the HP demand profile with and without load shifting, for example, a clear day in April. The result of this shifting shows the increase in self- consumption with solar PV production and the total demand is covered by on- site energy production without importing energy from the grid as shown in this figure (left). During this day, the HP is operating from 11 am to 4 pm (5 hours) to complete the whole heat demand in the house.

Considering winter day (4- December 2015 in Appendix- A, Figure -G), solar PV will not cover the whole HP load demand in the building but there are some hours where there is enough PV power production. From that figure(left), the HP is switched on and off during the whole day and thereby importing power from the grid to cover the demand. This figure (right) shows the HP after shifting at time with PV production. Because of lower PV production with higher HP demand for this day, the total load is not covered by only solar PV, it shares demand with grid.

For this condition for importing energy from the grid after load shifting, it is not very important to apply shifting control strategies during the period with lower solar PV production, especially winter seasons. To apply load shifting, it does not change the total load energy, therefore, the energy before and after load shifting remains the same as equality constraint. From this figure in general, the HP energy consumption remains equal to 14.63 kWh for both cases (without and after shifting) as highlighted in figures. In this shifting, the HP is operating continuously during daytime to maximize the available solar PV energy until its total energy becomes the same as before shifting.

It is important to note that, for the case with HP load shifting, the HP is not receiving energy before the availability of solar PV irradiances because the whole HP demand is shifted at time with higher solar PV and the DHW tank in not receiving heat from HP. When the solar PV energy becomes high, the HP is electrically supplied from solar PV source, and the heat generated is supplied to the DHW tank and this tank is used as heat storage, when the stored heat will be used for the next time (during the night). Design of volume of DHW tank is referred to the time required to heat water up to 90 ^{o}C as shown in Figure 52.

5.5.2. Cost of heat pump energy before and after shifting

In this section, the impact of HP load shifting was evaluated with regards to the cost of importing and exporting electrical energy from or to the grid. From Figure 37 to Figure 40 the cumulative costs of imported energy and profit of exported energy before and after load shifting are shown. From Figure 37, due to high PV production as clear day in May, the import energy after HP load shifting is zero, meaning that there is no cost for importing energy from the grid during this day, and the corresponding values are highlighted in Table B from Appendix- A.

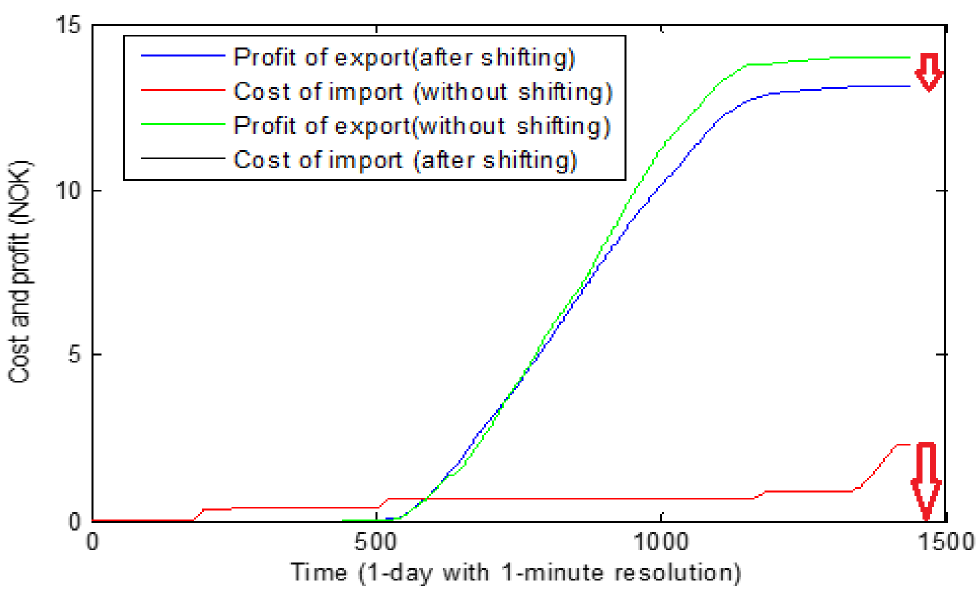

Figure 37: Cost of import and profit of export before and after shifting, H2, 25-May-2016

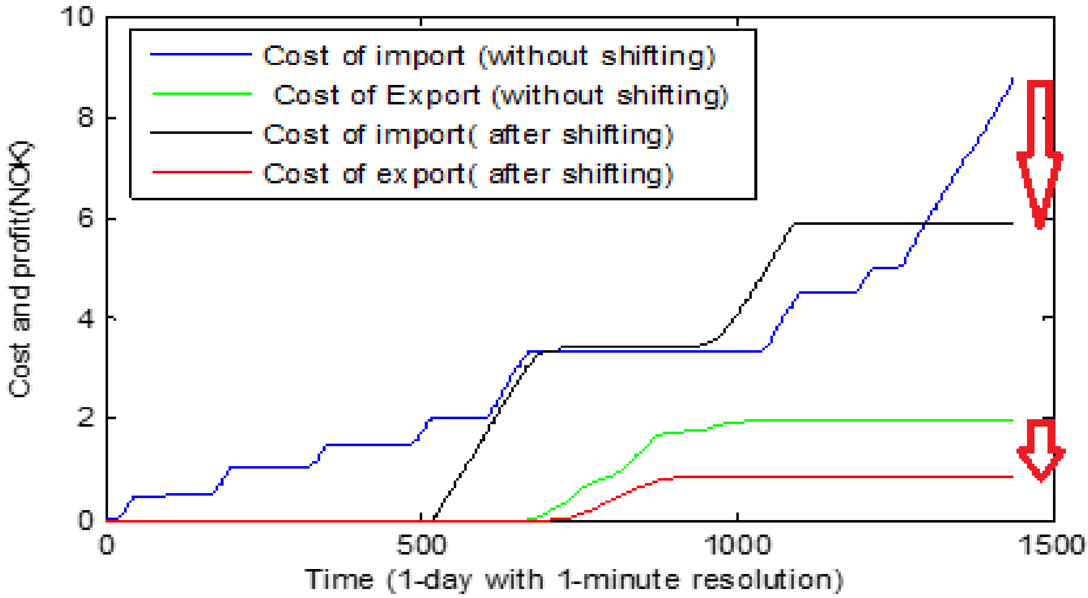

Figure 38: Cost of import and profit of export before and after shifting, H2,4-December- 2015

Figure 38 shows how cost of import and export is reduced after applying load shifting. In this analysis, the time with high PV production are considered during the shifting of HP demand. Generally, in December, there is low PV production with high power demand, which affects the house owner and the power grid company. After shifting HP, the cost of import is reduced from 8.76 to 5.89 NOK, while the profit of exporting energy to grid is reduced from 1.96 to 0.88 NOK. From Figure 39 of 3rd February-2016, after shifting HP, the cost of import is reduced from 6.25 to 2.50 NOK, while the profit of exporting energy to grid is reduced from 4.29 to 2.88 NOK.

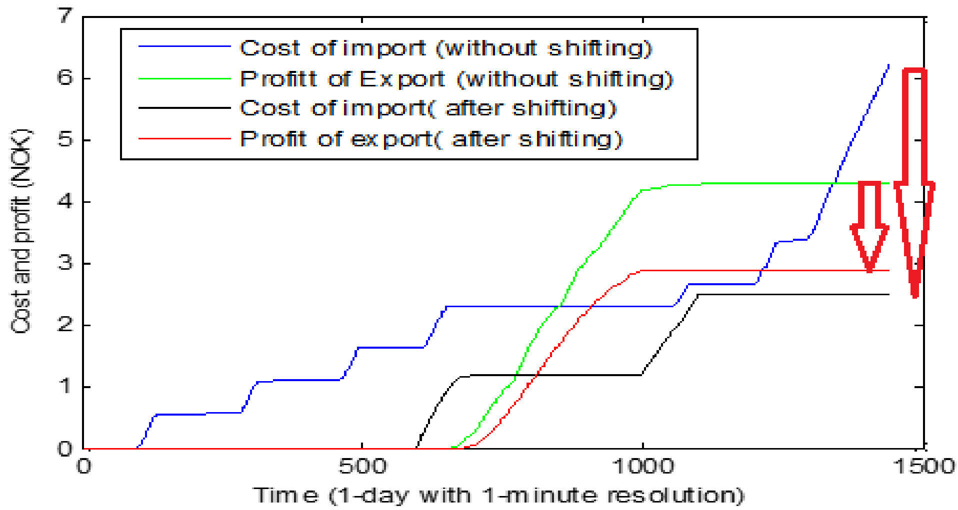

Figure 39: Cost of import and profit of export before and after shifting, H2,3-February -2016

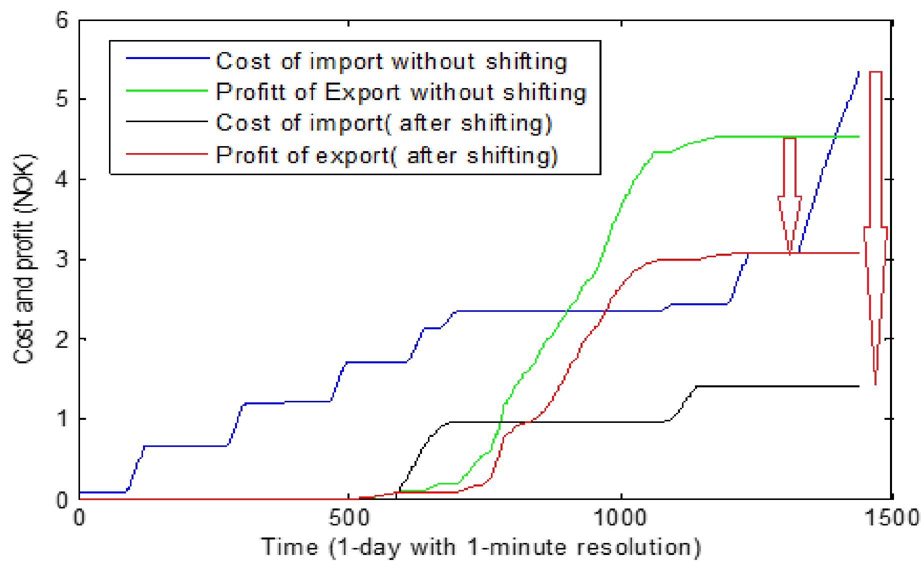

Figure 40: Cost of import and profit of export before and after shifting, H2,26 March -2016

During this analysis, clear (weekend and working) days within six months have been selected. From Figure 41, the cost of importing power from the grid and the profit of exporting power to the grid are reduced with help of load shifting.

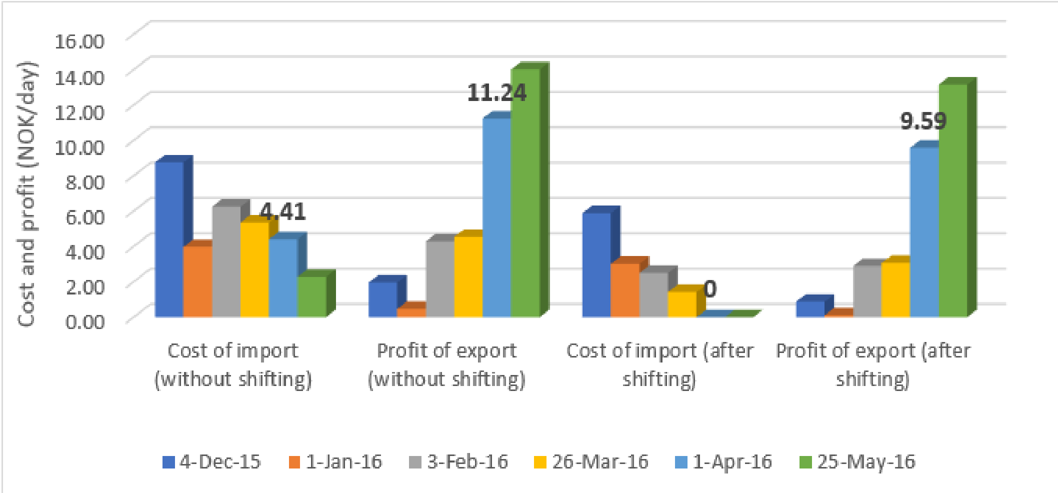

Figure 41: Daily cost and profit before and after shifting HP for selected days (H2, 1-minute resolution)

For the time with high solar irradiation, after HP load shifting, the cost of imported energy is reduced up to zero cost. For example, refer to the moth of April in Figure 40, the cost of import energy is reduced from 4.41 NOK to 0 NOK after shifting, while the profit of exporting is reduced from 11.24 NOK to 9.59 NOK. As results of load shifting, less amount of money is paid to the grid company due to the reduction in energy importation. This may help to improve grid stability because high peak demands are shifted at time with high PV power production. Thus, refer to [72], when the surplus energy is injected to the grid network, it may cause power quality issues, such as voltage violation. Under this condition, it is assumed that customer is not allowed to inject power into the grid if the BIPV is not well controlled and certified for grid energy exchange, thus, this requires advanced and modern technology to match the on-site power quality with that of grid. However, if the building owner can shift a percentage of the consumption to the high PV production period in the middle of the day, then the self- consumption could be increased.

5.5.3. Improving load factor with load shifting

The load factor(LF) expressed as percentage is obtained by taking the total kilowatt-hours (kWh) consumed in a month divided by the product of the maximum demand in kilowatts (kW) and the number of hours in that month. LS can also be explained as average load over maximum demand during given period [73] as shown in equation (5.1).

$$LF(\%) = \frac{Energy(kWh)}{peak.demand(kW)xhour} \tag{5.1}$$

The higher the LF is, the smoother the load profile is, and the more the infrastructure between grid and the building demand is being utilized. The highest possible load factor is 1, which indicates a flat load profile and the lowest is zero. Referring to equations from chapter two and four, load shifting is important in maximizing the load factor of grid system. Therefore, Figure 42 illustrates the percentages of LF before and after load shifting for selected clear days in six months, where for example the LF for the 1- day in March has been increased from 25.5 % to 38.5 %. It can be concluded that with load shifting, the LF is increased during for the whole selected days in the six moths.

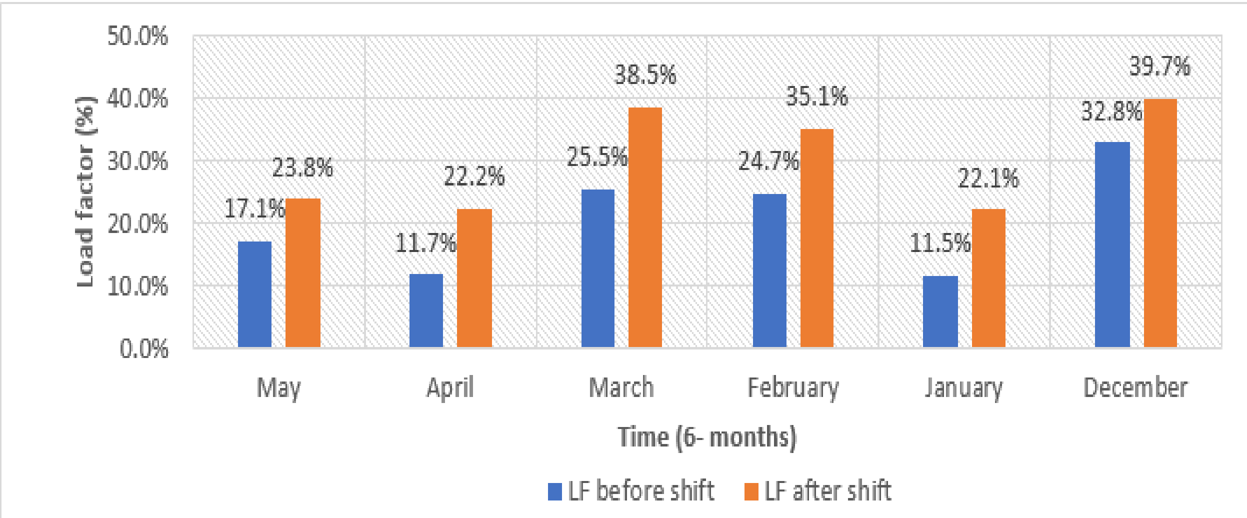

Figure 42: Load factor before and after load shifting in six months in H2

Furthermore, a good load factor implies a more constant rate of electrical use, because kW demand is held to a minimum relative to total overall use. In this context, the lower the existence of power demand with respect to kilowatt-hour (kWh) use, the better the load factor, the lower the relative cost for electric service.

5.6.Analysis of self-consumption with heat pump shifting

In this section, the HP shifting is done only for two months (May and April) in house H2, where there is more irradiance, which implies that the solar PV energy production is great than energy consumption for HP for the evaluation of PV self- consumption. Figure 43 and Figure 44 show the self-consumption during one week in May 2016 for heat pump with and without shifting with corresponding PV energy production respectively, based on 15- minute resolution data.

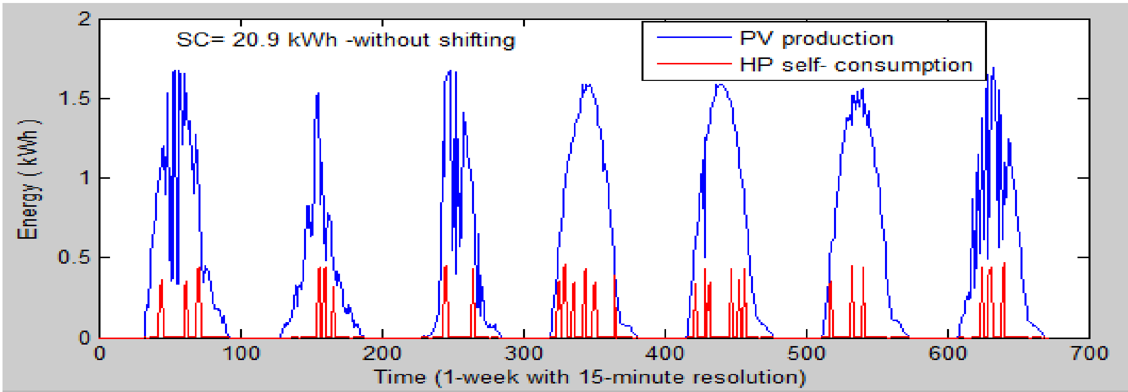

Figure 43: PV energy production and self-consumption for heat pump without HP load shifting, May-2016, H2

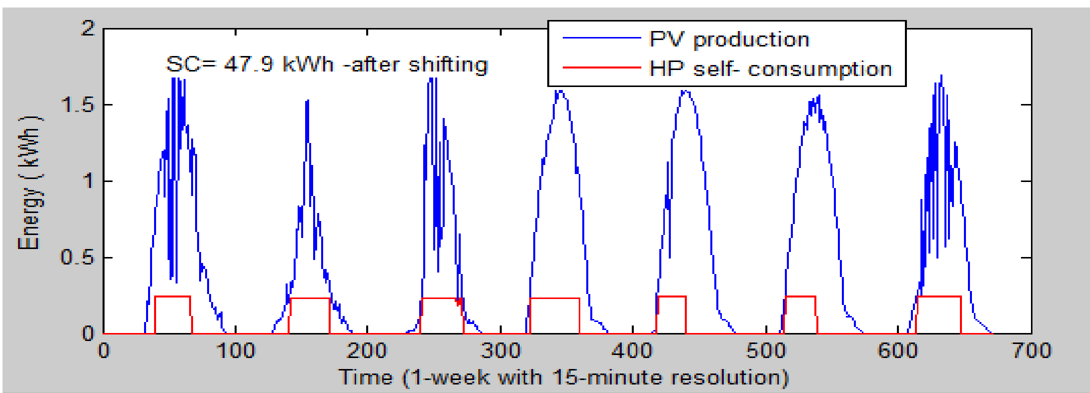

Figure 44: PV energy production and self-consumption for heat pump after HP load shifting, May-16, H2

From these two figures, the importance of shifting the HP is to increase the SC by 43.6% after HP load shifting as highlighted in both figures, which results in reduction of energy imported from or exported to the grid. The additional role of this shifting is that the HP is operating on a fixed rated value of 3.8 Watts, which results in minimizing the peak load operation of HP which reaches at 7.8 Watts (15:45:00) at the last day of this week when there is no HP shifting. This peak demand of HP is having an inconvenient to the grid distribution network because this causes the fluctuation in the grid system as explained previously.

Figure 45 shows two operating modes of HP when is shifting and not shifted with regards to the generated solar PV energy of 1081.64 kWh for one month in May 2016. Thus, the resulting data for SC without and after HP shifting for the month of May and April 2016 are illustrated in Figure 48, which shows that the shifting method is important because the SC is increased 2.2 times (from 84.1 to 188 kWh) that without HP load shifting. The figure for April-16 showing the SC without and after HP shifting is illustrated in Appendix- A Figure I. From Figure 45 , five days (22nd, 23rd, 29th, 30th and 31st) are with lower PV energy production with respect to the HP consumption [($P_{PV}(i)<P_{HP}(i)$], which makes load shifting impossible as explained in algorithm for load shifting in chapter four.

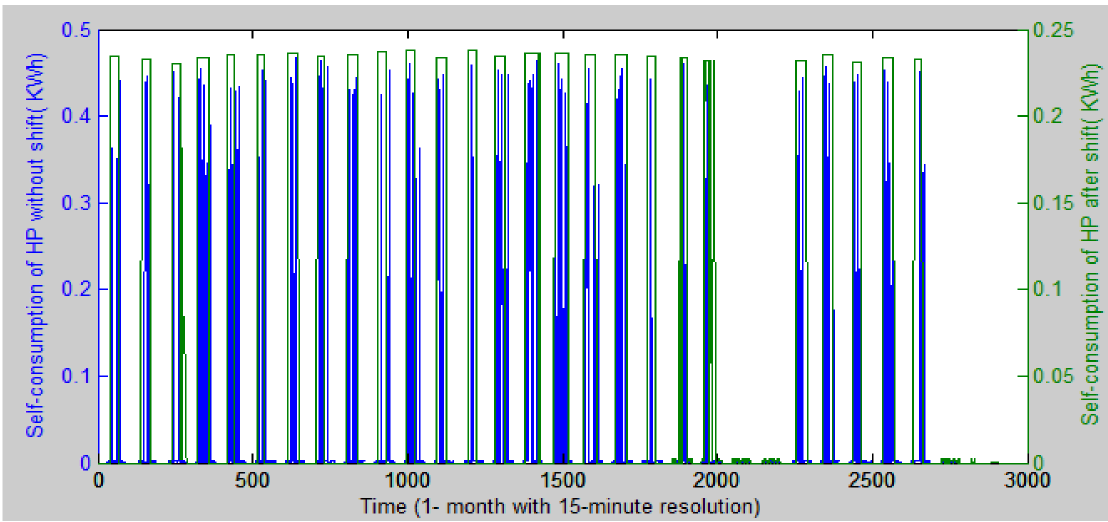

Figure 45: Self-consumption without HP shift(blue) and with HP shifting (green), May-16, H2

Figure 46 shows the SC without HP shifting and the required energy to be imported from the grid (green line) to cover the HP demand during 1-week in April. During this time, with the total solar PV energy produced 225.85 kWh and HP energy consumption of 65.98 kWh, the only self-consumed energy with HP from solar PV is 9.7 % o when there is no HP shifting, which implies that the energy required to cover the HP demand is to be imported from the grid. From Figure 47, the SC is increases by shifting the operation time of HP to the time with higher PV energy production, where this SC is improved up to 25.3 %. Comparing the SC without and after HP shifting this SC is increased 2.6 times that of without HP load shifting, with is important as strategy to increase PV SC with BIPV systems.

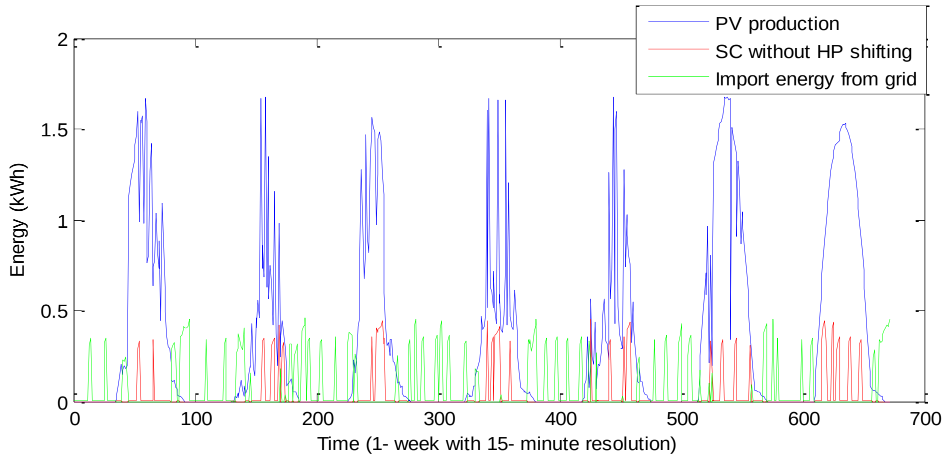

Figure 46: PV energy production, grid import and self- consumption without HP shifting in 1- week (14-20, April 16), H2

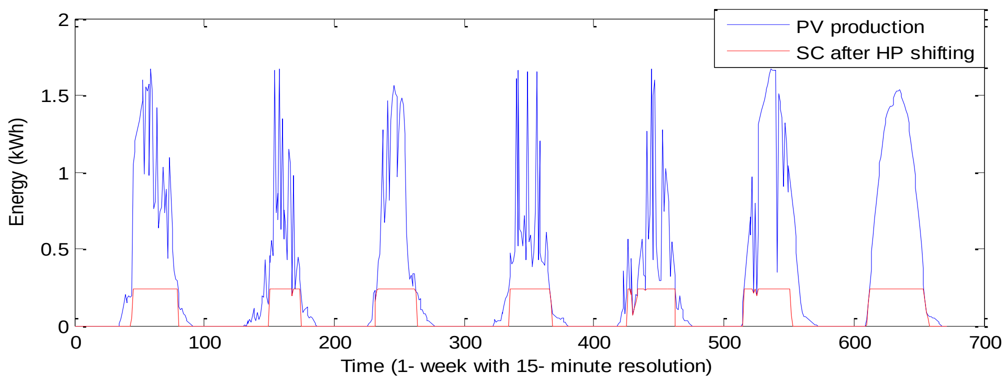

Figure 47: PV production and self -consumption after HP shifting in 1 week (14-20, April 16)

Figure 48 illustrates the summary of improved SC after HP shifting for both May and April with respect to the PV energy produced and HP consumption. From this figure, it can be observed that, with a HP consumption of 231.22 kWh in May, the SC is increased from 36.75 % to 81.31 %, while in April with the HP consumption of 286.18 kWh, the SC in increased from 27.15 % to 70.48 %. By analyzing energy flow from the grid and HP, the sum of energy imported from the grid with the SC energy is equal to the HP consumption without shifting.

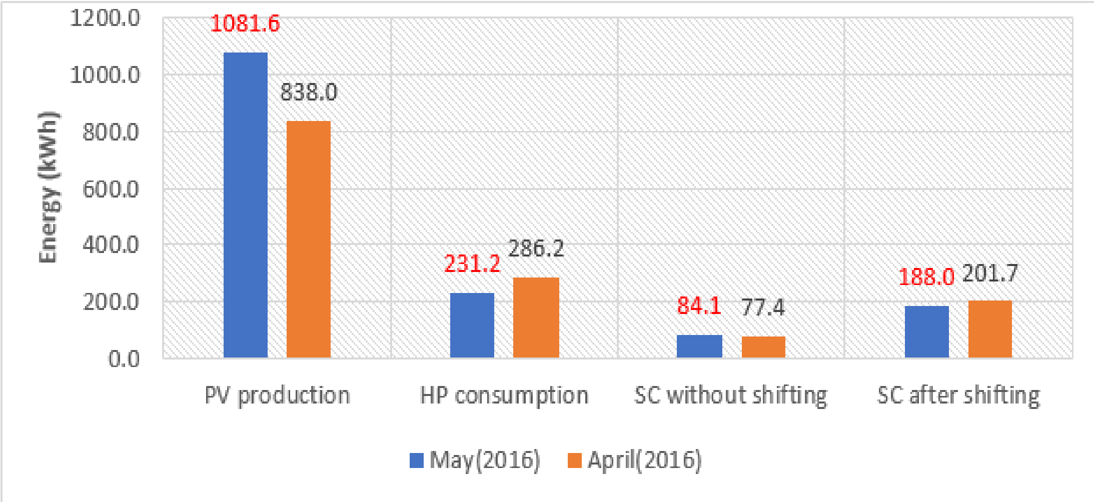

Figure 48: Summary of SC with solar PV and without and after HP shifting, May- April (2016), H2

Shifting the operation of the HP at daytime would be a possible means to greatly increase the SC of electricity production and reduce the grid interaction without an expensive technical effort. The results show that, the operation of the heat pump is limited to daytime from 10 am through 7 pm, where is higher solar PV production. The monitored data shows this is sufficient to heat the building and the domestic hot water. By reducing run-time also would further increase self-consumption and reduce grid interaction and run it continuously during the time where $P_{PV}(i)>P_{HP}(i)$ [43].

5.7. Heat pump and ground- source heat

A ground source heat pump increases the temperature from the ground by between one-and-a-half and four times [74]. During this thesis, the forward temperature (F_{Temp}) from ground heat source(GHS) to the heat pump and return temperature (R_{Temp}) from the heat pump to GHS are presented by considering data of the month of May. By using equation from chapter four, the heat flow from the HP (Q_{HP}) can be calculated with help of temperature difference and heat capacity or thermal capacity (Cp). Note that data for HP consumption after 30th May 2016 (16:20) are missing.

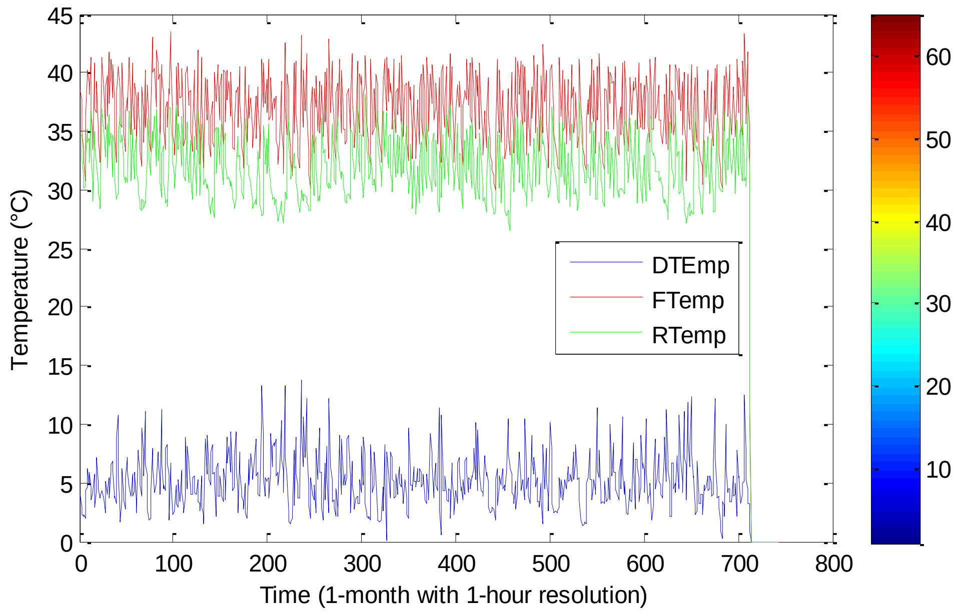

Figure 49: Time series of heat pump temperature, H2, May 2016, 1-hour resolution

The higher the difference in temperature between F_{Temp} and R_{Temp} with higher mass flow of water, the higher the heat production from HP. From Figure 50, the peak heat demand from the heat pump always happens in morning and evening, where people in the house need to use hot water.

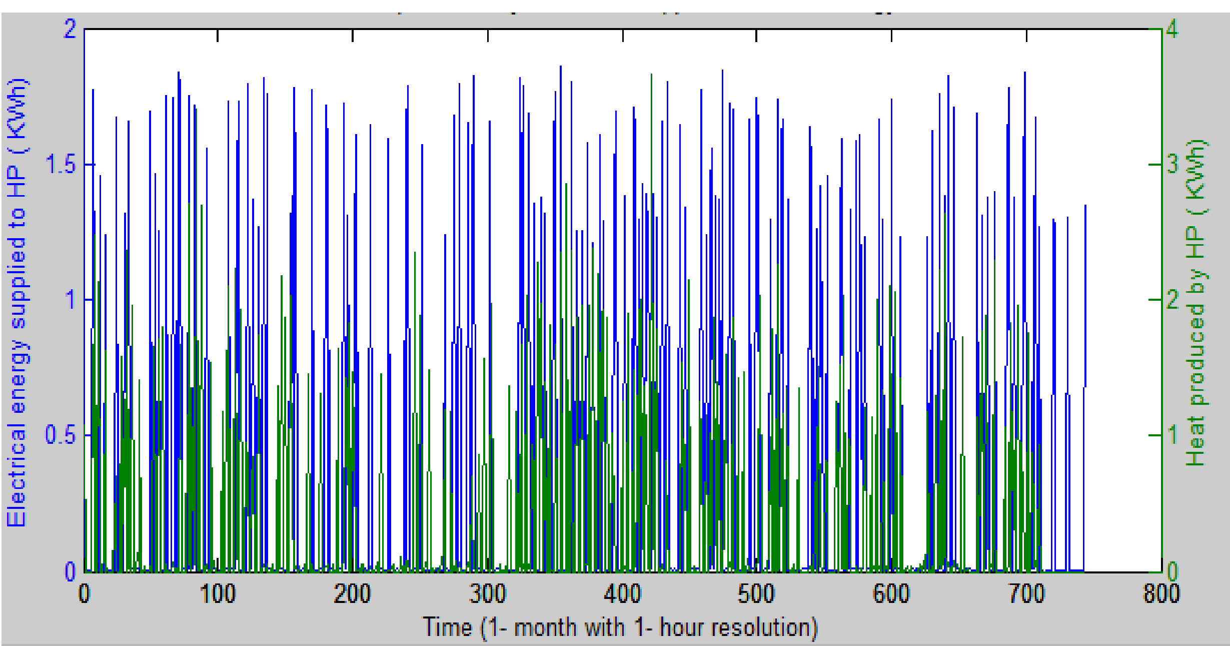

Figure 50: Electrical energy applied to HP and heat produced from HP to DHW tank (May 2016)

As shown in equations from chapter four, the heat produced by HP is equal the electrical power energy applied to the HP plus the ground heat source. Figure 51 shows the cumulative representation of the total electrical energy consumed from either grid or solar PV (P_{Ele}) and the corresponding heat produced from HP (Q_{HP}) with ground heat source(Q_{HS}).

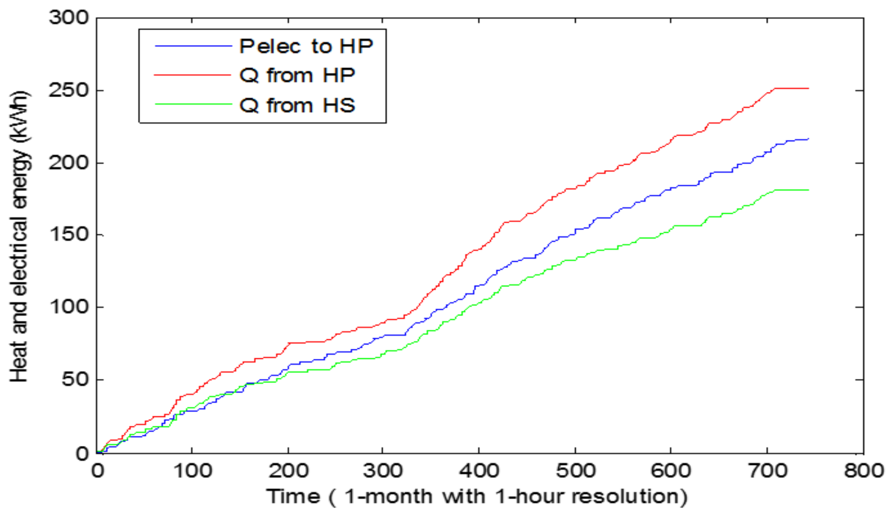

Figure 51: Cumulative electrical energy applied to HP, heat produced from HP and ground heat source

In the heating process, this heat from HP is applied to the DHW tank to heat water, which in turn will be used in hot water demand and building heating. The more the heat produced with corresponding temperature, the more the better performance of HP as result of equation (4.8). Thus, the better the HP, the more the temperature in the building for domestic use is produced.

5.8.Heat flow, temperature and volume of DHW tank

In this section, a model of 4 types of volumes is presented to evaluate the time required to heat up to 90 ^{o}C for a small volume and big volume tank of water. The excess sola PV energy is used to for DHW tank heating as heat storage instead of exporting it into the grid distribution network.

5.8.1. Analysis of hot temperature with different volumes of DHW tank as models

In this analysis, the time taken to get T_{hot} from 40 ^{o}C to 90 ^{o} C for four types of tank taken as models with 50, 100, 150 and 200 liters were found and results are plotted in Figure 52, by considering lossless heat flow from HP to the DHW tank. When the temperature in DHW get s higher than to 90 ^{o} C, the heat produced is considered as heat loss. The volume of DHW tank affects the time required to heat tap water up to the maximum hot water temperature. In this model, it is assumed that the HP is with rated power 0f 1 kW is considered to heat water up to maximum allowable temperature in the tank of 90 ^oC (T_{hot}), with cold water temperature of 40 ^{o} C (T_{cold}). Considering that there is no heat loss in pipes between HP and DHW tank, equation (4.8) and (4.14) are equal to find the T_{hot} in the storage tank. This T_{hot} can be found using equation (5.2).

$$T_{Hot} = \frac{Q_{\tan k}}{C} + T_{cold} \tag{5.2}$$

where, C: heat capacity of the of water.

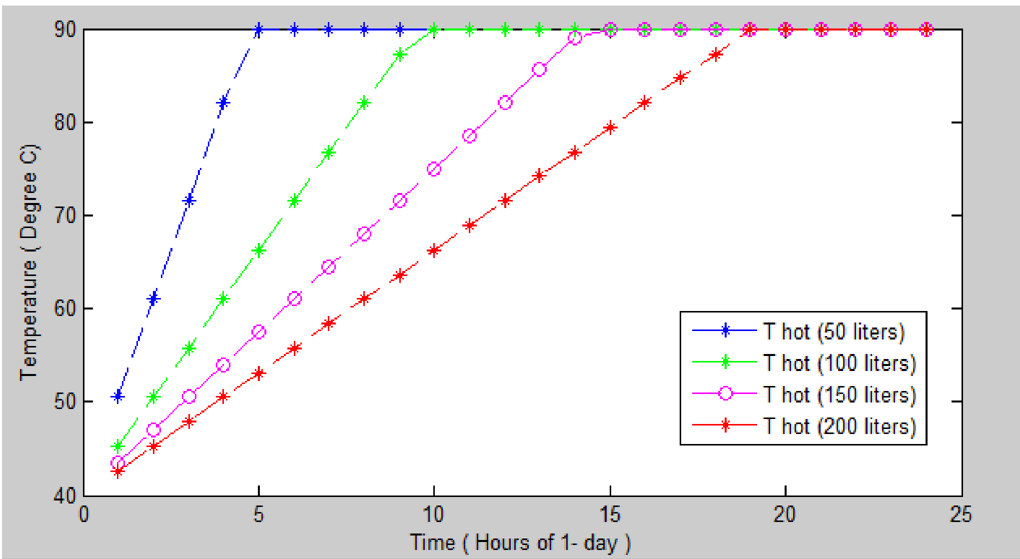

Figure 52: Hot temperature from HP using 50, 100, 150 and 200 liters of DHW tank as models

Comparing these four cases in one figure, it is shown that with increase in volume, the time required to heat tap water from low temperature to the maximum allowable temperature of DHW tank increases also. Thus, referring to the Figure 52, as the volume is doubled, the time required to heat the temperature up to 90 ^oC is also doubled. For example, it takes 5 hours to rise 50 liters up to 90 ^oC, 100 liters requires 10 hours, 150 liters is 15 hours, while 200 liters requires 20 hours.

This model is important is designing a backup DHW tank, which can be used to store the excess solar PV energy instead of selling to the grid. Generally, for a hot water tank, the volume of hot water consumption through a thermally stratified tank is less-compared to a mixed tank. The reason is that the temperature in the top part of a stratified tank as well as the outlet from the tank is higher, and therefore less volume of hot water is needed to supply a certain comfort temperature in the building to be used for showering and kitchen. Referring to Figure 11, the average temperature at the top of a stratified tank is generally higher than in a comparable mixed tank. Thus, the comfort temperature is more often available in a stratified tank, where it is shown in Figure 11.

5.8.2. Hot temperature in DHW tank in Skarpnes house

During this case, the HP is supposed to use electrical energy from either solar PV or from the grid, and with low HP energy consumption, the temperature in the DHW tank is towards the minimum allowable limit (here set 40 degrees Celsius) due to low heat generated from that electrical energy consumed by HP. The hot temperature of DHW tank is proportional to the heat stored in the tank. Figure 53 shows the profile of P V production and HP consumption energy for 1-week (22- 28 May 2016). The electrical energy of this HP converted into heat, which is then applied to the DHW storage tank. As shown in this figure, the HP consumption at day five is low, which results in low heat generation.

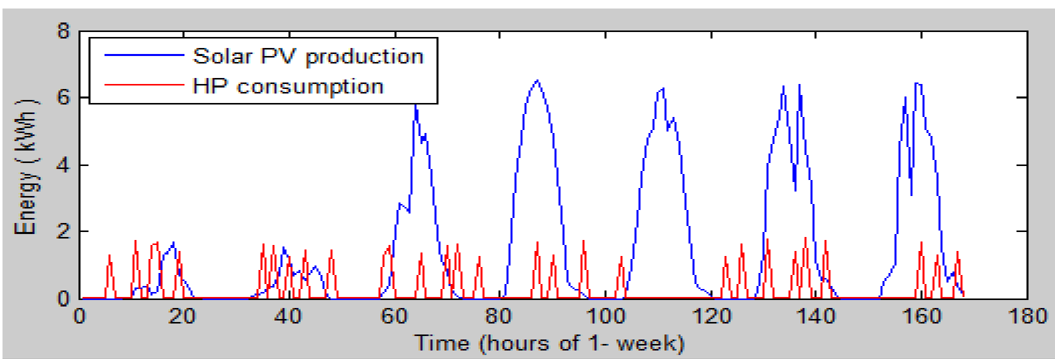

Figure 53: PV production and HP consumption energy for 1- week, (22- 28 May 2016)

Figure 54 and Figure 55 show the variation of hot temperature inside DHW tank with corresponding heat storage for one week in December and May, obtained as cumulative, where the DHW tank is heated for the whole day with assumption that no hot water is removed from the tank. As shown in Figure 54, the hot temperature for the day five does not reach to 90 ^{0} C due to low heat applied to the DHW tank from the HP, because at this day, the HP is using less electrical energy, which is converted into low heat.

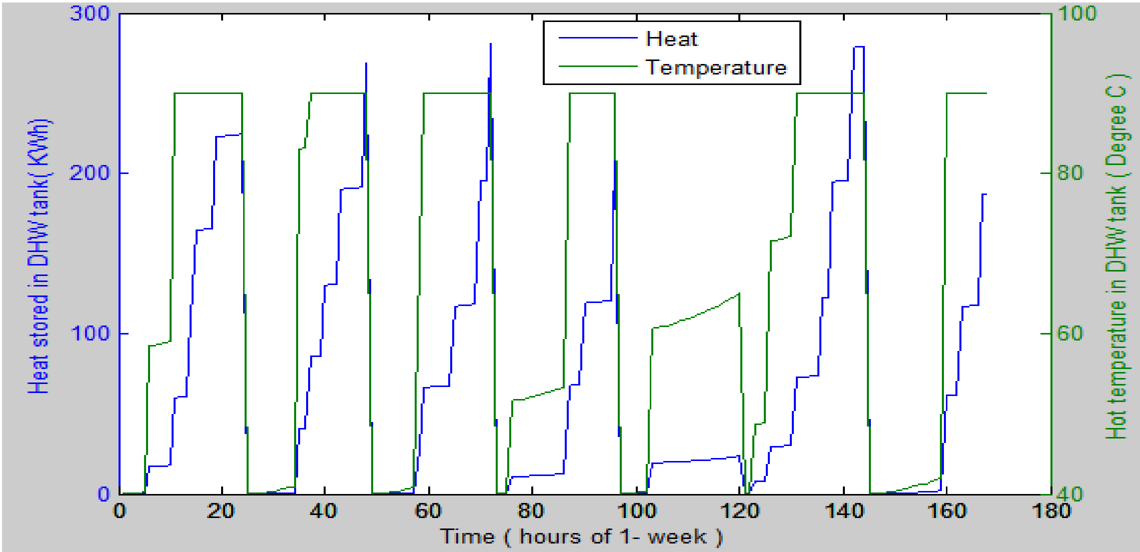

Figure 54: Hot temperature and heat stored in DHW tank, H2, 1-week (22-28 May 2016)

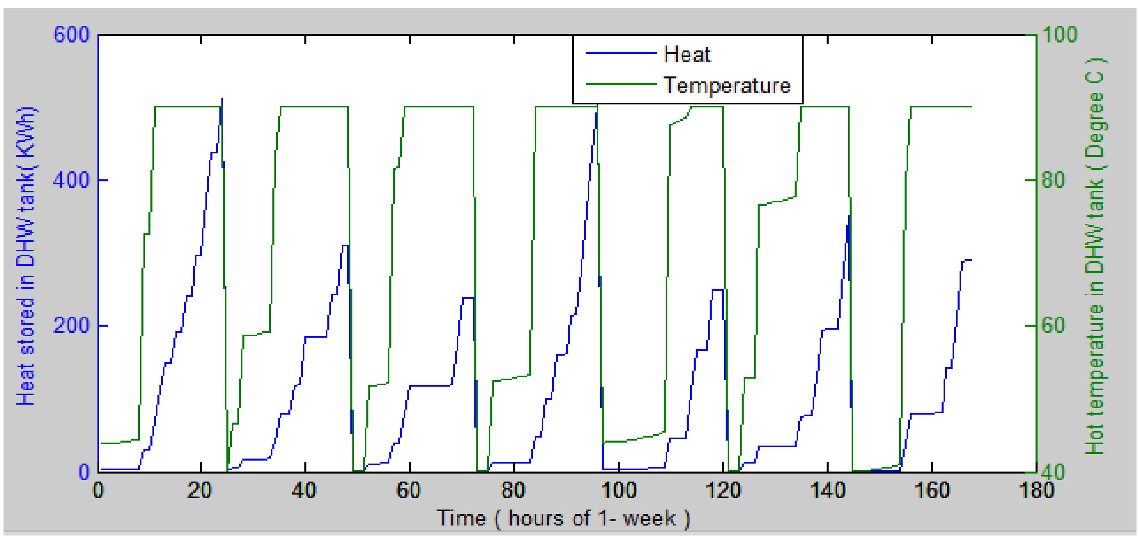

Figure 55: Hot temperature and heat stored in DHW tank, H2, 1-week (1-7 Dec 2015)

From these two figures, the heating process is done for rising the temperature in DHW tank from 40 to 90 ^{o} C. When the temperature reaches to 90 ^{o}C, the heating process is done at constant temperature, where the excess heat in this process is considered as loss. Thus, with backup heat storage in terms of DHW tank, this excess heat can also be reused for heating system in the building.

Figure 56 and Figure 57 illustrate the hot temperature distribution inside the DHW tank during one selected week between for December 2015 and May 2016 (refer to Figure 55 and Figure 56). From the figure of December, the hot water is heated 89 times reaching up to 90 °C and 38 times for 45 °C, while from the figure of May, it happens 73 times to heat water up to 90 °C and with 40 times for obtaining 45 °C, and this is clear that in December, it requires more heat to be applied to the DHW tank, where hot water is more needed for domestic services in comparison with that of May.

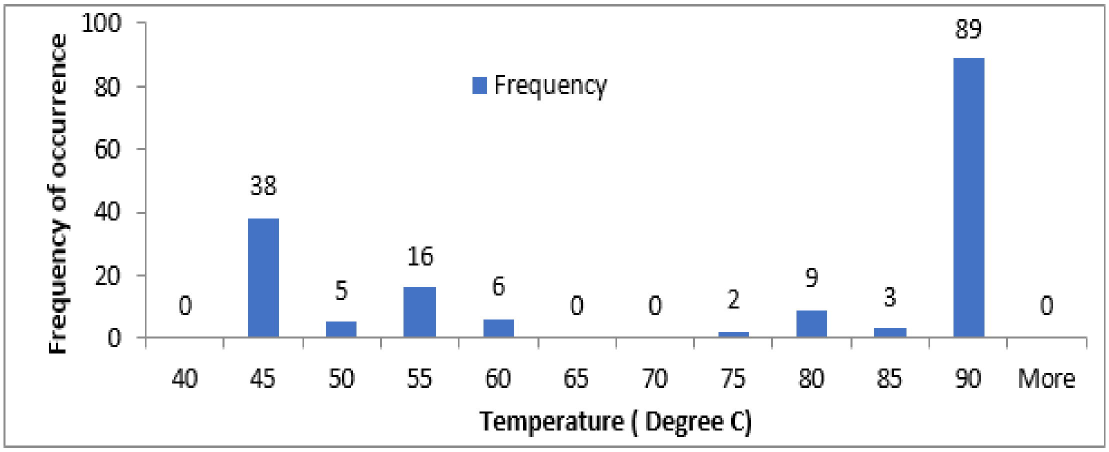

Figure 56: Hot temperature distribution in DHW tank, 1-7 Dec 15

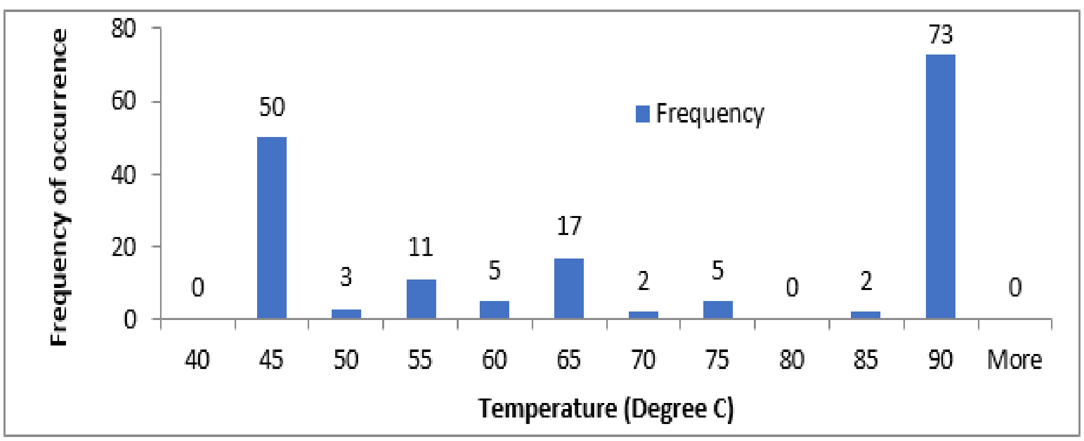

Figure 57: Temperature distribution in DHW tank, 22-28 May 16

However, it is necessary to keep the hot water tank at temperature set-points between 60 °C and 90 °C for eliminating health risks associated with Legionella proliferation, as well as guaranteeing high levels of comfort to the building owner as discussed in chapter two. Thus, the Figure 56 and

Figure 57 clarify that, most of the time, the hot temperature inside the DHW tank is between 60 and 90 ^{0} C.

5.8.3. Improving self-consumption using excess PV for hot water storage

From this section, the excess PV energy (for selected clear six days in six months) instead of being exported to the grid, it is used in DHW tank, where this energy is applied to the HP to produce heat. With the heat supplied to DHW, the time required to heat water from 40 ^{o}C to 90 ^{o}C is found in Figure 58. From this figure, the excess PV energy for only two days (in May and April) can be used to heat DHW tank up to 90 ^{o}C because of high solar irradiance (in spring season), while the maximum temperature in tank using excess PV energy for selected days in December and January are 54.1 and 41.1 ^{o}C respectively, and do not reach to 90 ^{o}C inside the tank.

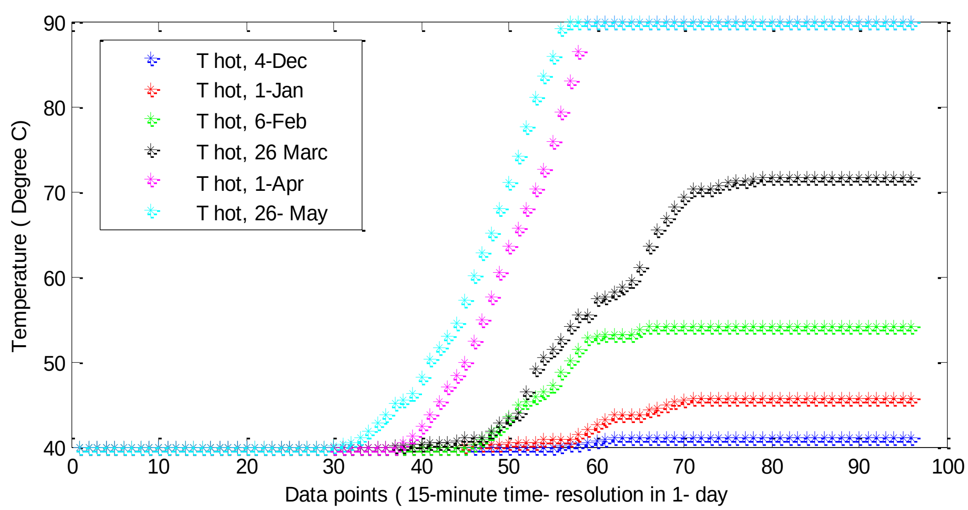

Figure 58: Excess PV energy to heat DHW tank and resulting hot temperature for selected days in H2

It can be concluded that the backup for storing the excess solar PV in terms of DHW storage tank is necessary in BIPV systems especially during the time with higher solar irradiance for saving the cost of energy imported from the grid, which is beneficial than selling the surplus PV energy back to the grid, which results in increasing sola PV self-consumption with HP.

5.9. Demand and supply cover factor analysis

As mentioned in chapter two, the graphical representation of load and supply cover factors gives a quite good picture of the correlation between on-site demand and supply of energy. During this thesis, demand and supply cover factor have been calculated using equation from chapter two, and it becomes useful to evaluate cover factors for HVAC loads and all electrical loads separately. HP shifting also shows the variation in cover factors where the values for both γD and γS before and after load shifting are presented, and as mentioned earlier, the values of γD and γS vary from 0 to 1. Lack of values for γS indicates periods with no solar PV generation, and at this time, γS corresponds to the value equals one. Thus, it is important to know that with a high value of **γ**S, the solar PV is generating least power and the load requires more energy from the grid. Nethertheless, for higher value of of **γ**D, the solar PV is generating more power and the load is covered at sunrise, whereby, the excess of power is to be sent to the grid as advantage for the house owner.

Refering to the work for others, Figure 59 shows demand cover factor γD and supply cover factor γS for the case study of SB6 house. For this case study, there is a significant seasonal variation of γD and γS. For example, in this house SB6, at 2 p.m. The γD varies between 0.38 and 0.99, and the γS ranges from 0.18 to 0.89. It is a result of big azimuth and altitude angle variations during the year. In consequence of it, during summer months the electricity load during the day is almost fully covered by the on-site generation, and still a significant party of the generated electricity, at noon it may even reach 90% or 0.9, is exported to the grid, referring to Figure 59 [63].

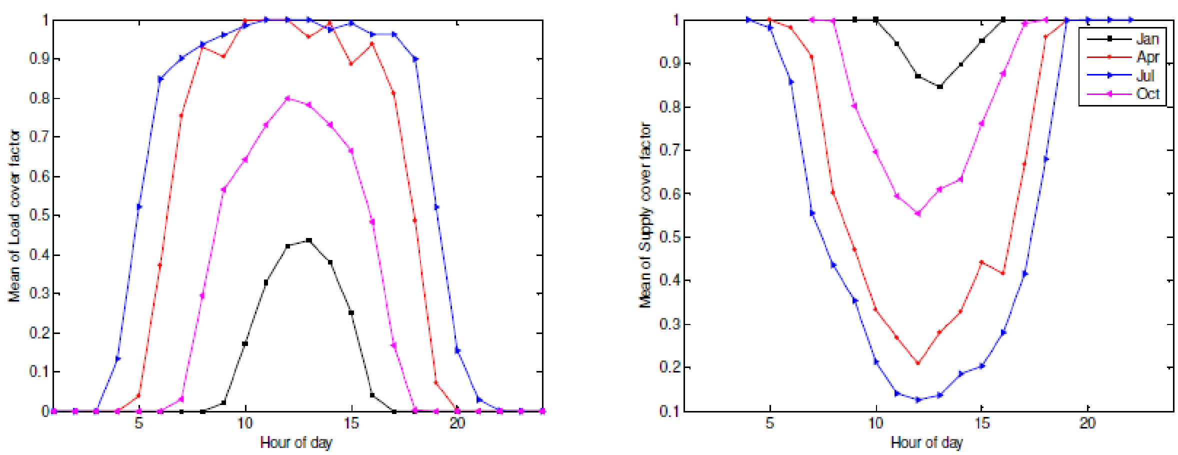

Figure 59: Mean daily load(demand) cover factor (left) and supply cover factor (right) in 4 months [63]

In this work, it can be observed are that, when the γS equals one, local generation is covered (or totally consumed) by local demand, and no excess locally generated electricity needs to be put on the grid. For the γD equals one, this would mean that all demand could be met by local generation. The analysis was made by using high resolution data from both monitored and simulated buildings. The hourly values of the cover factors (γD and the γS) give quite a good balance understanding between on-site demand and supply of energy compared to yearly and daily resolution [75].

5.9.1. Demand and supply cover factor with HVAC loads at Skarpnes

In this section, the γD and γS are modelled by considering energy consumption Pd(t) for HVAC loads in house H2. Figure 60 shows the demand cover factor for six months averaged in hours of day. The γD varies significantly with seasons (from Winter to Spring) and this factor is important in DSM, where it identifies the time at which the load is either covered by the solar PV power generation or not, which implies that there is import or export of energy. While installing the PV system especially in BIPV systems, the γD should be greater than zero and for clear day it can reach to 1 or 100% as shown from Figure 60.

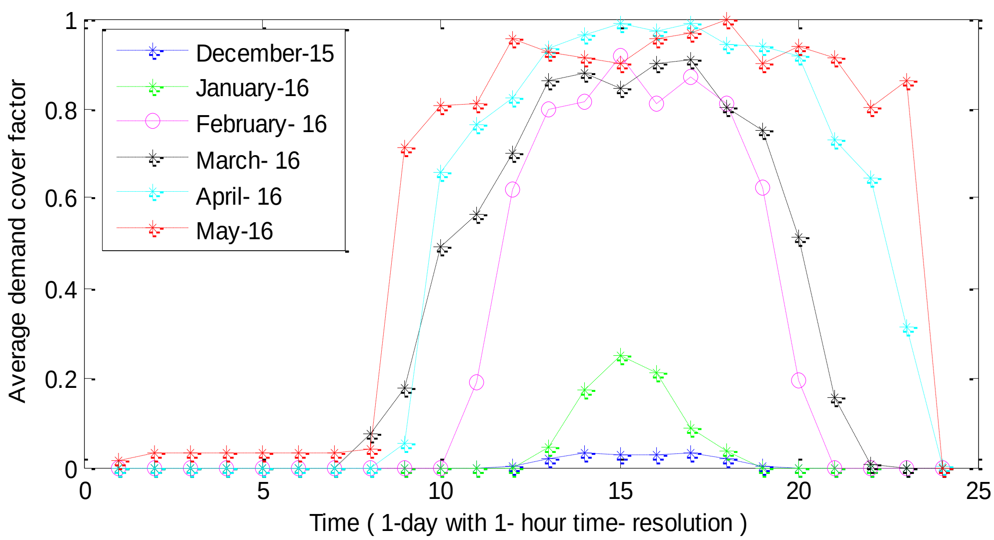

Figure 60: Average demand cover factor with HVAC loads, December 2015- May 2016 in H2

From Figure 60, the values of γD increase from December to May with the corresponding percentages illustrated in Table 6. This is explained that in December, only 0.7% of the load demand on daily average basis is covered the solar PV, while other 99.9% of demand is imported from the grid. For the month of May with higher solar irradiation, 56.7% of demand is covered by the on- site PV production, and it can export the surplus energy to the grid, especially at noon time. Comparing results from Figure 60, Table 3 and Table 6, this shows the variation of how the building is behaving towards the solar PV production, and as explained in chapter two, for γD equal to 1, the building energy is self-sufficient and no energy needed from the grid distribution network.

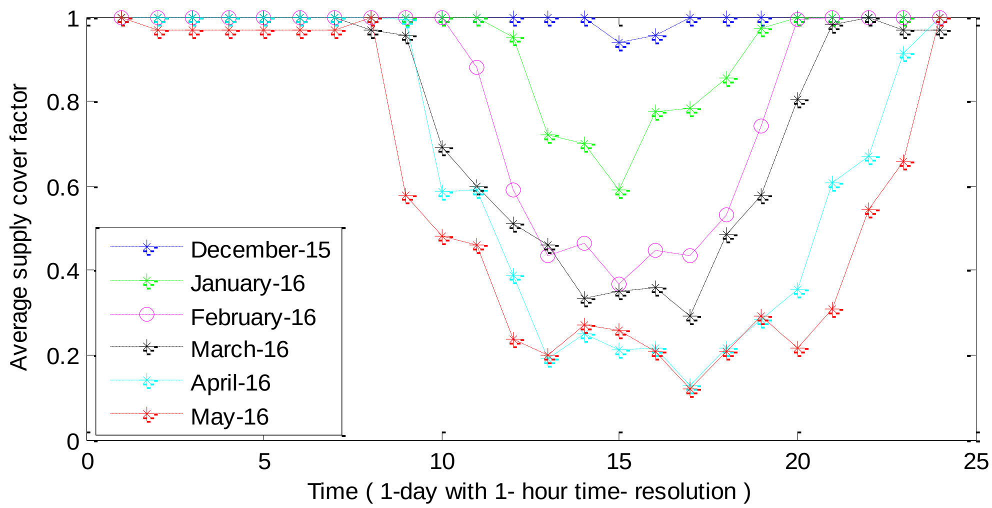

Figure 61: Average supply cover factor with HVAC loads. December 2015- May 2016 in H2

Figure 61 shows the decrease in average γS from December to May with HVAC loads, which explains the percentage of energy to be supplied to the household loads during this period. The higher the γS, the higher the demand required by the household to be covered from the grid.

Table 3: Demand and supply cover factor with HVAC loads in 6-months for H2

CF/ month	Dec	Jan	Feb	Mar	Apr	May
γS [%]	99.6	93.1	82.9	76.3	65.0	57.8
γD [%]	0.7	3.3	27.7	35.9	48.5	56.7

5.9.2. Demand and supply cover factor before and after heat pump shifting

Load shift with HP is also important in the evaluation of load matching indices (demand and supply cover factors). Table 4 shows the values of both γD and γS before and after load shifting with HP for the six selected clear days in the period from December 2015 to May 2016.

Table 4: Demand and supply cover factor before and after HP shifting

Cover factors	**γD before LS**	**γD after LS**	**γS before LS**	**γS after LS**
4-Dec-15	0.258	0.197	0.818	0.950
1-Jan-16	0.188	0.058	0.829	0.993
3-Feb-16	0.317	0.250	0.730	0.859
26-Mar-16	0.447	0.325	0.642	0.781
1-Apr-16	0.481	0.253	0.588	0.544
25-May-16	0.621	0.238	0.443	0.368

For the days where the total load is not fully covered by solar PV from this table, there is reduction in γD and an increase in γS after HP shifting. Considering the example of 4- December-15, γD is reduced from 0.258 to 0.197 after shifting, while γS is increased from 0.818 to 0.950.

5.9.3. Demand and supply cover factor for total electrical loads in H1 and H2

In this section, it is important to quantify the γD and γS on monthly basis averaged in one day for evaluating how the house is covered with the on- site PV energy generation. Also, there is a comparison of cover factors for both houses. The resulting values for γD corresponding to May, April and December for H1 and H2 are presented in Figure 62 and Figure 63. From these figures, due to high solar irradiances in May, these two houses have high values of γD than December and more energy is sold to the grid. To evaluate the γD by comparing two houses H1 and H2, Table 5 shows the average values of these CF. As the solar panels at the rooftop of these two house are fixed at different orientation, and this affects the values of CF.

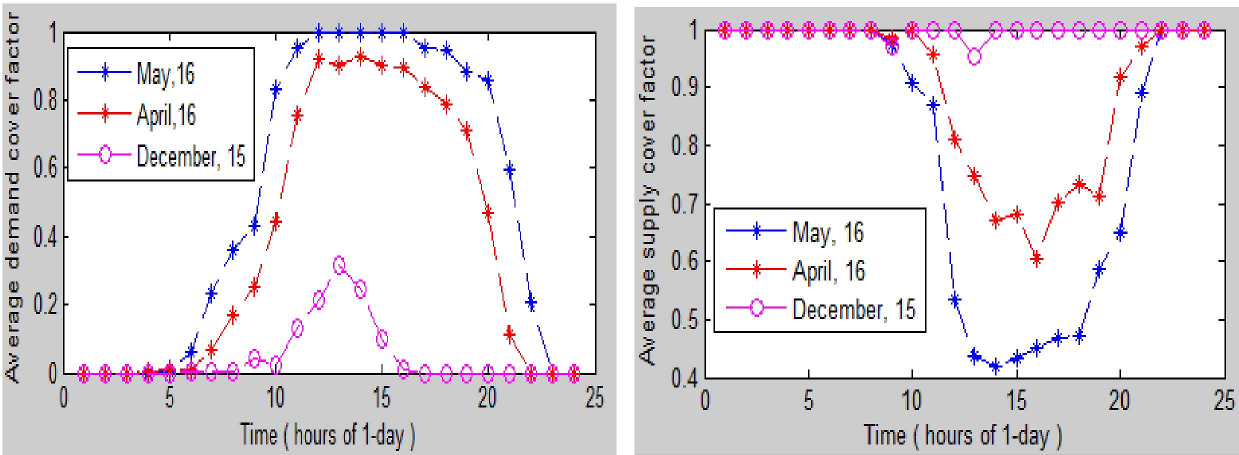

Figure 62: Daily average demand(left) and supply (right) cover factor for 3- months, H1

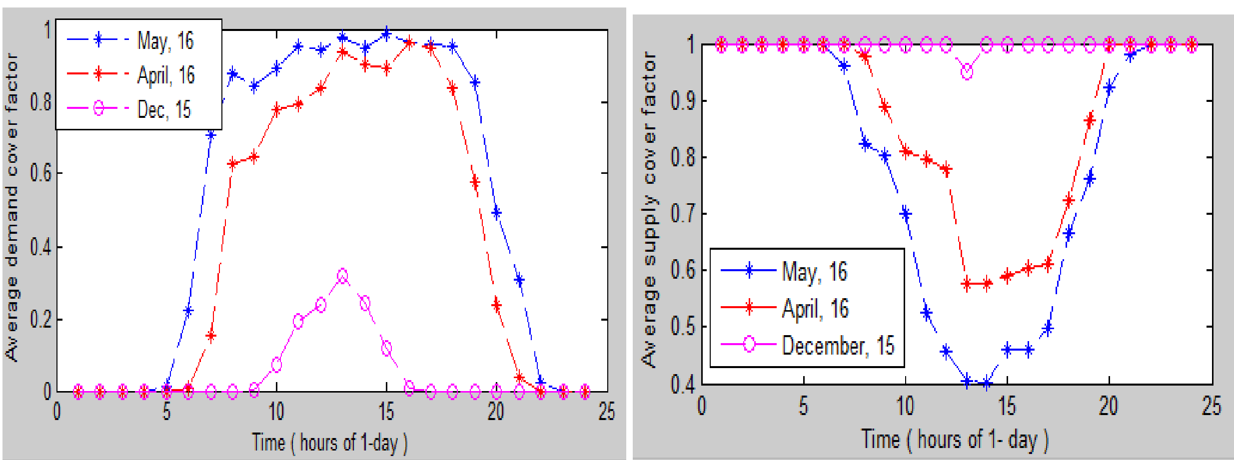

Figure 63: Daily average demand (left) and supply(right) cover factor for 3- months, H2

From Figure 63 and Figure 63 (left) , it can be observed that H2 starts getting values for γD great than zero (5:00 am) before H1 (6:00 pm). Due to the defference in demand profile and PV production as well, the H2 covers more the loads than H1 as seen in Table 5. This difference is due two basis parameters. The first is that, the orientation of solar panels on the rooftop of both houses are fixed in different direction as mentioned earlier. The second parameter is the household loads energy consumption which is different for both houses, meaning that the H2 is more comfortable than H1 towards the energy management.

Table 5: Comparison of cover factors in H1 and H2 for 3-months

Cover factors		May- 2016	Apr- 2016	Dec- 2015
H2	γD	0.538	0.424	0.049
	γS	0.784	0.867	0.998
H1	γD	0.513	0.382	0.045
	γS	0.795	0.895	0.997

In additional, there is significant seasonal variation of γD and γS. For example, considering H2, the average γD varies from 0.049 in December to and 0.538 in May, and γS varies from 0.998 (December) to 0.784(May) as shown in Table 5.

5.10. Loss of load probability analysis

During this thesis, the loss of load probability (LOLP) is calculated to evaluate the system reliability for generation system in house H2 using 1-hour and 1- minute time- resolution as shown in Table 6. To quantify the behavior of power generation from BIPV with respect to the domestic load consumption, LOLP is an important parameter to use, because it shows how often during a given period for the household loads to not be covered by on-site power generation.

Table 6: Loss of load probability in 6-months for H2

Indices	Dec	Jan	Feb	Mar	Apr	May
LOLP [%] (1-hour)	**93.1**	**99.0**	**76.3**	**69.1**	**56.7**	**48.3**
LOLP [%] (1-minute)	**91.9**	**95.0**	**76.0**	**68.6**	**55.9**	**48.3**

Using 1- hour resolution for house H2 in December 2015, 93.1 % of the load is not covered by BIPV generation, while in May 2016, 48.3 % of the loads is not covered. Comparing 1-hour and 1-minute resolution, this shows that it is advantageous to evaluate the LOLP with higher time steps (1-minute resolution) because there is a decrease in LOLP in the corresponding months during the mentioned period. For example, refer to Table 6, in December the LOLP decreases from 93.1 (for 1-hour) to 91.9% (for 1- minute), while in April it decreases from 56.7 (1-hour) to 55.9 % (for 1-minute).

This index suffers from the fact that it does not show the uncovered part of load in terms of electrical energy, it shows only the percentage values, and the data for electrical energy to import or export are found in Table 2 and Table. Therefore, the LOLP analysis is helpful for illustrating the percentage of required energy from the on- site generation system (here solar PV) for not covering the domestic load during a given period. By using the LOLP factor, designing companies of buildings with solar PV systems for the purpose of behaving as nZEB have to evaluate various load control strategies for maximizing the utilization of on-site energy generation by increasing self- consumption.

Chapter 6. CONCLUSION AND FUTURE WORK

In this chapter, the general conclusion about the work regarding this thesis is summarized by showing the facts and figures resulting from the objectives of this research. For continuous studies at Skarpnes village, the recommendation for future studies are also highlighted.

6.1. CONCLUSION

The objectives of this study were to evaluate the maximization of on-site solar PV energy production by increasing the self- consumption with domestic electrical loads at Skarpnes zero energy village. During this thesis, DSM strategies with load shifting are discussed as mean to increase the self-consumption of electricity produced locally from solar PV systems, which is important for limiting the injections of electricity into the grid distribution network. It has been shown that, the load-shifting techniques was a better method for household load management in BIPV systems, because they do not change the total production output and are easier to implement by help of programmable settings. Load shifting techniques suffer from the flexibility of customers (building users) to accept and plan for the time without heat pump in use by waiting the availability of solar irradiance, where heat pump must be in service.

This load shift is applied to minimize the charges on domestic loads (specifically shiftable loads) and maintain system reliability on the grid distribution utility company due to the reduction in demand at time without PV production. The results show that, it is economical to apply shifting strategies for the day where the total solar PV production is greater than the HP energy demand. The results of HP shifting for one week in May, the SC is increased from 36.75 % to 81.31 %, while in April, the SC in increased from 27.15 % to 70.48 % of the whole PH energy produced energy in corresponding week, which shows the importance of load shifting.

PV self-consumption at Skarpnes zero- energy village can be economically attractive option for using the on- site generated solar PV electricity in nZEB systems. Heat pumps can be used to increase PV self-consumption with DSM control strategies. A variable speed heat pump offers the flexibility to follow the household heat demand scheduling time, and with help of smart metering, the HP consumption is regulated to be shifted at time with higher PV energy production. The results have shown that heat pump with domestic hot water storage offer the opportunity to shift electricity loads e.g. to periods with high solar radiation, which significantly increase the PV self-consumption rate and help to reduce the cost of importing energy from the grid. By using the excess PV generation in DHW storage system instead of sending it into the grid, it has been found that this energy can boost water from 40 ºC to 90 ºC during April and May (for selected clear days) without assistance from the grid network. Demand and supply cover factors have been used to quantify the matching between the on- site PV generation and household loads in BIPV. Results show that γD increases from December to May, while γS decreases from January to May. Comparing two houses H1 and H2, it has been found that γD for H2 is higher than that of H1, meaning that, the household loads in H2 are more cover by the on- site solar PV energy,for example in April, γD for H2 was found as 0.424, γD for H1 was 0.382. Contrary, γS for H2 for the same month of April (0.867) is less than that of H1(0.895). LOLP has been used to show how often during a given period for the BIPV is not covered by on-site power generation. Using 1-minute and 1-hour resolution datasets, the results have shown that, for H2 in December2015, the LOLP decreases from 93.1 (for 1-hour) to 91.9% (for 1- minute), while in April 2016 it decreases from 56.7 (1-hour) to 55.9 % (for 1-minute).

6.2. RECOMMENDATION FOR FUTURE STUDY

During this work, DSM with load shifting coupled with DHW storage tank has been used to study the increase of PV self-consumption. Thus, a programmable system could be installed on shiftable loads with smart control to monitor and allow shifting demand at the time with higher solar PV production. For the future work, the presence of on-site battery storage of type Lithium ion which can be used to store excess solar PV energy during clear day could be further investigated as a mean to increase PV self- consumption with BIPV and to improve the energy matching of the building.

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APPENDIX -A

Electrical Data Measured at Standard Test Conditions (STC): irradiance of 1000W/m², AM 1.5, and cell temperature 25° C		
Peak Power (+5/-3%)	P_{max}	230 W
Efficiency	η	18.5 %
Rated Voltage	V_{mpp}	40.5 V
Rated Current	I_{mpp}	5.68 A
Open Circuit Voltage	V_{oc}	48.2 V
Short Circuit Current	I_{sc}	6.05 A
Maximum System Voltage	UL	600 V
Temperature Coefficients	Power (P)	-0.38% / K
	Voltage (V_{oc})	-132.5mV / K
	Current (I_{sc})	3.5mA / K
NOCT		45° C +/-2° C
Series Fuse Rating		20 A

Table A. *Electrical data of solar panel used at Skarpnes*

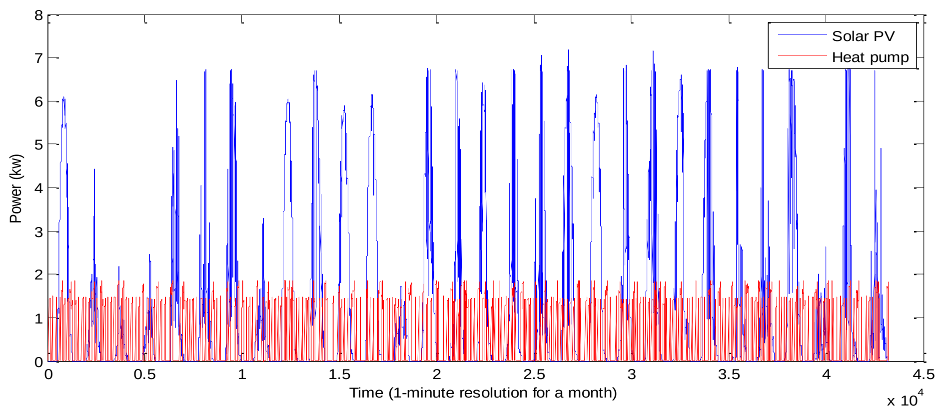

Figure A*. Solar PV and Heat pump, H2, April 2016*

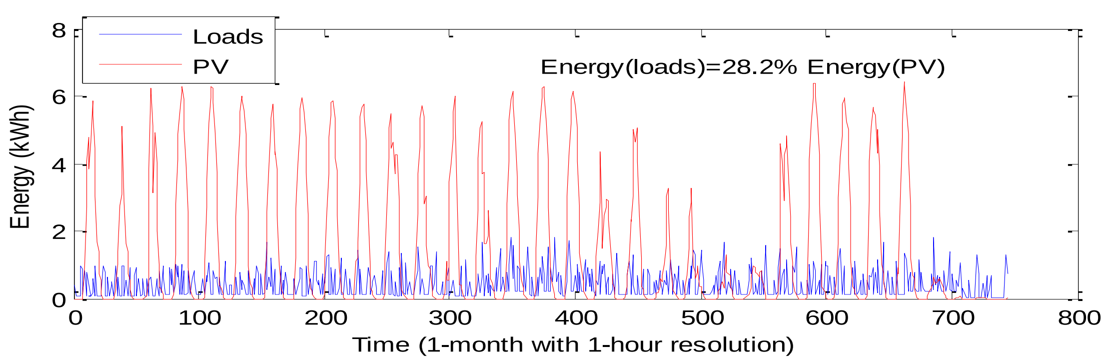

Figure B*. PV production and total domestic loads, H1, May 16*

Table B. *Peak energy, time for peak energy, and average energy for PV production, heat pump (HP), ventilation, circulation pump (CP) and fan convector (FC). Data for H2 for the 6-month period Dec-15 to May-16, 1-minute time- resolution).*

Time	Categories	PV (Wh)	HP (Wh)	Ventilation (Wh)	CP (Wh)	FC (Wh)
Dec-15	Peak energy	54.86	31.07	30.80	1.56	0.50
	Time for peak	12/3/2015 13:05	12/1/2015 22:39	12/27/2015 5:10	12/15/2015 6:06	12/19/2015 7:21
	Average energy	1.71	6.41	2.44	0.69	0.18
Jan-16	Peak Demand & PV	59.91	30.97	31.0	1.35	0.67
	Time	1/31/2016 14:38	1/30/2016 5:17	1/16/2016 5:56	1/5/2016 19:01	1/27/2016 7:26
	Average	0.80	6.65	1.94	0.58	0.16
Feb-16	Peak Demand & PV	95.92	30.91	30.73	1.31	2.00
	Time	2/22/2016 13:46	2/6/2016 13:03	2/12/2016 1:50	2/18/2016 9:00	2/5/2016 12:18
	Average	10.00	10.04	1.50	0.82	0.18
Mar-16	Peak Demand & PV	112.01	31.00	30.94	1.37	0.93
	Time	3/29/2016 12:08	3/8/2016 4:13	3/1/2016 5:53	3/4/2016 10:11	3/13/2016 19:47
	Average	12.10	8.42	1.40	0.78	0.15
Apr-16	Peak Demand & PV	119.63	31.12	30.69	1.21	0.92
	Time	4/19/2016 14:22	4/28/2016 23:59	4/23/2016 6:16	4/30/2016 11:26	4/29/2016 18:24
	Average	19.489	6.583	0.817	0.698	0.103
May-16	Peak Demand & PV	119.692	31.460	30.505	1.120	0.771
	Time	5/3/2016 14:24	5/10/2016 19:34	5/4/2016 7:40	5/6/2016 7:16	5/18/2016 5:38
	Average	24.350	5.153	1.106	0.547	0.057

Table C. *Summary of cost before and after shifting for selected days (H2, 1-minute resolution)*

Categories	Cost of import (without shifting)	Profit of export (without shifting)	Cost of import (after shifting)	Profit of export (after shifting)
4-Dec-15	8.76	1.96	5.89	0.88
1-Jan-16	3.98	0.47	3.02	0.11
3-Feb-16	6.25	4.29	2.50	2.88
26-Mar-16	5.35	4.54	1.41	3.06
1-Apr-16	4.41	11.24	1.52	10.16
25-May-16	2.28	14.01	0.00	13.16

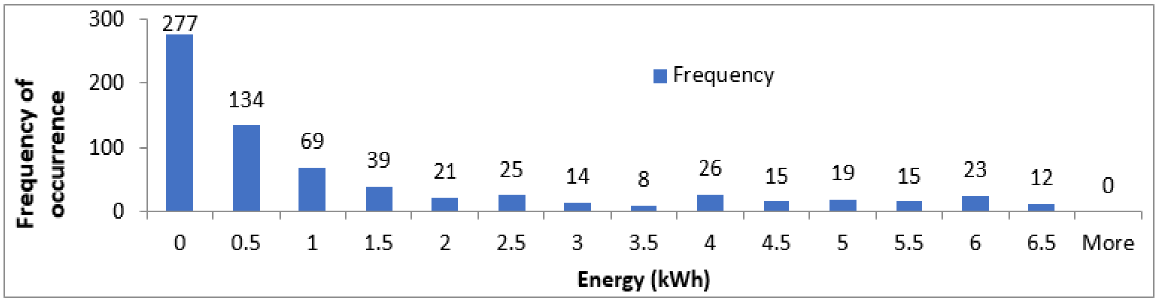

Figure C. *Distribution of PV energy production, Apr2016*

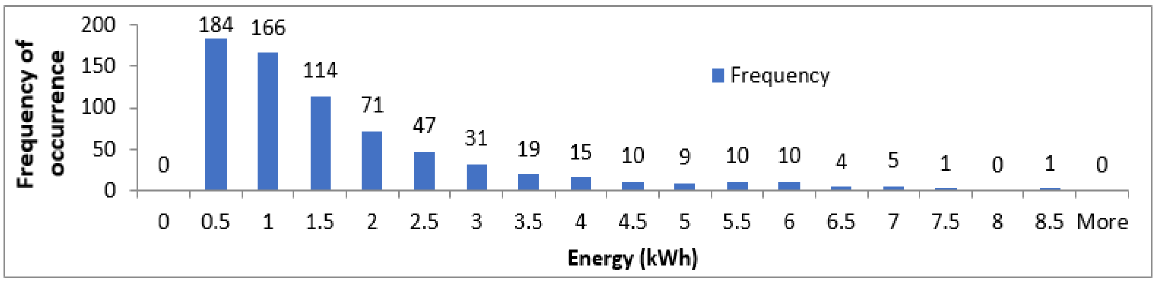

Figure D. *Distribution of total load energy consumption, Apr 2016*

With IVT Premium Line® HQ we are introducing a whole range improvements - and a revolution. It is namely prepared Smart Grid. It means the heat pump can be connected directly at the power exchange and even adapt so that it works hardest when the electricity price is lower. *

Figure E. *Liquid / water heat pump installed at Skarpnes*

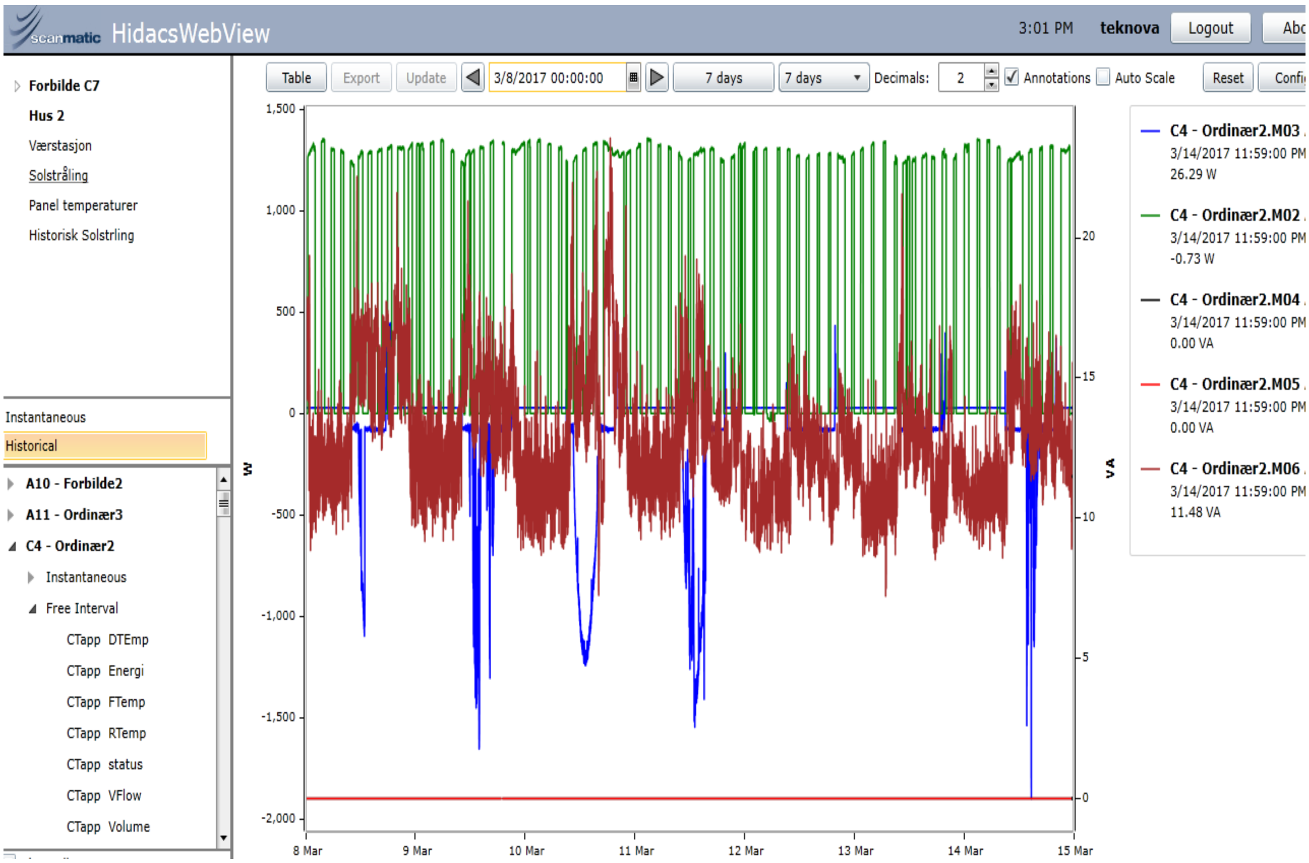

Figure F. *Example of results from Hidacswebview*

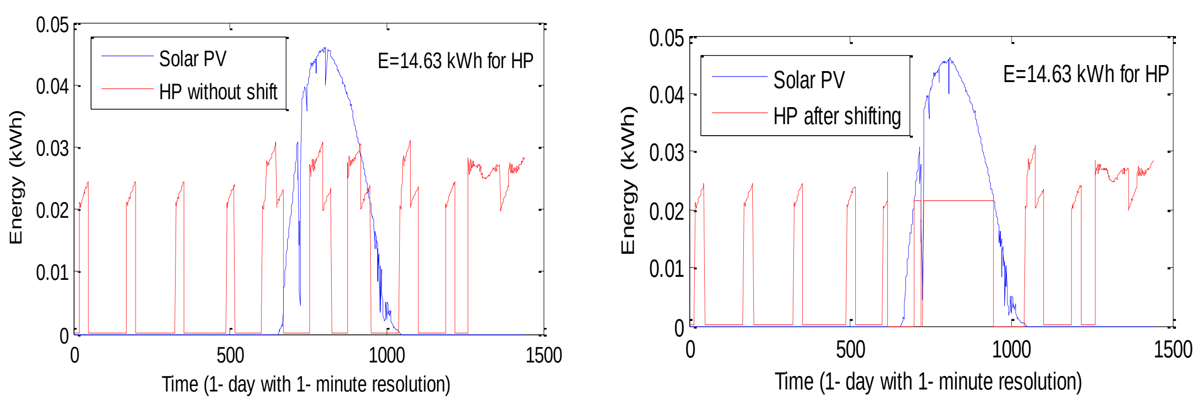

Figure G. *HP without shifting(left) and HP shifted (right), H2,4-Dec-15*

Figure H from Appendix- A, shows a circuit in which a refrigerant circulates (clockwise). The evaporator, which is a heat exchanger in which the refrigerant evaporates with the absorption of heat from the heat source. The evaporated refrigerant passes through the compressor, increases in pressure and temperature, and goes to the condenser. This system is working as heat exchanger in which the refrigerant condenses to release heat to the heating medium. The heat absorbed by the evaporator is released in the condenser at elevated temperature together with the compressor heat. In this way, the heat pump shifts the evaporated heat [40]

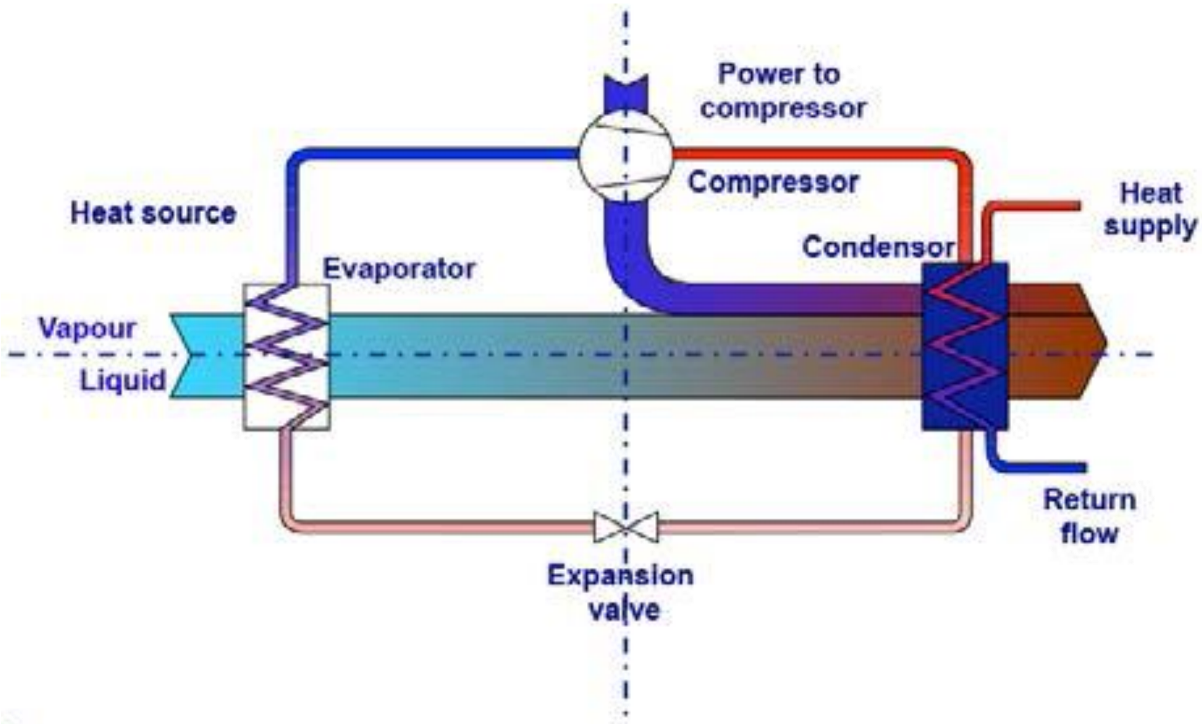

***Figure H**. Schematic diagram of a heat pump* [40]

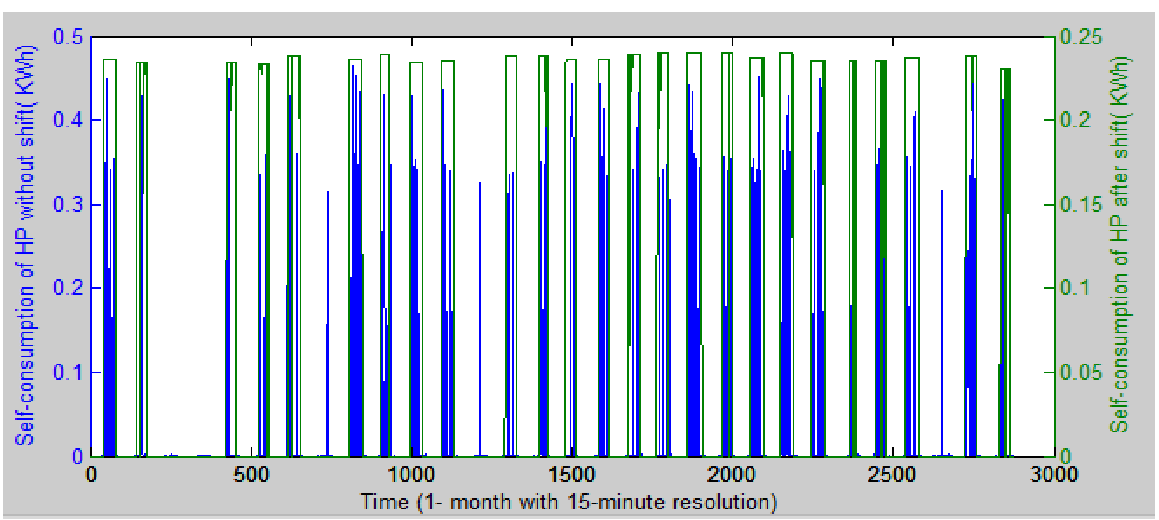

***Figure I.** Self-consumption without HP shift(blue) and with HP shifting (green), April-16*

Table D: Cost of import and export energy in H2 for 6 months

Months	Export- PV to grid(kWh)	Import- grid to house(kWh)	Cost of exported PV (NOK/ month)	Cost of import from grid (NOK/ month)
Dec-15	43.97	401.29	13.19	321.03
Jan-16	23.46	404.27	7.04	323.42
Feb-16	295.87	401.82	88.76	321.45
Mar-16	411.22	351.12	123.37	280.90
Apr-16	700.12	212.50	210.04	170.00
May-16	935.37	154.75	280.61	123.80

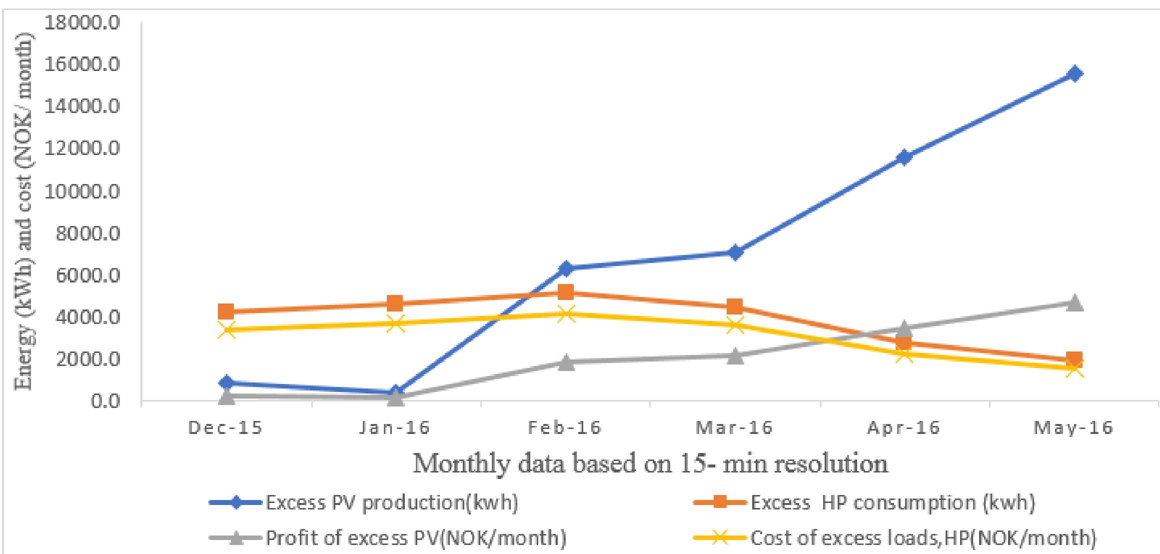

*Figure **J**: Monthly values of excess PV and HP energy and associated profit and cost for H2, Dec 15- May 16(calculated from 15- minute- resolution data)*

APPENDIX -B

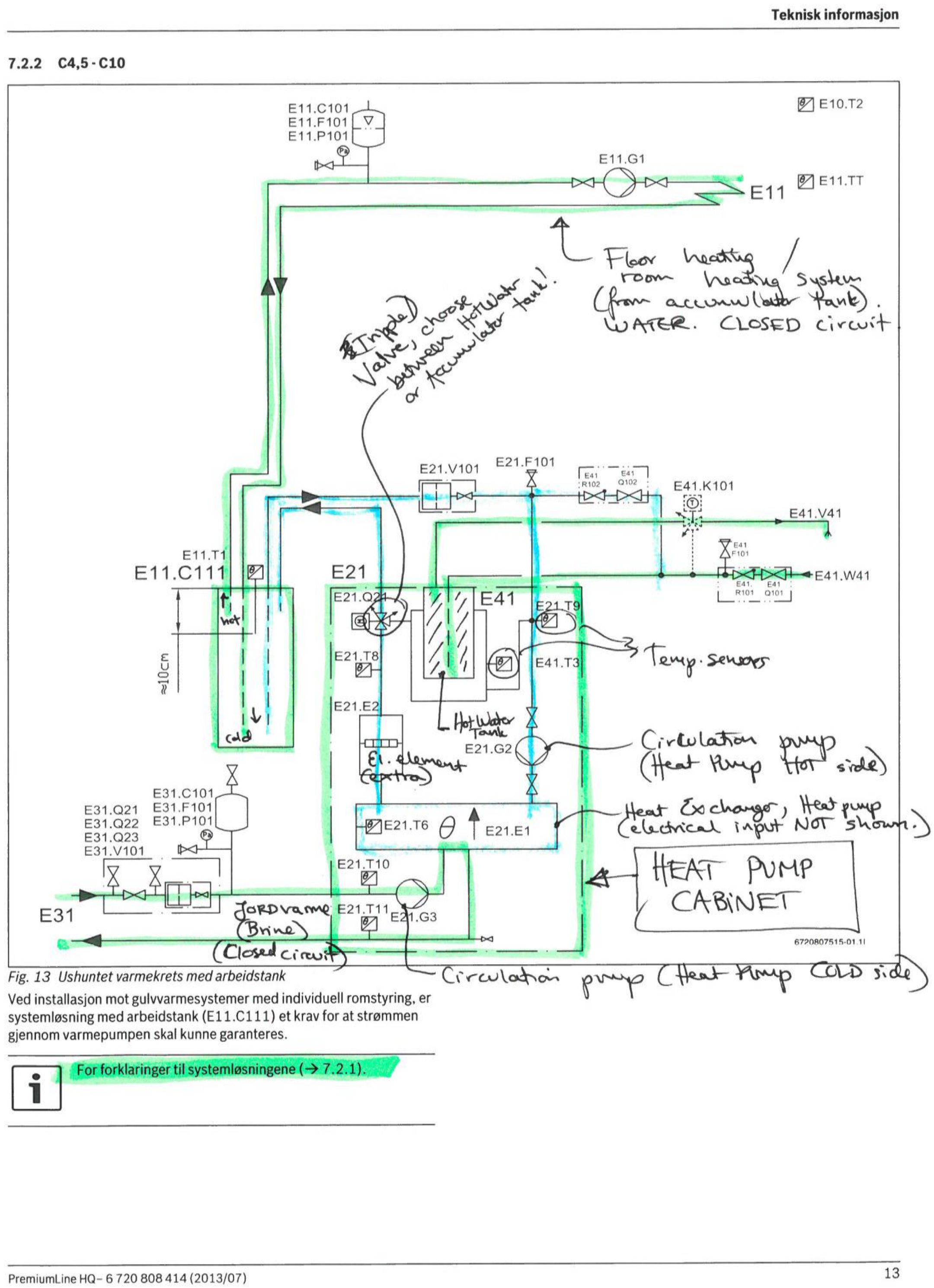

Fig. 13 Ushuntet varmekrets med arbeidstank

Ved installasjon mot gulvvarmesystemer med individuell romstyring, er systemløsning med arbeidstank (E11.C111) et krav for at strømmen gjennom varmepumpen skal kunne garanteres.

For forklaringer til systemløsningene (→ 7.2.1).

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Figure ***A****: Diagram of heating for domestic hot water and building heating system with heat pump*

7.3 Tekniske data

7.3.1 C4,5 - C10

	Enhet	C4,5	C6	C8	C10
Drift væske/vann					
Varmeeffekt (B0/W35)[1)]	kW	4,7	5,8	7,6	10,4
Varmeeffekt (B0/W45)[1)]	kW	4,4	5,6	7,3	10,0
COP (B0/W35)[1)]	–	4,2	4,4	4,7	4,7
COP (B0/W45)[1)]	–	3,3	3,4	3,6	3,7
Kuldebærer					
Nominell vannstrøm	l/s	0,30	0,36	0,47	0,64
Tillatt eksternt trykkfall	kPa	49	55	90	90
Maks. trykk	bar	4			
Innhold (internt)	l	5			
Driftstemperatur	°C	–5... +20			
Tilkobling	mm	Ø 28			
Kompressor					
Type	–	Copeland fixed Scroll			
Vekt kjølemiddel R410A[2)]	kg	1,55	1,55	1,95	2,2
Maks. trykk	bar	42			
Varmesystem					
Nominell vannstrøm	l/s	0,20	0,20	0,26	0,36
Min./maks. turledningstemperatur	°C	20/62			
Maks. tillatt driftstrykk	bar	3,0			
Varmevann inkl. yttermantel varmtvannsbereder	l	47			
Tilkobling	mm	Ø 22			
Varmt tappevann					
Maks. effekt uten/med 9kW strømtilskudd	kW	4,7/13,7	5,8/14,8	7,6/16,6	10,4/19,4
Nytteinnhold varmt tappevann	l	260			
Min./maks. tillatt driftstrykk	bar	2/10			
Tilkobling	mm	Ø 22			
Verdier for elektrisk tilkobling					
Elektrisk tilkobling			400 V, 3N~, 50 Hz		
Sikring, treg, ved strømtilskudd 1-3/6/9 kW	A	10/16/20	10/16/20	16/16/20	16/20/20
Maks. Startstrøm med mykstart (tilbehør)[3)]	A	27	27	24	25
Beskyttelsesklasse	IP	X1			
Generelt					
Tillatt omgivelsestemperatur	°C		+10... +35		
Lydeffektnivå[4)]	dBA	45	46	47	47
Mål (bredde x dybde x høyde)	mm	600 x 645 x 1800			
Vekt (varmtvannsbereder, kobber/rustfri)	kg	230/200	238/208	251/221	230

Tab. 10 Tekniske data

1) Med intern pumpe i samsvar med EN 14511

2) Global Warming Potential, GWP_{100} = 1526

3) C6: Maks. Startstrøm uten mykstart

4) Følge EN 3743-1

*Figure **B**: Technical data for heating system with heat pump in the house.*