Impact of Renewable Energy Installations and Utilisation of Smart Energy Management Systems on low-voltage networks - a study case at Östergarnslandet, Gotland

Sujith Sudhakaran
Abstract

Impact of Renewable Energy Installations and Utilisation of SEMS on low-voltage networks

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This thesis carries out an analysis of PV panel installations in the region of Östergarnslandet, situated in the Swedish island of Gotland. A low-voltage grid of 0.4 kV in the region is examined with the help of software Open DSS. This is done with the data provided by the distribution grid owner, Gotlands Elnät AB (GEAB). The potential impacts created by the PV installations in terms of exceeding currents, voltages and harmonics are assessed and thereby the hosting capacity of Solar PV in the houses and on the whole grid is studied.

Moreover, a theoretical review of the Smart Energy Management System (SEMS) is investigated about the performance and the devices involved in the system. Also, a battery which is a part of SEMS is modelled, taking into account the production and consumption of a single household connected in the grid. The battery sizes for various PV installations at the home is suggested via NPV analysis with the intention to increase the self-consumption and to reduce the cost of the electricity bill.

In addition, a survey is conducted in the region with support from the Department of Earth Sciences, Uppsala University Campus Gotland. The survey is made to determine the attitude of the people in Östergarnslandet towards an energy transition.

The results show that the maximum amount that can be installed or the hosting capacity of solar in the studied grid is 120 kW. From the simulations, it shows that the impacts created by these PV installations do not violate the specified Grid norms.

From the theoretical analysis, SEMS is found to be a better solution for energy management at homes. The performance study done shows that 33% of the solar energy produced in the home is directly used at the time of production. The remaining energy is used for battery charging for the future supply of power and feeding to the grid. The battery modelled for 10- kW PV installation in the home is found to be 9-kWh and the same for a 15-kW installation. Meanwhile, for a 20- kW installation, a 15-kWh battery is found to be ideal from the study.

The survey conducted in the region has turned out to be positive as people are supportive of the energy transition. The responders have marked photovoltaics as the prime option for investment in energy production which assures that it has a good future in the area.
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Table of contents

1 Introduction ................................................................................................................................. 1
  1.1 Background .............................................................................................................................. 1
  1.2 Project Goals ............................................................................................................................ 2
  1.3 Limitations of the Project ......................................................................................................... 3
  1.4 Outline of the thesis ................................................................................................................ 3

2 Literature review .......................................................................................................................... 4
  2.1 Solar power production in Sweden .......................................................................................... 4
  2.2 Policy for solar framework in Sweden ..................................................................................... 5
  2.3 Power quality standards .......................................................................................................... 6
  2.4 Impacts of grid-connected PV ................................................................................................ 6
    2.4.1 Overvoltage ....................................................................................................................... 6
    2.4.2 Losses ............................................................................................................................... 7
    2.4.3 Voltage Phase Unbalance .................................................................................................. 7
    2.4.4 Harmonic distortion .......................................................................................................... 8
  2.5 Battery .................................................................................................................................... 9
    2.5.1 Types of battery and usage .............................................................................................. 9
    2.5.2 Terminologies for battery .................................................................................................. 9
    2.5.3 Storage capacity and Load management ......................................................................... 10
  2.6 Smart Energy Management System (SEMS) ......................................................................... 11
    2.6.1 Energy Manager ............................................................................................................... 11
    2.6.2 Energy meter .................................................................................................................... 12
    2.6.3 Communication system ................................................................................................... 12
    2.6.4 SEMS profile .................................................................................................................... 13
    2.6.5 SEMS performance ........................................................................................................... 14

3 Methodology .................................................................................................................................. 16
  3.1 Theory ..................................................................................................................................... 18
    3.1.1 Open DSS overview .......................................................................................................... 18
    3.1.2 Net Present Value (NPV) .................................................................................................. 19
    3.1.3 Total Harmonic Distortion (THD) .................................................................................... 19
  3.2 Analysis of data ....................................................................................................................... 20
    3.2.1 Grid data .......................................................................................................................... 20
List of figures

Figure 1: PV installation trend ................................................................. 4
Figure 2: PV installed per-capita in Sweden................................................... 5
Figure 3: Harmonics distortion ................................................................. 8
Figure 4: Load management .................................................................. 10
Figure 5: Smart Energy Management System ............................................. 12
Figure 6: Energy Profile for Dresden.......................................................... 13
Figure 7: Load Shape .............................................................................. 16
Figure 8: Open DSS architecture ................................................................ 19
Figure 9: Production profile for 45 kW ....................................................... 21
Figure 10: Line Connection used ............................................................... 23
Figure 11: Voltage profile basic case ......................................................... 27
Figure 12: Voltage with PV ...................................................................... 28
Figure 13: Phase amplitude with PV ............................................................ 29
Figure 14: Harmonics with 74kW .............................................................. 29
Figure 15: Harmonics in nearby home ....................................................... 30
Figure 16: Harmonics near transformer ...................................................... 30
Figure 17: Voltage profile with 74 kW ....................................................... 31
Figure 18: Current profile with 74 kW ....................................................... 32
Figure 19: Voltage in neighbouring Line 1 ................................................ 32
Figure 20: Current in neighbouring Line 1 ................................................ 33
Figure 21: Voltage in neighbouring Line 2 ................................................ 33
Figure 22: Current in neighbouring Line 2 ................................................ 34
Figure 23: Scenario one 10 kW ................................................................. 37
Figure 24: Scenario one- difference profile ................................................. 37
Figure 25: Scenario two 15 kW ................................................................. 40
Figure 26: Scenario two- difference profile ............................................... 40
Figure 27: Scenario three 20 kW ............................................................... 42
Figure 28: Scenario three- difference profile .......................................... 43
Figure 29: Survey result 1 ........................................................................ 45
Figure 30: Survey result 2 ........................................................................ 46
List of tables

Table 1: Limits of harmonic distortion ................................................................................. 8
Table 2: SEMS performance analysis case 1 .......................................................................... 14
Table 3: SEMS performance analysis case 2 .......................................................................... 15
Table 4: Consumption for year 2015 .................................................................................... 21
Table 5: Harmonic Values Injected ...................................................................................... 24
Table 6: Scenarios ................................................................................................................. 26
Table 7: Hosting capacities of houses ................................................................................... 34
Table 8: Hosting capacities of busbars .................................................................................. 35
Table 9: Effects on main lines ............................................................................................... 36
Table 10: Scenario 1 ............................................................................................................... 38
Table 11: NPV analysis scenario 1 ....................................................................................... 39
Table 12: Scenario 2 ............................................................................................................... 41
Table 13: NPV analysis scenario 2 ....................................................................................... 42
Table 14: Scenario 3 ............................................................................................................... 43
Table 15: NPV analysis scenario 3 ....................................................................................... 44
### List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>HVDC</td>
<td>High Voltage Direct Current</td>
</tr>
<tr>
<td>SEMS</td>
<td>Smart Energy Management System</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaics</td>
</tr>
<tr>
<td>GEAB</td>
<td>Gotlands Elnät AB</td>
</tr>
<tr>
<td>THD</td>
<td>Total Harmonic Distortion</td>
</tr>
<tr>
<td>P.U</td>
<td>Per Unit</td>
</tr>
<tr>
<td>kW</td>
<td>Kilo Watt</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilo Watt Hour</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
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1 Introduction

The environmental consequences of using conventional energy sources have led to the development of non-conventional energy resources that have minimal impacts on the environment. The Paris agreement has also made a significant contribution to the rise in renewable energy sources in the market.

The Swedish Energy Agency has established the energy policy stating that by the year 2050, Sweden will not be an emitter of greenhouse gases to the atmosphere and will have a sustainable and resource-efficient energy supply [1]. Over the past few years, there has been tremendous growth in the renewable energy sector, especially in solar and wind energy. Sweden thusly is moving towards a greener and smarter future with the inclusion of renewable energy sources which share a major part of the production.

In this chapter, a brief introduction is given to the thesis background, the goals, the limitation of the thesis. Further, an outline of the thesis is also discussed.

1.1 Background

The electric grid is under constant development with the addition of new technologies, like the storage and introduction of PV and other renewable energy sources. The consumers have started to produce their own electricity and have become prosumers, which is being the producers and consumers of electricity. Consequently, people have started to install solar panels on their rooftop or in the fields nearby which can be owned by community funds.

Östergarnslandet, a region situated to the east of Gotland, has a community that has a similar interest in becoming prosumers. This interest has led them to initiate a project in the region to promote the self-sustaining of energy and encourage each of the households to become a prosumer. As a beginning to this project, they have developed an idea of energy clusters in which various homes become a part of the cluster and they get controlled at different levels and eventually at a higher level by an aggregator. An aggregator is an organisation or an individual that brings the retail energy customers together as a group with the objective of obtaining better energy prices, services or other benefits when acquiring energy services.

In response, this can reduce the energy consumption in the area which can be an aid to the utility provider managing the peak loads. Moreover, this can help in reducing the maintenance cost of the grid lines and save some amount of money. Also, being the producers of electricity, the community has the intention to help the utility provider with energy that can be used at times of shortages. The storage of energy produced by the consumers plays a vital role in supporting the utility provider with energy and this can only be made smoother with the help of a battery in the households. Further, the efficient use of energy in households is intended to get managed by the Smart Energy Management System (SEMS) that schedules the loads in homes according to peak hours and maximise the domestic usage of solar energy.
The community in Östergarnslandet has decided to install solar panels, a battery, and SEMS at a household as a pilot scheme to the energy level in the region. The study will be conducted at this household and through this, an insight is provided to the people in the area about the system installed. Furthermore, this will help them to get an idea about energy transition and would convince them to be a part of the energy cluster.

Subsequently, the community aims to extend the system implemented to various households in the locality. This thesis will examine the possibility of the extension of the system, assessing the available infrastructure, considering the single household as the bottom floor for the expansion. This study would help the community to identify the challenges and benefits associated with it in becoming a pilot organisation for the energy transition.

1.2 Project Goals

Considering the intention of the community to extend this concept, it is important to know the hosting capacity of solar panels for the grid in the area and the effects that can be caused due to the penetration of PV into the grid.

The specific goals of the thesis include:

- Evaluate the impact on Gotland’s electricity grid (low voltage network) in Östergarnslandet of PV panel installations at the household level for a given topology in terms of voltage stability, overvoltage, overcurrent, and harmonic distortion.
- Simulate different load scenarios to calculate the hosting capacity of PV installation for the given grid topology.
- Estimate the utilisation of SEMS theoretically at the household level and provide an insight into the system.
- Analyse the size of the battery to be used in the home as a part of SEMS, considering the production and consumption of energy.
- Conduct a survey about the attitude of people in Östergarnslandet towards the energy transition.
1.3 Limitations of the Project

The thesis is done with the following constraints:

- Evaluation of the grid is done only for low voltage network and the effects on the higher voltage networks in the region is not considered.
- The economic analysis for the PV panels and SEMS is not done as this depends on market fluctuations and household usage. Also, the variability in electricity prices is not considered in the economic analysis of the battery.
- The usage of SEMS is examined theoretically and real-time data with regard to the household is not included.

1.4 Outline of the thesis

The thesis unfolds as follows:

The thesis begins with an introduction including the background, goals, and limitation of the thesis named Chapter 1. Chapter 2 deals with the theory behind the PV panels, its market in Sweden and the impacts it can create on the grid. Also, battery types and load management are discussed. Moreover, a detailed theory of SEMS is given. The methodology and data description are given in Chapter 3. Chapter 4 includes the modelling of the simulations performed and the results are given in Chapter 5 followed by the discussion in Chapter 6. Lastly, Chapter 7 contains the conclusion of the thesis and future work suggestions are stated in Chapter 8.
2 Literature review

This chapter presents a brief history of the trend of PV power production in Sweden and the policies involved in the installations of PV panels. Also, an insight is given to the total installed PV power capita in Gotland. Moreover, power quality regulation standards and the challenges caused by the integration are discussed which is vital in determining the impacts caused by the PV integration on to the grid.

The section also covers the basic characteristics of the battery, the types, the load shift, and power management. Most importantly, the theory involved in SEMS, the working of SEMS is also reviewed.

2.1 Solar power production in Sweden

Over the years the solar power production has developed tremendously in Sweden. It has been reported that in the early days of PV introduction into the market most of the installations in the country were Off-grid and lately the trend has changed from Off-grid installations to On-grid [3]. The On-grid installations have made considerable progress not only in Sweden but in other parts of Europe as well. Taking figures into account, it was reported that 18 MW had been installed in the year 2013 and further on it displayed an increase of 100 % in the consequent years (Figure 1) [3].

Since the consumers have started becoming prosumers, the contribution by them has almost doubled compared to On-grid installations in the year 2014 which was 35.1 MWp [3]. The maturing market for PV in the country has led the way for tax benefits and falling prices have attracted more people to the installation. The study conducted by [3] reports that the prices for the residential system have shown a decrease from SEK 17/Wp to a fraction above SEK 15/Wp by the start of the year 2015 while for the commercial customers this was around 13 SEK/Wp [3].

![Figure 1:PV installation trend](image-url)
The reports depict that in Gotland, the installed PV plants are calculated to be 2281 kW and this accounts to be 1.6% of the total capacity installed in Sweden [4]. As shown in Figure 2, the expansion of PV over a period of one year has been significant and the highest installed capacity is in the municipality Linkoping [3]. Gotland is one of the most trustable regions for solar and has exhibited a per capita growth of about 100% in the period considered.

![Figure 2: PV installed per-capita in Sweden [3]](image)

### 2.2 Policy for solar framework in Sweden

The integration of PV panels on the grid is bound to have definite regulations that prosumers are expected to follow. According to the Electricity Act, electricity produced via renewable energy sources can have an approach to the grid and the electricity fed should be transmitted and distributed [3]. The Swedish system guarantees a subsidy for the installation of PV panels since the year 2009 [3].

In addition to that for big installations, green certificates are also available which promotes the use of renewable energy resources. To represent a measure of electricity consumption, it is necessary for every consumer to purchase the greenhouse certificate which was initiated in the year 2003 [3]. The prosumers get an added advantage by trading the green certificate on the market thereby earning extra revenue to invest in renewable energy production.
2.3 Power quality standards

With the considerable development of integration of PV onto the grid, it is essential to ensure the power quality standards that flow through the lines and also the quality at the consumer end. The expansion of PV has led to the introduction of several quality problems on the grid and the distribution operators are facing issues trying to match the regulation standards for the power supply. For instance, the overvoltage, losses and voltage stability have to be as per the specified norms.

For European countries, the standards mentioned are as per EN 50160 and each of them is supposed to follow and meet the criteria specified. The power quality is determined taking several factors into consideration stated by Grid code EN 50160. This comprises of voltage regulation, flickering, voltage imbalance, and harmonics.

The following conditions are mandatory according to the Grid code EN 50160 [5]:

i. Voltage unbalance for three-phase inverters → max 3%
ii. Voltage amplitude variations → +/- 10%
iii. Frequency variations → max 1%
iv. Total Harmonic Distortion → max 5%

2.4 Impacts of grid-connected PV

The impact created by the integration of PV into the grid is a matter of concern and has to be addressed and mitigated. The main problems include the rise in voltage, voltage flickering, instability in the voltage, over current and harmonics [6]. The impacts have been examined in different studies and in different ways. In this section, the most important impacts to be considered are discussed in detail.

2.4.1 Overvoltage

The voltage rise effects are regarded to be very minimal if the PV penetration is less than 25% of the maximum load on a specific feeder [7]. In the case of minimum load, the limit reaches its maximum level where no more PV can be included and this can further worsen if the power system has already reached its limits [8].

In these situations, the inverter has to trip down, restricting the voltage to be in acceptable ranges as the power will not be produced. Since this affects the payback period and production it is not advisable to practice this method [8].

The storage system is suggested to be a better solution for maintaining voltage and decreasing the fluctuations. It stores the energy at peak hours of solar panel production and then discharges at off peaks [8]. The study by [30] also concludes storage as a key to retain the voltage profile within the limits.
If a feeder with uniform load and no fixed reactive compensation is assessed, and if the PV generation is combined at the far end of the feeder, the boundary limit of penetration is 15\% [10]. The problem of overvoltage becomes notable when the PV generation is either at the end of the line or at the start of the feeder. The line voltage rise can be problematic if the penetration exceeds 50\% provided that the generation is spread evenly through the feeder [10].

### 2.4.2 Losses

The PV generation has also an effect on the losses in the system which can increase depending on the penetration level. The profile for the losses depicts an inverse parabolic shape according to the penetration level [11]. The losses in the system are declined up to a certain level beyond which it can increase [11]. [6] made a study that suggests distribution losses reach a minimum value when the penetration is around 5\%. Furthermore, it is important to note that generators are placed close to the inverters to reduce the ohmic losses and to increase the conversion efficiency [12].

### 2.4.3 Voltage Phase Unbalance

The voltage unbalance in the system happens when the measure of the voltage having the phase difference between the three phases changes from default 120 degrees or the amplitude of the voltage between them changes [19]. Usually, when the installation capacity is small, it is connected to a single-phase system, but the issue occurs when the power fed in exceeds the amount that a single-phase can withstand. Usually, the loads from the consumer side are evenly distributed among the three phases [31]. Moreover, if it is not connected equally between the three phases, the phase unbalance occurs and can shift the neutral voltage to dangerous levels [6]. The phase unbalance can also be a result of different load demands between the houses, random PV locations and power ratings [9]. The trouble of voltage unbalance becomes more concentrated at the end of the feeder rather than at the initial side of the feeder [13].
2.4.4 Harmonic distortion

Harmonics is the form of unwanted signal that can create problems when the voltage distribution caused by the harmonic currents rise above a fixed limit [14]. The power converting devices like inverters can inject harmonic currents into the power network system and can increase the distortion of the signal transmitted [14]. The non-linear loads are also a cause of harmonics currents and can get changed to harmonic voltages due to the impedance that the network grid possesses. The harmonic limits must be kept within the standards specified by the grid code EN 50160 for the safe operation of all the electrical equipment connected to the network [5].

![Figure 3: Harmonics distortion](image)

The harmonic effects can cause issues in the network like overheating of the transformers, the cables connected, the capacitors, and the generators [14]. Moreover, this can create flickering in the monitoring devices and may lead in giving false meter readings. When an inverter is involved in the power network for a PV installation, the level of harmonics generated by the inverter directly depends upon the operating temperature, the solar irradiance, and the power production and efficiency of the PV panels installed [16].

The reduction of the harmonic currents in the network can be achieved either by the use of the harmonic filter or making changes in the structure of the power network [14]. The harmonic distortion occurs in high magnitude at the far end of the feeder especially in the distribution transformers regardless of the PV production [16].

As per the Grid code EN 50160 the limits for the harmonics are specified below (Table 1):

<table>
<thead>
<tr>
<th>Odd harmonics</th>
<th>Even harmonics</th>
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<tbody>
<tr>
<td>Not multiples of 3</td>
<td>Multiples of 3</td>
</tr>
<tr>
<td>Order h</td>
<td>Relative voltage (%)</td>
</tr>
<tr>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
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<tr>
<td>19</td>
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</tr>
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<td>23</td>
<td>1.5</td>
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<td>25</td>
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</table>

Table 1: Limits of harmonic distortion
2.5 Battery

As mentioned in the previous section, energy storage is one of the solutions for mitigating the problems caused by the integration of PV to a certain extent. Charging the battery with the energy produced by the PV can be an aid in managing peak loads for households which in turn helps the utility provider. Also, situations like switching off the inverter to avoid overvoltage can be solved with the battery that can store the excess energy produced after the consumption in households.

2.5.1 Types of battery and usage

Batteries are classified into two main types; primary and secondary. Primary batteries are non-rechargeable while the secondary batteries can be recharged and reused. The batteries used in households are secondary types of batteries where they can be recharged and used again. For instance, the rechargeable batteries include lithium-ion, lead-acid, lead gel batteries [18].

The battery used in connection with PV panels is a better way to utilise the energy produced as it gives the possibility to use the power when there is no irradiation from the sun or even when there is no output from the panels. In situations where there is no opportunity for storage, the produced energy has to be used immediately. This can be not worthwhile for the households since most of the consumption hours are later during the day when the sun is not shining [18].

2.5.2 Terminologies for battery

- **Discharge rate and charge rate**: Discharge rate and charge rate are defined as the time taken by the battery to charge and discharge [17]. The quantities are indicated in C. To be precise, if the amount is 1 C, the battery will take 1 hour to charge to its full capacity while if it is 0.5 C, it takes 2 hours to charge fully.

- **State of charge**: State of charge depicts the charge that is left out in the battery. The quantity is measured in percentage considering the present charge and fully charged battery [17].

- **Depth of charge**: It is defined as the percentage of charge that is available that can be utilised for specific energy applications [17]. A battery is never supposed to be discharged below the depth of discharge as it affects the lifetime of the battery.

- **Lifetime and Cycle life**: When the capacity of the battery changes to 80 % of its primary capacity, this can be described as the lifetime of the battery. The number of cycles taken by the battery to attain this condition is called cycle life [17].

- **Battery management system (BMS)**: They are mainly used to extend the battery life by controlling the operating temperature ensuring it is well within the specified limits [17].
2.5.3 Storage capacity and Load management

When the houses are not connected to the grid, the storage capacity of the battery must be sufficient enough to store the energy required for a household to meet the respective consumption demand. Precisely, the battery should be able to supply power for the home throughout the night. Inaccurate calculation of the consumption in homes can lead to the improper size of the battery [18]. If the battery size is small, it cannot meet the demands according to the energy consumption in the home. On the other hand, if the size of the battery is more than required this can cause the power to store for an indefinite period of time affecting the lifetime of the battery [18]. Typically, for a household consisting of an average of four persons with a consumption of 4500 kWh annually, a battery size of 4 to 8 kWh is adequate [18].

Load management can be explained as the transfer of the loads from the peak hours to operate it in off-peak hours [20]. There are different ways to manage the peak load hours with the help of stored energy from PV production. One way of organising loads is to charge the battery to be used for peak hours and purchase the electricity from the grid at times of off-peak hours. In this case, the battery must have the capacity to provide energy for peak hours during the day.

Another method of load management is to store the excess energy produced by PV in batteries during the high production hours and to use the stored energy when the production from PV does not exist especially in the night. Figure 4 depicts the latter method of load management.

Figure 4: Load management
2.6 Smart Energy Management System (SEMS)

Smart Energy Management System is primarily used to attain the performance of the system at households with a limited amount of energy consumption (Figure 5). The SEMS are automatically controlled devices that schedule the power flow in buildings thereby reducing the consumption substantially [18]. The system is aimed at maximising the domestic usage of solar energy and works on smart house infrastructure. As a result, the house owner can make decisions on reducing consumption, controlling the energy resources via scheduling of loads at homes [21].

In addition to that, SEMS can provide a review of the power generation of solar PV installed and also support better power flow in households. Moreover, reducing consumption can help in the reduction of electricity bills and ensure a safe supply of electricity [21]. The peak load demand is reduced by the installation of SEMS and eventually, it helps in the control of blackouts with the demand response program. SEMS can be steered with the use of panel inside homes, tablet or smartphones [21].

SEMS provides many benefits that can be achieved with the installation of the system. They include; automatic switching off the load, use of another energy which is renewable, and finally the communication between the household and the customer [22].

[23] declared in their study that Smart Energy Management Systems stabilises the energy efficiency and the savings making it suitable for the homes. Further, according to [24] SEMS is a way to integrate both conventional energy and renewable energy to manage the issue of electricity cost and energy efficiency. While [25] found SEMS as a way to stabilise the efficiency of power and cost confirming customer satisfaction. Moreover, the study also showed that this enables the user to forecast the load and generations which makes to plan accordingly.

The load forecasting in SEMS should be done one day before relying upon the weather to use the distributed generation to its full potential [21]. Smart grid technologies are complemented by the SEMS system approach resulting in energy balance [21].

2.6.1 Energy Manager

The component involved in the system “Energy Manager” with its intelligent control works ideally in tandem with all the devices and collects all the information regarding the batteries, inverters, panels and other devices included in the system. Moreover, the consumption of each device in the home is measured by the energy manager and then regulates household energy consumption. On one hand, the system allows the luxury for the home user to choose the operation of appliances according to specific plans [18]. On the other hand, the energy manager can also plan the load automatically depending on the daily energy usage [18].
2.6.2 Energy meter

Energy meters in SEMS are devices that quantify the energy consumption of household and make a communication to the power utilities [26]. The meters are in correlation with modern instrumental technique and communication. Consequently, the customers are allowed to make a decision on the usage of appliances, the energy resources, and the storage system.

The functions of the energy meter include; maintaining communication with the energy manager and provide information on consumption via circuit [26] [21]. Also, managing loads efficiently and working in tally with energy manager by automatic switching off the loads or load shedding. Moreover, providing data for the homeowner reference [21].

2.6.3 Communication system

As mentioned previously, the energy manager data can be accessed from any internet-connected devices to have a proper grasp over the data at home as well as away. Many communication techniques have been mentioned in various studies. For example, ZigBee [28] is a system that helps in communication and further allocates different network tasks to components involved. Bluetooth was also suggested considering as an easy way to fix in the smart devices and household appliances [27].

![Image: Smart Energy Management System](image-url)
2.6.4 SEMS profile

The profile for the examination of SEMS performance and efficiencies is taken from the web portal of SEMS manufacturer “Solar Watt”. The company offers energy management solutions and solar PV panels. Considering, the components for SEMS, Energy manager is supposed to be the heart of the system. So, collecting data for the record is more about learning the use of Energy manager and the components involved.

The data available in the portal is from two different locations namely Dresden and Freudenstadt, Germany. The former location installed SEMS in August 2016 while the latter installed it in January 2017. The household installed SEMS in Dresden has a size of 3 persons while in Freudenstadt, the household size is 5 persons. This depicts an average usage of electricity for various locations around Europe.

The components installed in both places include heat pumps and batteries. The battery used in Dresden with a home size of three people is 8.8 kWh, at the same time in Freudenstadt, the capacity is 4.4 kWh. The panels installed in these homes are 8.5 kW and 4.6 kW in the locations of Dresden and Freudenstadt respectively.

Figure 6 shows the profile of energy production for a day from the location Dresden. The produced energy in excess is stored in battery with a capacity size of 8.8 kWh and the energy is later used in times when there is no sunlight.

From the two locations specified in the web portal, Dresden is chosen for the study as the temperature profile for Gotland and Dresden are nearly the same. The efficiency and benefits of using the system are scrutinised with the demo accounts available on the web portal.

The accounts are from originally installed places that share the information about the total production, the consumption, the battery charge, and its supply and also about the amount of power that is fed to the grid along with the power purchased from the utility provider.
Furthermore, it shares the data about the use of the Energy manager in the system which supervises the power flow. These details are the major tool in estimating the performance of the SEMS.

### 2.6.5 SEMS performance

The Energy manager portal provided by the SEMS manufacturer allows the user to access the energy profile from the locations installed. As mentioned in the previous section about the location, Dresden is chosen for the performance analysis. An overview of the system is taken in two cases:

**Case 1:** Instantaneous analysis

**Case 2:** Daily analysis

**Case 1:** The performance of the system is checked in the portal for a particular instant of time and evaluated the power flow. The power flow was checked on 7th July 2019 at 19.34 hrs and on 8th July 2019 at 19.48 hrs and 19.52 hrs. The results are shown below (Table 2):

<table>
<thead>
<tr>
<th>Instant</th>
<th>PV production (W)</th>
<th>Self-consumption (W)</th>
<th>Total consumption (W)</th>
<th>Feed-in (W)</th>
<th>Power purchase (W)</th>
<th>Battery charge (W)</th>
<th>Battery supply (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>386</td>
<td>351</td>
<td>351</td>
<td>35</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>261</td>
<td>261</td>
<td>305</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>194</td>
<td>194</td>
<td>387</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>189</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>1</td>
<td>393</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>392</td>
</tr>
</tbody>
</table>

*Table 2: SEMS performance analysis case 1*

The readings in Table 2 are taken and studied to suggest about the performance of the installed system. At instant one on 7th July 2019 19.34 hrs, the PV production is used in the home and the rest of the power is fed to the grid. At this instant, there is no supply from the battery and the battery is fully charged at this point of time.

At instant two, on 8th July 19.48 hrs, the PV production is reduced but the consumption is a bit more than the production so the power is taken from the battery and the rest of the power is fed to the grid which shows the efficiency of the system. The battery has started to discharge from this instant and will be used for the rest of the day.
Instant three, the system operates in correlation with the grid by power purchase of 4 W while the production from panels is completely used in the home. The excess amount of power is supplied by the battery for the usage. The system was analysed on the 8th of July 19.52 hrs.

Instant four is the situation when there is very little production of 1 W. The power is supplied by the battery and most importantly, a power of 2 W is fed into the grid which increases its possibility of using in the home even when there is less solar power. The instant was on the 8th of July, 20.32 hrs.

**Case 2:**

A daily overview of the system is selected from the portal and included in the inspection of performance. A day in the summer month is considered as the production will be higher during the period. Table 3 contains the obtained results.

<table>
<thead>
<tr>
<th>Instant</th>
<th>PV production (kWh)</th>
<th>Self-consumption (kWh)</th>
<th>Total consumption (kWh)</th>
<th>Feed-in (kWh)</th>
<th>Power purchase (kWh)</th>
<th>Battery charge (kWh)</th>
<th>Battery supply (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>32.4</td>
<td>7.6</td>
<td>10.6</td>
<td>18.3</td>
<td>0.0</td>
<td>6.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

*Table 3: SEMS performance analysis case 2*

In a day, the production of panels is at an appreciable amount with its rated capacity and consumption directly from the solar is 7.6 kWh. The total consumption including the power taken from the battery is recorded to be 10.6 kWh. The power fed into the grid is of a remarkable value of 18.3 kWh and this rates the system to be better in terms of operation with the grid. The battery is efficient with providing 6.5 kWh power with a charging rate of 3 kWh per day.

From the results, it shows to be independent of the Grid as there is no power purchased during the day and the consumption is met by the production from solar. Out of the power produced, 33 % is self-consumed and rest is fed to the grid and stored for future use.

However, the day discussed above is sunny and contains more hours of sunlight which increases the production but in winter months the power production will be very low and power has to be purchased from the grid. But from the results, it can be seen that the energy manager efficiently supervises the power flow in the system discussed above by feeding the right amount to the grid, operating battery at times of low production and in the night. Moreover, controlling the consumption in the home by scheduling the working of appliances at the right time.
3 Methodology

The study is done as three different sections; Firstly, in order to analyse the hosting capacity of the given grid topology, a model is created in software Open DSS. The same model is again used to examine the impacts on the grid with the penetration of PV panels. The simulation is done in “static mode” of Open DSS. The outcome of the simulation suggests if the parameters are rightly illustrated. In the first case, the static mode results give the active power and reactive power that the grid network contains which is similar to the data supplied by GEAB at that particular instant.

Moreover, the PV required for the study is modelled in the software with the available irradiation data. The simulation of the PV is done in “daily mode” of Open DSS to represent the production and its effects on the grid for a day. Once the PV is integrated into the circuit, line monitors are included in the circuit to examine the voltage variations and violations in the circuit. The results generated are exported as an excel file from Open DSS and plotted graphs to determine the rise in voltage and change in phase amplitudes. This is done by specifying a rating to the PV with a notable value.

The data provided shown below (Figure 7) is used as the load shape for the PV.

![Load Shape](image.png)

Figure 7: Load Shape

The load shape above (Figure 7) is transformed in accordance with each of the ratings given for the PV in the simulation and in all cases done, after the simulation, the voltage variation and the current of the lines are checked to know if any of these quantities have increased beyond the limits. The current limits for the cable are known from the cable datasheet. Since the type of cables was supplied, the datasheet is obtained from the cable manufacturer. Once, the limits have gone beyond the cable ratings, the simulation is stopped to check the rating of PV which is the hosting capacity.
The amplitude variations of voltage in the cable are also checked to ensure that the variations have not broken the limited range. Moreover, time series simulation is done to know if at any instant the voltage is violating the specified limits.

The data obtained from the results helps in deciding the hosting capacity of the grid for solar in one way. The rating of the PV is increased step by step and simulation is done a multiple number of times until the voltage amplitude violates the standards specified by the Grid code EN 50160. The voltage results from the excel file give the values which can be used to inspect if the voltage limit is violated.

Simultaneously, it is important to keep an eye on the amount of current that flows through the cables. Each cable is modelled to withstand a certain capacity of current based on its parameters. For this reason, the current flow and voltage variations over the cable are noted and made sure that the current does not go beyond ratings of cable and voltage variation is in permissible limits. Moreover, effects on the adjacent cables and main cables on the grid are also taken into consideration.

Another most important part of the simulation is to calculate the effects of harmonics on the grid with PV integration. In the circuit, a default spectrum of harmonics is injected and the variations in voltage and harmonic limits are investigated.

The simulation for harmonics is done in “static” or “snap” mode of open DSS since the time simulations don’t yield accurate results and will produce errors. The results are again exported to excel where data is in multiples of the fundamental frequency. Total Harmonic Distortion (THD) for voltage and current is calculated in the line where the PV is connected and is monitored for every simulation done. The results are checked together with the simulation and guaranteed that limits of harmonics are well within the acceptable ranges.

In addition to this, the hosting capacity of PV for the other 10 houses in the grid is also examined with the same technique mentioned above. Furthermore, the effects on the grid caused by these panels for respective lines are assessed to know if it is within the Grid norms. Eventually, the hosting capacity of Solar PV for the studied network is concluded taking all these factors into account.

Secondly, the size of the battery is determined for the usage in the household considering the production and consumption data of the analysed household. The data of production and consumption is handled in excel and graphs are plotted to determine the difference between the two quantities. The battery must also be capable enough to feed power to the home during peak hours as well.

The simulation is done by tallying the hourly data of production and consumption. The difference between the two quantities is determined each hour for a month and eventually for a year. The data handling is done in excel and the simulation for the battery is done in MATLAB. A code is generated in MATLAB to find the size of the battery to be used in the home by using the files which include the data for the difference between production and consumption.
The battery size for different PV systems is evaluated considering installation and the production data of solar is varied depending upon the PV systems installed in the home. For this reason, three scenarios are reviewed for different PV sizes, in which the production for these sizes is computed with the data available by multiplying the per unit.

Three battery capacities are chosen to test which suits the best for each PV system. The capacity is varied up to a certain limit for above which the battery becomes oversized. The difference between production and consumption (PC) is the main function in formulating the three quantities mentioned below.

i) Power supplied by the battery that saves from buying from the grid
ii) Grid supply which depicts the consumption of home
iii) Price of the battery

Once the simulation is done, the results obtained are analysed to record the savings that the battery provides. Finally, the three battery capacities are compared based on their Net Present Value (NPV), the size of the battery is optimised which provides an increase in self-consumption and a reduction in the electricity bill for the home.

Moreover, a survey is conducted in Östergarnslandet with the help of Uppsala University, Campus Gotland to study the attitude of people towards this energy transition. Since the survey done contained 25 questions, it was vital to filter out questions within the scope of the thesis. There were two main questions related to the thesis which are stated in the data analysis section of the survey. Each of the responses from 113 residents is picked for these two questions and majority answers are assessed to impart the outlook of people towards energy change from conventional to non-conventional sources.

3.1 Theory

3.1.1 Open DSS overview

Open DSS is a frequency domain-based software that was developed by Electric Power Research Institute (EPRI). The software is developed to design unbalanced and balanced networks, three-phase distribution systems and many other power system analyses. The main feature of Open DSS is the inspection of harmonics which can be done quite easily on circuits compared to other grid-related software. The simulation in Open DSS can be performed in various ways as static, daily, yearly and duty cycles. Moreover, Open DSS allows an association with other software like MATLAB with Computer Object Model (COM) interface thereby exploiting new areas of simulation. A sample program of Open DSS is shown in (Appendix B).

Figure 8 shows the internal architecture of Open DSS:
3.1.2 Net Present Value (NPV)

Net Present Value (NPV) is a way of estimating the investment where the discount rate is taken into account in which the estimation is done based on the present value [37]. The Net Present Value gives a sum of the cash flow for a given period of time with the discount rate. It is calculated by the equation below:

$$NPV = \sum_{t=1}^{L} \frac{C_t}{\left(1 + \frac{r}{100}\right)^t}$$  [37]

Where $C_t$ is the net cash flow occurring during the period considered, $L$ is the total number of periods in years, and $r$ is the discount rate given in (%) [37].

3.1.3 Total Harmonic Distortion (THD)

Total Harmonic Distortion (THD) can be defined as the ratio of total voltage to the fundamental voltage [38]. It is an important parameter in determining the level of harmonics in the system. It can also be explained as in which the harmonic content is compared to its fundamental value. THD is calculated using the formula:

$$THD = \frac{V_{\text{rms without fundamental}}}{V_{\text{rms fundamental}}}$$  [38]

Where $V_{\text{rms}}$ is calculated by $V_{\text{peak}}/\sqrt{2}$
3.2 Analysis of data

The data required for the study is provided from various sources including the utility provider Gotlands Elnät AB (GEAB) who were a part of the project. The analysis of data is required to assure the proper simulation results which are substantial to realise the focus of the thesis.

3.2.1 Grid data

The grid data is given by the utility provider Gotlands Elnät AB (GEAB) in the region, Östergarnslandet. The given grid topology consists of low voltage grids with a 0.4 kV line which is a subsection of the mainline 10 kV. The grid contains subscriptions for 11 consumers and a rated transformer of 100 kVA which steps up the voltage from 0.4 kV to 10 kV.

In addition to that, the length of the cable from one node to another node, the resistance of the cable, the reactance and the capacitance of the lines are also provided. The length of the cables is given in units of kilometres. The capacitance, reactance, and resistance of the lines are given in default units of microfarad (µF), ohm (Ω) respectively. Moreover, the type of cable used in the connection is also allotted making it easier to determine the capacity of the lines in terms of currents that eventually determine the effect of penetration.

The grid study is further made smoother with the schematic diagram and inspection of the feeder bus supplied by GEAB. The document also contained feeder load at a particular instant and the losses of the bus.

3.2.2 Solar production

The solar production profile is created artificially by scaling down the historical data from a test site located in central Gotland. This site was used as a part of the project “Smart Grid Gotland” and owned by GEAB. The data is recorded for a period of four years starting from October 2013 to June 2017. The site contains three panels with each having a rating of 3.2 kW and six panels having 7.5 kW each. The hourly production data is in units of kWh.

From the installed details, it is evident that the panels have a production peak of 9.6 kW and 45 kW. This means, during the period of high sunlight hours, for example at 12.00 o'clock midnight, the production from solar panels will be either 9.6 kW (3*3.2 panels) or 45 kW (7*7.5 panels) provided if the efficiencies of panels and inverter are at appreciable values. Out of the production profile year, 2015 is taken for the study (Figure 9).
3.2.3 Household consumption

The data for consumption is to be acquired from the home where the evaluation is intended to take place. A consumption data for a period of four years is attained from the consumer webpage “My GEAB” with the consumer identity. The data received from the webpage is yearly consumption for the home and in kWh. For determining the size of the battery, the yearly consumption has to be changed into hourly data in order to have more resolution than the data obtained.

The purpose is achieved with the help of software “Load profile generator” which generates a realistic load profile for the original household with the given consumption data. The input is given in the form of desires and the output from the software generates the household profile for a month or a year. Thereby, the load profile is created in such a way that the software produces the same amount of consumption at the end of the year as recorded. The resolution of output can be decided by the user which can be hourly or per minute of energy usage. The consumption recorded for the year 2015 in the house is as given below (Table 4):

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>March</th>
<th>April</th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3589</td>
<td>2957</td>
<td>2748</td>
<td>1509</td>
<td>940</td>
<td>522</td>
<td>753</td>
<td>463</td>
<td>643</td>
<td>1347</td>
<td>2307</td>
<td>3555</td>
</tr>
</tbody>
</table>

*Table 4: Consumption for year 2015*
3.2.4 Survey

A survey was conducted in the region of Östergarnslandet to account for the attitude of people towards the energy transition. The survey results are provided by the Department of Earth Sciences in the Uppsala University Campus Gotland. There were 113 respondents to the survey out of which 67% of them were men and 23% of them were female. In the survey, the responders mainly have summer houses which accounts for 54% whilst 37% of them are individual homes.

It is important to survey the attitude of the people towards this energy transition and a questionnaire was prepared and send out to them through e-mail. There were 25 questions regarding the change and people were voluntarily asked to fill the survey. Since the project is revolved around solar installation, two questions were asked to the residents in the survey that “Would they be interested in investing any of the following energy production or energy storage technologies?” Also, people were asked, “how would they like to invest in the technologies for the energy transition?”.
4 Modelling

As mentioned before, the model of the grid is created in software Open DSS to determine the hosting capacity and also to get an idea about the impacts that can be created with the penetration of PV. The hosting capacity would help in recognising the amount of solar that can be included in the grid without risking the grid infrastructure and violating the standards mentioned as per Grid code.

4.1 Grid design

The grid topology given consisting of 11 consumers (Appendix A) is modelled with an approach to examine the low voltage network. First and foremost, with the help of a schematic diagram the buses involved in the grid are identified. In open DSS each bus of the given grid is taken into account and also the lines connected to the network.

4.1.1 Line

The line from each bus is defined as four-phase lines including the neutral. The line is defined as a three-phase line with the neutral line also simulated. Usually, the neutral is not considered in a three-phase system as there is no current if the system is balanced. The neutral line is simulated in this project to study the effect of one phase connection of PV systems and the effect in harmonics. The schematic representation of the line connections is presented in Figure 10.

The resistance, reactance, and capacitance of the lines are described as per the document along with the line lengths as well. The characteristics of the line are crucial in specifying the limits of PV penetration on to the grid as well as to assure power quality to consumers.
4.1.2 Load

Loads in the grid are identified earlier with the schematic diagram and as stated before, there are 11 houses connected to the grid. Apparently, all the houses connected to the grid are three-phase loads, so the line to line voltage is 400 V and line to neutral will be 230 V. The feeder load at a particular instant of time is given in the document and the house where the analysis is taking place is located.

All the loads in the system are delta connected in the simulation and to spot the house, is a substantial step because the PV will be connected to the grid from this point.

4.2 PV modelling

In Open DSS, there are various ways to define a PV system. The common way of expressing the PV system is with variables Irradiance, kW of panels, the efficiency of the inverter, and the temperature-power factor. The simulation can be done in either daily, yearly or duty cycle modes and the load shape for the panels is also described in either of these modes mentioned.

Since the energy data for PV production is available over a specific period, it is better to state the PV as a generator in Open DSS connected to the grid. Here, the PV is considered a generator that has the profile of production for a day described as Load shape. A daily load shape is suited for the definition and ratings of the generator are given in kW. Precisely, it depicts the ratings of the PV panels connected to the grid. The connection is done from the same bus feeder where the house is connected so it, in turn, applies as PV connected from home to the grid (Appendix A).

To analyse the harmonics involved in the grid when the PV is connected, a harmonic spectrum is injected into the grid along with the PV modelled. In Open DSS, a default spectrum of harmonics is already present in the loads. The default spectrum is removed from the loads to show there are no other harmonic sources in the grid except the inverter of the PV systems. In addition, it is assumed that the inverters have the same harmonic values presented in Table 5.

<table>
<thead>
<tr>
<th>Multiples of frequency</th>
<th>% of magnitude</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 5: Harmonic Values Injected [39]*
The harmonics values are injected into the grid and are measured at times of peak production of solar especially in 11.00, 12.00, 13.00 and 14.00 hrs. This is presented to depict the worst-case scenario when there is high solar production and to analyse the maximum value of harmonics that can occur in the grid during this period.

The values of harmonics are measured at three different points on the grid:

i) On the line connecting the home where PV is connected
ii) On the line, where the adjacent home is connected
iii) Close to the transformer

4.3 Model of battery

As declared before, the model of battery or the capacity of battery is described in the thesis taking the production and consumption data into account. To produce a precise size of the battery it is important to have the right production and consumption data with regard to the house studied.

4.3.1 Production

The production data has to be changed in accordance with the home production for analysing the size of the battery. Most importantly, from the data supplied one year of production is chosen for thesis purpose. Production from the year 2015 is taken, as the panels have produced energy close to the installed capacity.

Firstly, the data has to be converted for usage and is done by taking the per unit of production. The production from 6*7.5 kW panels is transformed into the production in the home. The house has already 4.5 kW panels installed, so the initial conversion is done to 4.5 kW.

Per unit is calculated by:

\[
p.u = \frac{\text{Solar energy hourly production}}{6*7.5}
\]

Initial step: Production at home = \( p.u \times 4.5 \text{ kW} \)
4.3.2 Battery Control

The production data contained hourly results while the outcome of Load profile generator for consumption was for every minute. The resolution was set to one minute to portray minute by minute usage of energy in the home. Since the unit of time has to be the same for both production and consumption, the consumption data is changed to hourly units. Moreover, the size of the battery will be in units of kWh, it will be easier to examine in hourly data.

For optimising the size of the battery, three battery sizes are chosen and simulated for different PV installations to know which battery is optimal. The different PV and battery sizes considered are as follows (Table 6):

<table>
<thead>
<tr>
<th>Cases</th>
<th>Initial case</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (kW)</td>
<td>4.5</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Battery</td>
<td>NA</td>
<td>9</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>Capacity (kWh)</td>
<td></td>
<td>15</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

*Table 6: Scenarios*

Three batteries 9kWh, 12kWh and 15 kWh are tested for each of these installations and their NPV’s are tabulated for a period of 10 years. The discount rate for the calculation is assumed to be 4.55 % which is according to the Swedish Energy Market Inspectorate [34]. This helps to identify the optimal battery size for the installation in the home.

The battery modelling is assigned control to maximise the self-consumption and reduce the electricity bill amount at the home studied. The code in MATLAB is generated with the following conditions:

- When the PV production is high, the battery is charged when there is capacity in the battery. If there is no capacity, the battery is charged to its potential and rest is sent to the grid.
- When the PV production is low, if there is energy in the battery, the power is used. If there is not enough energy in the battery, the energy left is emptied in the battery and the rest is received from the grid.
5 Results

The simulation results are presented in this section which is the prime focus of the thesis. The outcome of the simulation for PV integration is compared with the base cases containing with and without PV connection. The simulation output is given for overvoltage, harmonics, and phase unbalance obtained from the line connecting house number 1 (LAB1 in diagram). With all these taken into account, the hosting capacity for solar in the grid topology is specified.

In the second part of the results, the size of the battery to be used in the home is specified with three scenarios considered as stated earlier. Relied on the production of solar, battery size for each PV installation is illustrated. Finally, the survey results will be discussed.

5.1 Overvoltage impacts

The power output from the PV system is not continuous throughout the day but changes influenced by the sunlight hours and the weather conditions on that particular day. Since the data has the variations of the day included and PV being declared as a generator in Open DSS, it adjusts automatically. Two cases are considered for the simulation:

- **Case 1**: Without the integration of PV to the grid
- **Case 2**: With the PV connected to the grid

**Case 1**: The simulation is done without PV integration and Figure 11 shows the voltage profile for a day considered with a constant load. The voltage units are given in per units and V1, V2, V3 represents the voltage in each of the three phases.

![Figure 11: Voltage profile basic case](image-url)
As Figure 11 shows, without the inclusion of PV into the grid, all three phases of voltage are well within the limits specified by the Grid code. The voltage variations are constant in the plot as the load changes that occur during the day is considered to be invariant for the cable connecting the home where the PV is supposed to be installed.

**Case 2:** The simulation done is done with PV integration and Figure 12 shows the voltage profile for a day considered. The voltage units are given in per units and V1, V2, V3 represents the voltage in each of the three phases.

![Voltage profile with PV (Line LAB1)](image)

*Figure 12: Voltage with PV*

For the above simulation, the generator rating is given to be 8 kW connected to a single phase. Plotting the graphs (Figure 12) it is evident that voltage variations are present in the system. This voltage level attains a maximum value of 1.023 p. u at the time where the solar production is at its peak. The variations are not desirable for a system operating with constant voltage conditions.

However, the voltage amplitude variations are within the limits while integrating a panel with 8 kW. As per the grid code EN 50160, the voltage amplitude variations are allowed to a maximum limit of 10 % of nominal voltage. In Sweden, the nominal voltage is 230 V. The overvoltage will be one of the prime factors in deciding the hosting capacity.

### 5.2 Phase unbalance

The phase unbalance can be described with the change in phase angles or the measure of voltage changes in amplitude between the three phases. Due to restrictions in quantifying the phase angles of the voltages in Open DSS, the changes in amplitude are examined when PV is connected. The generator rating in the simulation is 8 kW.
The phase-amplitude difference of voltage between the three phases varies when the PV is connected (Figure 13). The value deviates greatly for the amplitude difference between the first and second phase as well as for the first and third phase especially at times of peak production.

![Phase amplitude difference with PV](image)

**Figure 13:** Phase amplitude with PV

5.3 Harmonics

The harmonic values for the regional grid with the integration of PV is simulated by injecting harmonics into the system as specified in the modelling section. The results from the simulation are plotted and the THD values are assessed at periods of peak production. Figure 14 below represents the harmonic levels measured at the end of the line where PV is connected to.

![Harmonic Level (Line LAB1)](image)

**Figure 14:** Harmonics with 74kW
The highest THD value of 4.15 % occurs at 12 o'clock and 13 o'clock at noon where solar production is at its peak. So, it is clear that with the increase in the production of solar, the harmonic content also increases. Even though the limits have increased, they have not violated the Grid Code specification which is 5% THD since the maximum value obtained being 4.15 %.

It is important to note that each PV system has its own harmonic profile and here only one case is simulated. This may lead to problems if other harmonic sources are present or if the inverter has a different harmonic profile.

Also, the harmonic effects in the nearby home are measured when PV is connected to house number 1. Figure 15 below shows the plot.

![Harmonics in nearby home](image1)

The plot shows that in the nearby home, the harmonic levels are with minimum values. The maximum value of THD attained at times of peak production is 2.5%. This value does not create any significant effect on the grid as there is no violation of limits.

![Harmonics near transformer](image2)
It can be seen that with the distance, the decay of harmonics occurs and to prove this fact, the values of the harmonics near the transformer are checked (Figure 16). From the figure, even at times at high production, the maximum THD value near the transformer is 1%. The values of harmonics have considerably reduced with distance from 4.15% in the home to 1% when checked near the transformer.

So, it can be declared that values of harmonics are under safe limits and the PV operation is with minimum interference to the power signals.

### 5.4 Hosting capacity

To acquire the results for the hosting capacity of solar for the home with respect to the grid, the system model was started with a simulation of 4.5 kW as the house has already PV panels installed of this capacity. Gradually, the ratings are increased concurrently with the simulation checking the voltage variations and current ratings of the cable (LAB1) along with the Grid Code norms for house number 1. Moreover, when house number 1 is generating PV, the effects on the main lines (LA1, LA2, LA3) are also noted in deciding the hosting capacity.

According to the cable datasheet, the maximum current that connected cable (LAB1) could withstand is 198 A and 292 A for the cable (LA1) connected to the main busbar. Figure 17 represents the voltage change in calculating the hosting capacity.

The PV ratings in this simulation are given to be **74 kW** carrying ratings from 4.5 kW. The voltage change is checked and the maximum voltage obtained is 1.069 p. u at 12.00 and 13.00 hrs where the production is at its peak. The Grid norms are checked for the amplitude variations and there is no breakage of standards as +/- 10% of nominal voltage is allowed.

![Voltage Profile (Line LAB1)](image-url)  
*Figure 17: Voltage profile with 74 kW*
The current changes are also examined (Figure 18) and the maximum current is at 13.00 hrs with a value of 108.42 A followed by 107.44 A at 12.00 hrs. Both these instances are at the time of peak production which is under the rated capacity of cables.

![Current Profile (Line LAB1)](image1.png)

*Figure 18: Current profile with 74 kW*

Before concluding the hosting capacity of solar for the home, it is vital to ensure that the effects of PV installed on this line cause a minimal effect on the neighbouring lines or the houses connected to it. For this reason, simulation is done to check for the effects on the neighbouring lines. There are two main neighbouring lines, in which the other 7 houses are connected to. Figure 19 and Figure 20 represent the voltage and current variation in the neighbouring line (LA2) while Figure 21 and Figure 22 plots the voltage and current variations in the neighbouring line (LA3).

![Voltage Profile (Line LA2)](image2.png)

*Figure 19: Voltage in neighbouring Line 1*
From Figure 19, it is clear that there are voltage variations occurring in the neighbouring lines 1 where other houses are connected to. The voltage variations reach a peak of 1.04 p.u at times of peak production but it is within the allowed standards.

![Current Profile (Line LA2)](image)

*Figure 20: Current in neighbouring Line 1*

Similarly, the current changes are noted in the line which can be inferred from Figure 20. The current drops value of 0.65 A which can be considered as a minimum value change.

![Voltage Profile (Line LA3)](image)

*Figure 21: Voltage in neighbouring Line 2*

Figure 21 has the plot from the neighbouring line 2. The plot shows the effects are evident and voltage increases to a value of 1.04 p.u which is the same as the other line. Since the variations are within the limits, it doesn’t cause a significant effect.
Likewise, the current variations in the neighbouring line 2 are close to 1A that is regarded as minimal with no effects on the lines (Figure 22).

At this point in the simulation, the hosting capacity of house 1 can be declared to be 74 kW. Similarly, the hosting capacities of solar panels for other houses are calculated as for house 1. The results for the maximum hosting capacity of each of the houses are presented in Table 7.

<table>
<thead>
<tr>
<th>Busbar</th>
<th>House number</th>
<th>Max. Hosting capacity (kW)</th>
<th>Maximum voltage (p.u)</th>
<th>Maximum current (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>2</td>
<td>45</td>
<td>1.04</td>
<td>68.55</td>
</tr>
<tr>
<td>AB</td>
<td>3</td>
<td>73</td>
<td>1.068</td>
<td>120.34</td>
</tr>
<tr>
<td>AB</td>
<td>4</td>
<td>44</td>
<td>1.04</td>
<td>67.73</td>
</tr>
<tr>
<td>AC</td>
<td>5</td>
<td>40</td>
<td>1.03</td>
<td>67.46</td>
</tr>
<tr>
<td>AC</td>
<td>6</td>
<td>42</td>
<td>1.05</td>
<td>67.10</td>
</tr>
<tr>
<td>AC</td>
<td>7</td>
<td>44</td>
<td>1.056</td>
<td>67.18</td>
</tr>
<tr>
<td>AD</td>
<td>8</td>
<td>67</td>
<td>1.064</td>
<td>109.84</td>
</tr>
<tr>
<td>AD</td>
<td>9</td>
<td>45</td>
<td>1.045</td>
<td>67.07</td>
</tr>
<tr>
<td>AD</td>
<td>10</td>
<td>66</td>
<td>1.064</td>
<td>103.66</td>
</tr>
<tr>
<td>DE</td>
<td>11</td>
<td>64</td>
<td>1.085</td>
<td>100.81</td>
</tr>
</tbody>
</table>

Table 7: Hosting capacities of houses
From the above Table 7, the maximum amount of solar that can be installed in each of the houses is obtained. The maximum voltage and current variations occurring in each of the cables connected to main lines are checked from graphs (Appendix C) to know if it is within the limits. Table 7 shows values when each of these houses generates solar energy and is connected to the grid when neither of the other houses is generating.

Now after the results obtained for the hosting capacity for each of the houses, it is necessary to check the hosting capacity for the whole network or the grid considered. For this, the same method for analysing the hosting capacity for each house is used. The analysis is done in two steps where:

**In the first step**, the PV is connected to the busbar where each of the houses is connected. For instance, in the first simulation, the PV is connected only to busbar AB, then in the second simulation, the PV is connected to AC and then finally to busbar AD. In this case, the main lines of respective busbars are checked to know if any violations occur when PV is connected only to either of these busbars. The results are shown in Table 8 with the values of main lines when their respective busbars are connected to PV.

<table>
<thead>
<tr>
<th>PV connection (at busbar)</th>
<th>Hosting capacity (kW)</th>
<th>Main Line</th>
<th>Max. Voltage (p.u)</th>
<th>Max. Current (A)</th>
<th>Harmonics (THD %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>75</td>
<td>LA1</td>
<td>1.048</td>
<td>97.5</td>
<td>1.00</td>
</tr>
<tr>
<td>AC</td>
<td>58</td>
<td>LA2</td>
<td>1.039</td>
<td>83.29</td>
<td>0.85</td>
</tr>
<tr>
<td>AD</td>
<td>67</td>
<td>LA3</td>
<td>1.044</td>
<td>90.70</td>
<td>0.93</td>
</tr>
</tbody>
</table>

*Table 8: Hosting capacities of busbars*

As can be seen from Table 8 above, when the PV is connected to busbar AB, the maximum amount of solar that can be installed is 75 kW while when it is connected to busbar AC the capacity has reduced to 58 kW. The busbar AD possesses a maximum capacity of 67 kW of solar in the grid. Here, the voltage and current variations occur only in respective lines, for example, when PV is connected to **busbar AB**, the voltage and current variations occur in **Line LA1** while in other lines the current remains constant but the voltage varies within limits.

Also, the values of the harmonics presented in the table are examined near the transformer and at times of peak production (12 o’clock). The values obtained are under safe limits with 1% and less.
In the second step, the PV is connected to all the busbar AB, AC, and AD simultaneously which depict the hosting capacity for the whole grid. The voltage and current variations in all the lines connected are checked in determining the final value. The current and voltage values in the main lines (LA1, LA2, LA3) connected are shown as these lines connect the busbar AB, AC, AD to the busbar A (Table 9):

<table>
<thead>
<tr>
<th>Main line</th>
<th>Max. voltage</th>
<th>Max. current</th>
<th>Harmonics (THD %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA1</td>
<td>1.07</td>
<td>38.57</td>
<td>1.63</td>
</tr>
<tr>
<td>LA2</td>
<td>1.07</td>
<td>58.58</td>
<td>1.63</td>
</tr>
<tr>
<td>LA3</td>
<td>1.07</td>
<td>40.61</td>
<td>1.63</td>
</tr>
</tbody>
</table>

*Table 9: Effects on main lines*

The above results are obtained with a hosting capacity of 120 kW in the grid and to ensure the value, the voltage variations of all the lines connected to busbar A are checked to know if it’s within the specified grid norms along with the current ratings to identify whether it has exceeded the cable ratings. Moreover, the harmonics near the transformer is also checked. The values are in limits and to check the actual value, the rating is increased by 1 kW but it violates the current rating of the transformer of 138 A. Therefore, the maximum amount of solar that the given grid topology can withstand is 120 kW.

5.5 Battery capacity

The analysis of battery size is done with the prescribed method in the methodology section. Three scenarios are selected in relation to the installation in the home. The time series is taken for a period of one year with a time constant of 60 minutes. Production profile is changed in accordance with PV ratings while the consumption data is kept constant for the year 2015 considered. The house considered here is number 1 as the study done is primarily concentrated in the house 1.

Scenario 1:
In scenario 1, the PV capacity increased to a rating of 10 kW and the production profile is changed accordingly. Figure 23 plots the production and consumption of the home with stated ratings and can be seen below.
From the plot, it is clear that in the period of winter months, the production is very low or not present. The consumption is very high in the month of January, February, and March where the sunlight hours are very low in Sweden. The consumption rose up to 9.58 kWh in the first and last months but in the second half of the year starting from mid-May to late September, the production has considerably increased. The highest value obtained is 8.70 kWh of production which is at times of high sunlight hours.

It is important to note the difference between these two quantities to inspect the amount of energy that has to be stored and the capacity to store it. The plot below (Figure 24) helps to visualize the idea.
The profile above is loaded into MATLAB to account for the self-consumption that the battery provides. The battery capacity as mentioned is taken as a parameter to test different capacities for the PV ratings.

In the above scenario, three different capacities of batteries are tested to know which is suitable for the 10-kW installation in the home. Furthermore, the electricity bill reduced while using the battery is compared in the three cases along with the economic analysis of battery to know which is more feasible to install.

The annual energy consumption in the home for the year 2015: **21333 kWh**

The price of electricity transmission: **29.00 ore/kWh** [32]

The price for energy tax: **43.38 ore/kWh** [32]

Therefore, the annual electricity bill for the home: **SEK 15440.82**

Now, the three batteries are checked to know the self-consumption and bill reduction for a 10-kW installation. The results are given below (Table 10).

<table>
<thead>
<tr>
<th>Battery (kWh)</th>
<th>Supply by battery (kWh)</th>
<th>Grid Supply (kWh)</th>
<th>Battery Price [33] (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1446</td>
<td>15391</td>
<td>25000</td>
</tr>
<tr>
<td>12</td>
<td>1794.6</td>
<td>15080</td>
<td>28500</td>
</tr>
<tr>
<td>15</td>
<td>2002.4</td>
<td>14873</td>
<td>35000</td>
</tr>
</tbody>
</table>

*Table 10: Scenario 1*

To identify the best suitable battery for a 10-kW installation, the following calculations are done to check the amount of savings obtained in comparison with the electricity bill. The savings obtained are then compared via Net Present Value analysis (NPV) as mentioned before. The cash flow is assumed to be constant as the yearly average consumption in the home is similar to consumption in the year 2015. The time period considered is 10 years.

**Battery -9 kWh**

New Consumption: 15391 kWh

Electricity bill for the home: **SEK 15440.82**

New bill for the home after the use of battery: $15391 \times 0.7238 = \text{SEK 11140}$

Savings with using the battery: **SEK 4300.82**
**Battery -12 kWh**

New Consumption: 15080 kWh

Electricity bill for the home: **SEK 15440.82**

New bill for the home after the use of battery: 15080*0.7238 = **SEK 10914.9**

Savings with using the battery: **SEK 4525.92**

**Battery -15 kWh**

New Consumption: 14873 kWh

Electricity bill for the home: **SEK 15440.82**

New bill for the home after the use of battery: 14873*0.7238 = **SEK 10765.07**

Savings with using the battery: **SEK 4675.74**

**NPV analysis:**

<table>
<thead>
<tr>
<th>Battery (kWh)</th>
<th>Savings (SEK)</th>
<th>NPV (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>4300.82</td>
<td>8947.66</td>
</tr>
<tr>
<td>12</td>
<td>4525.92</td>
<td>7224.45</td>
</tr>
<tr>
<td>15</td>
<td>4675.74</td>
<td>1907.02</td>
</tr>
</tbody>
</table>

*Table 11: NPV analysis scenario 1*

From Table 11 above, 9 kWh battery has a high net present value compared to the other two battery capacities of 12 kWh and 15 kWh. So, from the calculations, it can be concluded that for a **10-kW** installation in the home, a **9-kWh** battery is ideal.

**Scenario 2:**

Similar steps are followed from the previous section but the production profile is transformed to 15 kW. The profile can be seen below along with the user profile for the home.
As the graph suggests (Figure 25) when the production is increased from 10 kW to 15 kW, there are notable variations. Since the consumption data remains the same, there are no variations involved in it while the energy produced by panels has risen to a maximum value of about 13 kWh in the months of high sunlight hours.

The variance between the two important quantities is charted below (Figure 26).

Likewise, to scenario 1, the steps are followed and calculations are done to identify which battery is suited for installation of 15-kW. Again, three batteries of the different capacities as in scenario 1 are tested in the simulation. The results are charted in Table 12 below:
<table>
<thead>
<tr>
<th>Battery (kWh)</th>
<th>Supply by battery (kWh)</th>
<th>Grid Supply (kWh)</th>
<th>Battery Price [33] (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1631.6</td>
<td>14533</td>
<td>25000</td>
</tr>
<tr>
<td>12</td>
<td>2015.6</td>
<td>14143</td>
<td>28500</td>
</tr>
<tr>
<td>15</td>
<td>2361.3</td>
<td>13849</td>
<td>35000</td>
</tr>
</tbody>
</table>

Table 12: Scenario 2

From Table 12, it can be seen that as the production increases there is a significant change in the grid supply which reduces the electricity bill amount. The following calculations justify this.

**9 kWh battery**

New consumption: 14533 kWh

Electricity bill for the home remains the same: **SEK 15440.82**

New bill for the home after the use of battery: $14533 \times 0.7238 = \text{SEK 10518.98}$

Savings with using the battery: **SEK 4921.84**

**12 kWh battery**

New consumption: 14143 kWh

Electricity bill for the home remains the same: **SEK 15440.82**

New bill for the home after the use of battery: $14143 \times 0.7238 = \text{SEK 10236.70}$

Savings with using the battery: **SEK 5204.12**

**15 kWh battery**

New consumption: 13849 kWh

Electricity bill for the home remains the same: **SEK 15440.82**

New bill for the home after the use of battery: $13849 \times 0.7238 = \text{SEK 10023.90}$

Savings with using the battery: **SEK 5416.92**
NPV analysis:

<table>
<thead>
<tr>
<th>Battery (kWh)</th>
<th>Savings (SEK)</th>
<th>NPV (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>4921.84</td>
<td>13849.56</td>
</tr>
<tr>
<td>12</td>
<td>5204.12</td>
<td>12577.68</td>
</tr>
<tr>
<td>15</td>
<td>5416.92</td>
<td>7757.38</td>
</tr>
</tbody>
</table>

*Table 13: NPV analysis scenario 2*

The net present values for three batteries are calculated again to select battery capacity for a 15-kW installation. In Table 13 above, the 15-kWh battery has low net present value among the three, so it is excluded from the list. Out of 9 kWh and 12 kWh, 9 kWh represents a higher net present value than 12 kWh. For this reason, 9 kWh battery is considered to be the best option to install in the home for a 15-kW solar panel installation.

**Scenario 3:**

Figure 27 represents the production profile for 20 kW along with the consumption for the home.

![Figure 27: Scenario three 20 kW](image)

The graph plotted for the highest amount of production that can be done shows variations as expected. From 15 kW to 20 kW, the production is increased and noted the difference between the two. As can be seen from the plot, the maximum production from panels is 17 kWh.
The capacity to store this energy is determined with the graph below (Figure 28) and it contains a maximum value of 14 kWh. With the production capacity increased, the variations also become noteworthy.

![Production-Consumption graph](image)

*Figure 28: Scenario three - difference profile*

Similar to the above scenarios, the simulation is done and the results are as given in Table 14 below:

<table>
<thead>
<tr>
<th>Battery (kWh)</th>
<th>Supply by battery (kWh)</th>
<th>Grid Supply (kWh)</th>
<th>Battery Price [33] (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1725.4</td>
<td>13979</td>
<td>25000</td>
</tr>
<tr>
<td>12</td>
<td>2182.6</td>
<td>13561</td>
<td>28500</td>
</tr>
<tr>
<td>15</td>
<td>2530.5</td>
<td>13224</td>
<td>35000</td>
</tr>
</tbody>
</table>

*Table 14: Scenario 3*

As in previous cases, the following calculations are done to determine the suitable size of the battery to be installed in the home. The battery capacities are chosen in accordance with the amount of PV installed in the home.
9 kWh battery

New consumption: 13979 kWh

Electricity bill for the home remains the same: SEK 15440.82

New bill for the home after the use of battery: 13979*0.7238 = SEK 10118

Savings with using the battery: SEK 5322.82

12 kWh battery

New consumption: 13561 kWh

Electricity bill for the home remains the same: SEK 15440.82

New bill for the home after the use of battery: 13561*0.7238 = SEK 9815.45

Savings with using the battery: SEK 5625.37

15 kWh battery

New consumption: 13224 kWh

Electricity bill for the home remains the same: SEK 15440.82

New bill for the home after the use of battery: 13224*0.7238 = SEK 9571.53

Savings with using the battery: SEK 5869.29

NPV analysis:

<table>
<thead>
<tr>
<th>Battery (kWh)</th>
<th>Savings (SEK)</th>
<th>NPV (SEK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>5322.82</td>
<td>17014.62</td>
</tr>
<tr>
<td>12</td>
<td>5625.37</td>
<td>15902.74</td>
</tr>
<tr>
<td>15</td>
<td>5869.29</td>
<td>17828.07</td>
</tr>
</tbody>
</table>

*Table 15: NPV analysis scenario 3*

Again, with NPV analysis, battery with the higher NPV values is selected (Table 15). Out of the three capacities chosen, the battery of 12 kWh is avoided since it provides the least NPV value. The other two batteries of 9 kWh and 15 kWh have considerable net present value.
Unlike the other two cases, here **15 kWh** has a high net present value than 9 kWh which makes it the most suitable battery for a **20-kW** installation in the home.

### 5.6 Survey Outcome

The responders of the survey in Östergarnslandet have a clear vision towards the energy transition which is observable from the survey. The plot below shows their response to the survey done for question 1 (Figure 29).

![Figure 29: Survey result 1](image_url)

A question was asked to the residents in the survey that “Would they be interested in investing any of the following energy production or energy storage technologies?”. People were given options of heat pump, geothermal, Photovoltaics, solar collectors, wind and fuel boiler. They were also given the option to suggest more if they are interested in any other technologies available. This was given as a multiple option question where they can mark more than one.

From the results, it is clear that most of the responders of the survey are interested in investing in a solar power plant. Out of 113 residents, about 88 of them marked photovoltaics as an option followed by wind and storage. Also, a certain percentage is not interested in investing but they are very few in number. The interest of people in investing solar can be regarded as a positive sign of the development of a solar power plant in Östergarnslandet and the extension of the system.
The next question was asked, “if they are interested, how would they like to invest in the technologies for the energy transition?”. The responses are plotted below (Figure 30):

![Survey result 2](image)

Figure 30: Survey result 2

This question was also given multiple options, where they were allowed to mark more than one. The options were given of: own investment, joint venture, buy shares and the other two is not relevant and does not know.

The responders have the majority opinion of buying shares of the production units of plant-like solar power that can be viewed as a better source of investment. About 60 of them have this opinion trailed by own investment. People are also interested in having their own power plants like rooftop solar panels. The response to this option is almost the same as buying shares of the production units. Common investment/Joint venture is also marked by people which shows that many are also interested in it. For instance, setting up a solar power plant with community funds can be of this regard where people share the production and feed excess energy to the grid.

On the whole, from the survey done it can be concluded that people in Östergarnslandet are interested in being a part of the energy transition from conventional to non-conventional sources with the intention of consuming clean energy.
6 Discussion

In this section, the discussion of the results obtained in all the simulations is presented and analysed.

6.1 PV Impacts and hosting capacity

The PV system connected to the distribution grid induces voltage and current variations when compared with the base case of non-PV. When PV is connected, at the time of production, the voltage and current values go higher and can exceed the limits specified. This can result in overheating of cables and in turn affect the power quality supplied to the consumers. The inverter manufacturers recommend to install a maximum of 8 kW in single-phase connection and above ratings to three-phase connection [35]. However, installation in three-phase above certain PV ratings can also violate the grid norms and current ratings of the cable. Therefore, it is important to keep the installation under control without any additional effects on the grid.

Similar is the case of voltage phase unbalance where the magnitude of voltage between the phases is checked. It is noticed that when PV is connected to the single-phase, unbalance occurs due to the voltage magnitude difference between the other two phases. This is high in peak production hours and varies throughout the day. Since the variations are within the limits it does not cause any significant effects for small installations like rooftop panels with ratings below 8 kW.

The most important analysis of the PV impacts is harmonic distortion. The THD is examined with a harmonic spectrum of PV injected considering inverter as the only source of harmonics in the network. When the PV is connected, the total harmonic distortion levels increase to a notable percentage and contain signals with distortion. This is a problem to rectify even though the THD levels are below the specified norms. The use of harmonic filters in the grid could be an option to filter out the harmonics caused by the non-linear loads because in the future if there are intentions to introduce electric car charging stations, the harmonic signals need to be taken care of. Moreover, different types of inverters may induce different harmonics and, in this study, other sources of harmonics are not considered except the inverter of PV systems. Also, an increase in the THD level leads to losses in the transformer even if it is within the limits.

The hosting capacity is one of the prime intentions behind the thesis and this is done by running the simulation of Open DSS in a loop. The ratings of the PV are constantly changed until the maximum limit of the grid exceeds. The value is determined in two steps as mentioned before. This is under the impression that the community in Östergarnsländet, may have plans to install solar panels on the field in which the production can be utilised by the people in the community.

As a result, PV installation is studied on three busbars on the grid as well as for the whole grid. The busbar installation can be shared by the homeowners belonging to the respective busbars in which their houses are connected to. This allows the house owners from other busbars to choose if they want to be a part of energy sharing.
Similarly, when the PV installations are done on the field in which all the busbars are connected, this opens up the possibility of having a community-owned solar power plant where people could buy shares of the production.

These parameters are involved in the analysis and the results for each of the busbar AB, AC and AD is found to be 75 kW, 58 kW, and 67 kW respectively. This shows busbar AB has high capacity compared to the other two but for the whole grid it is estimated to be 120 kW. The hosting capacity obtained is found to be sufficient enough to provide energy for all the 11 houses in the grid based on their yearly energy consumption.

6.2 SEMS and battery

For the Smart Energy Management System, the performance study done is a theoretical one. As per the results, the efficiency of the system is highly commendable with managing the power load, operating in coordination with the grid and the working of the battery by supplying power. But it’s hard to predict the efficiency of the system without real-time data and locations of the system.

The battery size determination as a part of SEMS is done with an economical approach in order to find the perfect capacity. The three scenarios show the amount of battery to be installed for various PV sizes with the available data. The battery size depends on the solar production profile used for the study and this may change if another production profile is used in the future. Also, the method is based on installation in homes, so when large installations are done by the community, the battery calculation has to be revised. Moreover, it can be inferred from the NPV analysis that batteries above some capacities can be uneconomical.

6.3 Survey

The survey results are satisfying as the people seem supportive of innovative technologies including investing in it. Most of the people took part in the survey and they are very much fascinated with this process. It is important to note in survey result 1, most people have preferred photovoltaics than solar collectors. Solar collectors/ thermal has the possibility of becoming the most beneficial for the houses as it provides heat and energy together. The collectors can be used to heat the water and are almost 70 % more efficient than PV [36]. In the larger systems, the technology can be used for heating in homes which could be of great significance. This result invites the possibility to rethink the option of photovoltaics over solar thermal.

In survey result 2, it is interesting to see that people are ready to buy shares which is a good sign towards the idea of community-owned solar power plants. More people in the community need to made aware of the benefits of having community-funded installations which can attract them towards the investment.
7 Conclusion

The thesis study is done evaluating the impacts of PV on the grid in terms of overvoltage, harmonics, and phase unbalance in Software Open DSS. The results suggest that the quantities are in specified limits of the Grid Code EN 50160 and no risk involved. The maximum capacity of solar for the grid, the hosting capacity is also determined and can be concluded to be 120 kW. It is not recommended to install beyond this capacity as it creates dangerous effects on the grid with inadmissible voltage, current, and frequency risking the power flow. As a result of this, frequent interruptions occur in the power supply.

The Smart Energy Management System is an efficient way to maximise the use of solar production at home and to reduce consumption by organising the electric load. The system helps in a systematic power flow thereby decreasing electric bills.

Furthermore, the battery to be used in the home for different PV capacities is also suggested taking the production and consumption profiles. It can be concluded that the battery modelled is sufficient to support the energy usage in the home. For a 10-kW and 15-kW installation in the home, a 9-kWh battery is a suitable option while for 20-kW, a 15-kWh battery is optimal.

With the survey, it is very distinct that people in Östergarnslandet welcomes the opportunity of energy transition and can be concluded that the extension of the concept from one point to another can be easily achieved with the cooperation of people in the region.
8 Future Work

This section proposes future work based on this thesis:

- **Different households**
  The grid analysis is done on a region with 11 houses and to check the same for various households in the other parts of Östergarnslandet would give a wider prospect of system implementation.

- **Effect on high voltage grid**
  Investigate the effects on the high voltage grid of 10 kV with more panels installed on various houses.

- **Real-time data**
  It would be interesting to inspect the performance of SEMS with real-time data when the system is installed at one of the houses.
References


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Appendix A

Figure 31: Grid in the region analysed
Figure 32: Grid in the region with PV connected
Appendix B

Below is an example of Open DSS program

New circuit. ABC
~ basekv=115 pu=1.0001 phases=3 bus1=SourceBus
New Transformer.Reg1 phases=1 bank=reg1 XHL=0.01 kVAs= [1666 1666]
~ Buses= [650.1 RG60.1] kVs= [2.4 2.4] %LoadLoss=0.01
New linecode. mtx601 nphases=3 BaseFreq=60
~ rmatrix = (0.3465 | 0.1560 0.3375 | 0.1580 0.1535 0.3414)
~ xmatrix = (1.0179 | 0.5017 1.0478 | 0.4236 0.3849 1.0348)
~ units=mi
New Load.671 Bus1=671.1.2.3 Phases=3 Conn=Delta Model=1 kV=4.16 kW=1155 kvar=660
New Load.634a Bus1=634.1 Phases=1 Conn=Wye Model=1 kV=0.277 kW=160 kvar=110
New Load.634b Bus1=634.2 Phases=1 Conn=Wye Model=1 kV=0.277 kW=120 kvar=90
New Line.650632 Phases=3 Bus1=RG60.1.2.3 Bus2=632.1.2.3 LineCode=mtx601 Length=2000
units=ft
New Line.632670 Phases=3 Bus1=632.1.2.3 Bus2=670.1.2.3 LineCode=mtx601 Length=667
units=ft
New Line.670671 Phases=3 Bus1=670.1.2.3 Bus2=671.1.2.3 LineCode=mtx601 Length=1333
units=ft
Set Voltagebases= [115, 4.16, .48]
calcv
Solve
Appendix C

Hosting capacities of other houses:

Figure 33: Voltage and Current profile - 45 kW (Line LAB2)

Figure 34: Voltage and Current profile - 73 kW (Line LAB3)

Figure 35: Voltage and Current profile - 44 kW (Line LAB4)
Figure 36: Voltage and Current profile - 40 kW (Line LAC1)

Figure 37: Voltage and Current profile - 42 kW (Line LAC22)

Figure 38: Voltage and Current profile - 44 kW (Line LAC24)
Figure 39: Voltage and Current profile-67 kW (Line LAD1)

Figure 41: Voltage and Current profile-45kW (Line LAD2)

Figure 40: Voltage and Current profile- 66 kW (Line LAD3)

Figure 42: Voltage and Current profile- 64 kW (Line LDE1)
Hosting capacity of busbar:

Busbar AB:

Figure 43: Voltage and Current profile- 75 kW (Line LA1)

Busbar AC:

Figure 44: Voltage and Current profile- 58 kW (Line LA2)

Busbar AD:

Figure 45: Voltage and Current profile- 67 kW (Line LA3)
Harmonics near transformer (Busbar connection):

![Harmonics near transformer](image)

*Figure 46: Harmonics of main lines with respective busbar connection*

Hosting capacity of the whole grid:

Line LA1:

![Voltage and Current profile - 120 kW (Line LA1)](image)

*Figure 47: Voltage and Current profile - 120 kW (Line LA1)*

Line LA2:

![Voltage and Current profile - 120 kW (Line LA2)](image)

*Figure 48: Voltage and Current profile - 120 kW (Line LA2)*
Line LA3:

Figure 49: Voltage and Current profile -120 kW (Line LA3)

Harmonics near the transformer (whole grid):

Figure 50: Harmonics of main lines- 120 kW