Grid Benefit from Micro-Scaled Solar Power Production in a Low-Voltage Grid

How to Compensate Facility Owners for the Grid Benefit that their Facility is Providing

Master's thesis in Electric Power Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

This thesis is done in collaboration with Göteborg Energi Nät AB. The main goal of the thesis is to investigate how solar panels in the local power grid benefits the grid. The owner of a micro power production facility that is connected to the grid should get financial compensation from the grid owner, for the reduction in costs that the grid owner experiences due to the connection of the production unit. The financial compensation should consist of a reduction in fees and reduction in cost for losses in the grid. It is also investigated if the current or voltage limits in the grid are violated if many micro production facilities would be integrated in the grid. To analyze the impact the production facilities have on the local grid, energy measurements of both production and consumption in one area in Gothenburg were gathered. The measurements were used together with the fees that the overlaying grid charges for the withdrawal of energy to obtain the changes in the fees. The measurements were also used together with the topology of an area in the grid in order to analyze the change in losses, and consequently the change in the cost for the losses. The measurements and the grid topology was used to calculate the current in the cables in the area at different amounts of installed power. A software called dpPower was used to analyze the voltage in the grid with different amount of installed production facilities. The results shows that the losses in the grid will be reduced when more production units are installed in the area, until the installed power reaches a break point where the losses will start to increase again. The resulting total change in cost at different levels of installed power production indicates that the current grid benefit compensation that Göteborg Energi Nät AB offers their customers could be slightly decreased in the current situation (at least in the investigated area). The compensation could be further decreased if more production units are connected to the grid in the area. No current or voltage limits seems to be violated.

Keywords: Solar power, PV, Energyy, Grid benefit, Cost for losses, Loss coefficient, Hosting capacity, Micro power production, dpPower, Fees.

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Linnea Sundberg, Gothenburg, June 2021

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1
Introduction

This thesis is done in collaboration with Göteborg Energi Nät AB (GENAB). GENAB is responsible for the local grid with 267 000 customers in Gothenburg and takes care of the planning and the construction of the grid, the connection of electrical facilities, maintenance of the grid and measurements of the transmitted power and energy.[1] In this introducing chapter, some background information about the thesis topic is provided. The aim, some limitations and the report outline are also presented.

1.1 Background

A reliable and stable electrical energy supply is of increasing importance in society as the dependence on electricity increases [2]. The importance of reliable electric power is not likely to be reduced with an ever-increasing share of electrical gadgets, as well as electric vehicles and household appliances. There are challenges related to the existing energy resources, related to both our dependence on ending resources of oil, gas and coal as well as to the climate change [3]. An integration of more renewable energy sources is an important step towards a future with more sustainably produced electrical energy.

The rate of installation of renewable energy sources is rapidly increasing in Sweden [4]. The local grid in Gothenburg is experiencing the same development which can be seen in Figure 1.1. The Figure shows the total number of installed micro- and small scaled solar power production units between January 2018 and January 2021. The trend is an increasing installation rate. An increased amount of renewable energy in the power system is an important step towards a more sustainable society with less emission of greenhouse gases [5] and should be encouraged.

With more micro-scaled renewable power production facilities integrated in the grid, there will be a change in the power flow and consumption patterns. This change gives new possibilities for (and demands on) the power system. The energy does not have to be transported through the entire grid if, for instance, the neighbour to a micro-scaled facility consumes the energy at the instant when it is produced. This results in less stress and losses in the grid. If there instead is high production in the facility at an instance when there is low consumption, the produced electricity has to be transported longer distances through the system to where it is needed. The facility could in this case instead increase the stress and the losses in the grid. Since

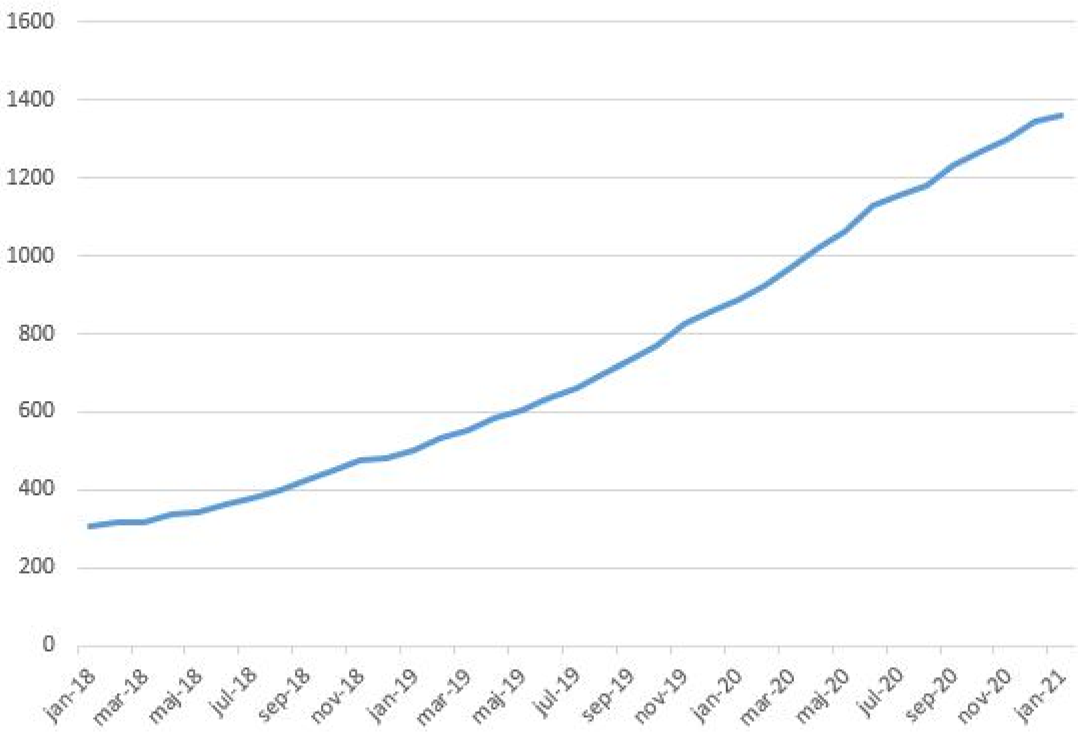

Figure 1.1: A graph over the installation rate in the local grid in Gothenburg between 2018-2021.

the power flow patterns change with an increased amount of micro-scaled production facilities it might also impact the demands on the grid, in terms of how much current the cables need to be dimensioned for and how the voltages are regulated to reasonable values within the limits.

The grid owner is obliged according to the law to compensate the owners of a production facility for the benefits the grid experiences due to the installed production unit. When electric power is injected into the local grid, there can be a reduction in the fees towards the regional grid for the transmission of power and energy. The losses in the local grid can also be changed when the energy is produced locally. If the losses are reduced when production units are installed, this will reduce the expenses the grid owner has for the lost energy. With an increased installation of micro-scaled solar power production units, it is more important to offer a fair and correct grid benefit compensation.

1.2 Aim

The aim is to conclude how the solar power could benefit the grid, society, and the environment and to link that to the law and financial compensation to the facility owner.

The expected output includes:

- a proposal of how to financially compensate the owners of solar power produc-

tion facilities
- a model of the grid in dpPower
- MATLAB scripts with calculations
- the final thesis report

1.3 Research Questions

1. Are the energy and power fees impacted by more solar power production?
2. How are the losses in the grid changing with different amounts of solar power production?
3. Does the grid have enough capacity to withstand large quantities of solar power production?
4. What is a reasonable financial compensation for the grid benefit a production facility provides?

1.4 Limitations

The thesis will only deal with solar power production facilities that are connected to the low-voltage grid. Facilities connected to the low-voltage grid are called micro- and low-scaled production facilities. The definition of a micro-production facility is in this case a facility that is connected to a 400V-grid, with a maximum hourly average of 43.5kW and a fuse with maximum 63A. The definition of a low-scale production facility is in this case that it should be connected to a grid with a voltage of 400V or 10kV, with a maximum hourly average of 1 500kW.

Due to limitation of time it is not feasible to look at all facilities in GENAB's entire grid. Only one area of interest is investigated.

Only customers with a production unit have meters that measure the reactive power, a power factor of 0.9 is therefore assumed in the cases where there are no reactive power measurements. The used measurements from the meters are hourly energy measurements. The power that is used to calculate the currents and the losses is therefore an hourly averaged power. The voltages at the customers are assumed to be constant at 400 V since there are no hourly voltage measurements at all points in the grid. The voltage is verified to be around 400 V from daily measurements at the customers. A constant nominal voltage is assumed at the transformers.

The cable lengths between a cable cabinet unit and the connected customers are averaged for simplicity.

1.5 Thesis Outline

This thesis begins with some background information about the topic, the aim and some limitations. Chapter 2 provides some theory needed for the calculations and the discussions. The theory focuses on the structure of the Swedish grid, the laws regarding financial compensation for grid benefit from micro produced energy injections and how the grid is impacted when micro production is introduced in the grid. Chapter 3 describes the methods that are used to obtain the results in Chapter 4. The results mainly contains calculations of the different parts of the grid benefit compensation and if the technical limits of voltage and current in the grid is violated with a large amount of installed power production. Chapter 5 is discussing the methods and how they might have impacted the results. Some sustainability and ethical aspects are also discussed, as well as further research that can be done within the area. Chapter 6 contains the major conclusions that are drawn from the result and the discussion.

2
Theory

2.1 Laws and Regulations

A financial compensation should be given to the owner of a facility that is injecting electricity into the grid. The compensation should, according to the Swedish electricity law (3 kap. 15 §), correspond to the reduction of losses in the grid and the reduction of fees towards the overlaying grid that the injection of electricity into the grid gives [6]. The Swedish Energy Markets Inspectorate, EI, is the Swedish authority that ensures that the energy companies in Sweden are following the laws and regulations. EI released a new memorandum (PM2020:4) last year about how they will assess the benefit that a production facility provides to the grid and how the compensation should be calculated based on hourly measurements [7].

The reduction of the energy losses should depend on[8]:

- the amount of injected electricity and at which time the injection takes place

The reduction of the fees towards the overlaying grid should be assessed based on[8]:

- the facility's power delivery capability
- the amount of injected electric energy and at which time the injection takes place

Each part of the grid benefit compensation (the change in cost for losses and the change in fees for energy and power) should be bigger than or equal to zero. A facility that contributes to increased losses should not be charged for that, the loss cost part of the grid benefit compensation should then be set to zero. The total grid benefit compensation consists of the sum of the reduction in the cost for the losses and the reduction of the fees for energy and power. [7]

2.2 General Topology in the Swedish Grid

The Swedish power system consists of subsystems at different voltage levels, spanning from 0.4kV-400kV. The voltage is lower closer to the customer and higher closer to high power production facilities. The selection of the voltage level depends on the transmission distance and the power level that is transferred. A certain power can be transmitted with a lower current at a higher voltage or a higher current at a lower voltage. A lower current results in lower losses and a smaller conduction area while a lower voltage demands less insulation and safety distances. All major power production units and regional grids are connected to the transmission grid, which usually has a voltage level of 400 kV. The regional grids typically have a voltage level of 130 kV, which means that they are connected to the transmission grid through 400kV/130kV transformers. There are multiple connections to the transmission grid to always ensure power supply to the region. The regional grid is usually connected in a loop, which gives redundancy in the power supply in the system. [2]

The local grid is connected to the regional grid at multiple receiving stations in the distribution area. This is usually done through receiving stations that are equipped with 130kV/10kV transformers. The high-voltage side in the different stations is usually connected in a loop to enable different paths for the power in case of disturbances. The low-voltage side of the transformer is connected to substations through several cables.[2] The grid in Gothenburg that is investigated in this thesis is a local grid.

Each substation in the local grid in Gothenburg has 1-3 10kV/0.4kV transformers. Several low-voltage cables are connected to the low-voltage side of the transformer. The single-line diagram in Figure 2.1 shows a substation with a 10kV/0.4kV transformer that is connected to two cables at the high-voltage side and seven cables at the low-voltage side. Each of the cables on the low-voltage side are connected to a cable distribution cabinet, in which cables to the different customers are connected. Figure 2.2 shows a single-line diagram over the low-voltage-cables that are connected to costumers through the cable distribution cabinets. There are electricity meters that measures the transmitted energy at each customer connection point. Micro-scaled power production facilities can be connected to the 0.4kV grid. If a micro-production unit is connected at the point, the energy meter is a four-quadrant meter that measures both the active and reactive energy in both directions, while the meter only measures the active power at connection points with only consumption.

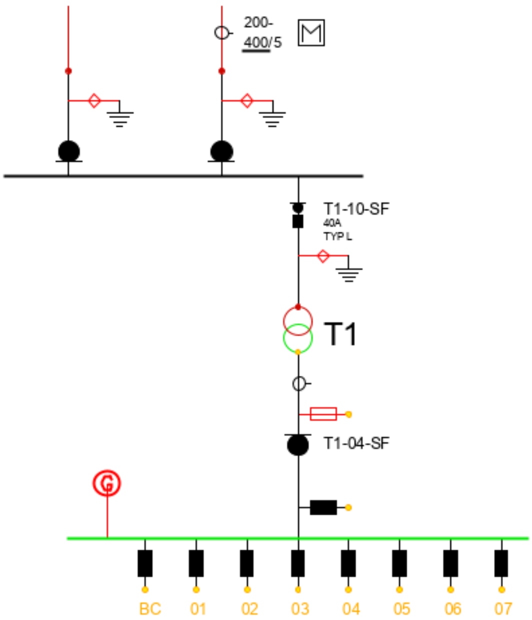

Figure 2.1: A single-line diagram showing a substation. The red lines in the upper part of the figure shows the incoming high-voltage cables that are connected to the transformer's high-voltage side. The green line in the bottom of the figure shows the low-voltage side, at which several low-voltage cables are connected.

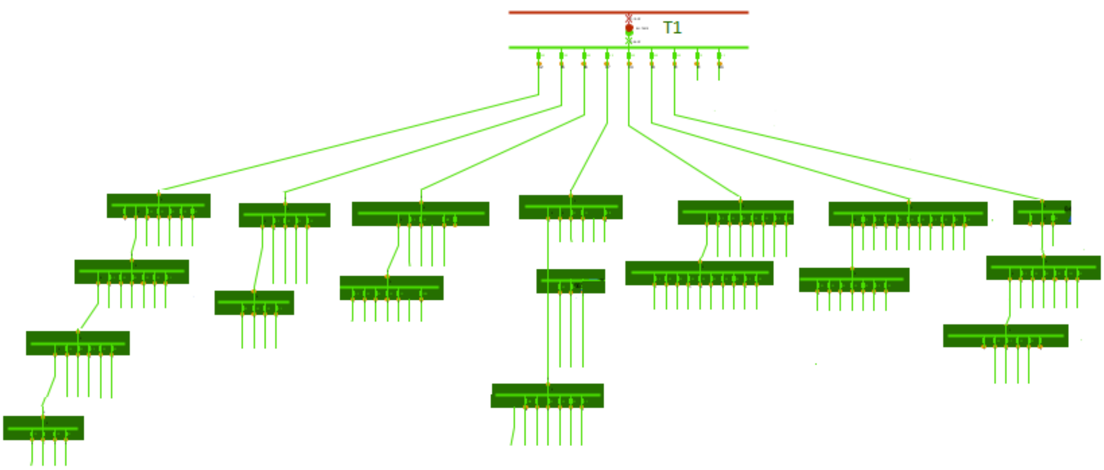

Figure 2.2: A single-line diagram over a low-voltage grid that is connected to a 10kV/0.4kV transformer T1. The red line in top of the picture shows the high-voltage side of the transformer. The green lines show the cables that connect the low-voltage side of the transformer to the different cable distribution cabinets. The green lines that goes out from the cabinets are connected to a customer or another cabinet. The small yellow dots at the outgoing cables from the substation and the cabinets shows the fuses.

2.3 General Power Flow

High power production facilities are usually connected to the high-voltage transmission grid while the customer usually is connected to the local low-voltage grid, as explained in Section 2.2. Since the power has to be consumed at the instant that it is produced [2], this gives a uni-directional power flow from the higher voltage levels towards the lower voltage levels where the customers are located. The power has to be transmitted through the entire system, from the production unit, through multiple transformers and long distances of cables to the customer. The unidirectional power flow is illustrated in Figure 2.3 where multiple substations are connected to the low-voltage side of the transformer in a receiving station. Multiple customers are connected to the low-voltage side of the transformer in the substations. Since there are no production units at the low-voltage side of the receiving station, there is only one possible way for the power to reach the customers.

An integration of more renewable low power production facilities that are injecting power in the low-voltage grid gives a power flow that could be bidirectional at some moments. The customers are now both consumers and producers. Figure 2.4 shows a situation with bidirectional power flow. There are small production units connected to the low-voltage grid at the customers connection points. During the time when the production unit produces more power than the household is consuming, the excess energy will be injected into the grid and consumed by other households in the area. If there are many production units that are injecting power at the same time while the consumption in the area is low, there might even be bidirectional power flow in the high-voltage parts of the system.

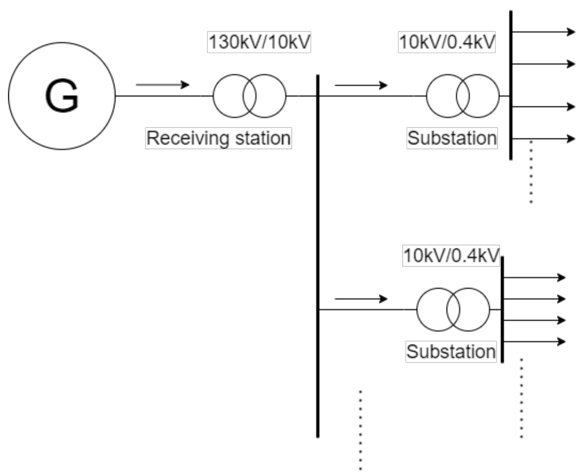

Figure 2.3: General unidirectional power flow.

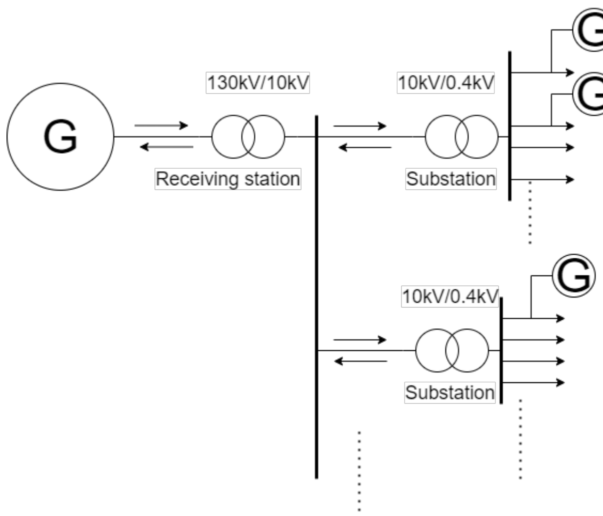

Figure 2.4: General bidirectional power flow.

All transmission of electric power generates losses in the equipment through which it is transferred[2]. In the case of no production units in the low-voltage grid, all consumed power has to be transmitted from the overlaying regional grid through the entire system, which would generate losses in the entire system. If some of the consumed power is produced locally, there will be less power that has to be transmitted from the regional and transmission grids. When less power has to go through the cables and transformers etc. there will be less losses in the grid. If there is excess energy in the area and much power has to be transferred to the local or regional high-voltage grid, the losses might instead increase again.

2.4 Losses

There are losses in all stages of the transfer of the electrical energy. The losses that are dealt with here are only those in the local grid. From the regional grid to the customer, the energy has to go through following equipment:

- 130kV/10kV transformer
- 10 kV cable
- 10kV/0.4kV transformer
- 0.4kV cable

2.4.1 Loses in the Transformers

A transformer has idle losses and load-dependent losses. A simplified model of a transformer can be seen in Figure 2.5. The active power losses comes from both the idle core losses and the load dependent copper losses.

$$P_{Fe} = \frac{U_1^2}{R_{Fe}} \tag{2.1}$$

$$P_{Cu} = R_k \cdot (I_2')^2 \tag{2.2}$$

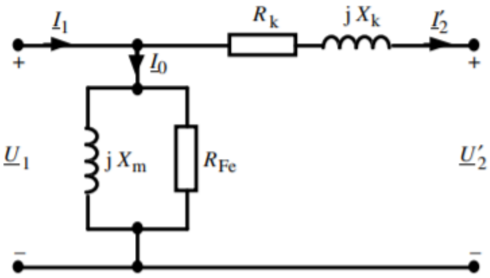

Figure 2.5: A simplified model of a transformer.

where R_{Fe} is representing the iron losses, U_1 the primary voltage, R_k the resistance in the coils and I_2' the secondary current.

The reactive power losses in the transformer are also divided into idle- and load-dependent losses.

$$Q_m = \frac{U_1^2}{X_m} \tag{2.3}$$

$$Q_\sigma = X_k \cdot (I_2')^2 \tag{2.4}$$

where X_m is representing the iron losses, U_1 the primary voltage, X_k the inductance in the coils and I_2' the secondary current.

The idle losses are constant as long as the transformer is connected to a voltage source with low voltage variations while the load-dependent losses are varying with the load current. [2]

2.4.2 Losses in the Cables

The cables have resistive, inductive, and capacitive elements. Figure 2.6 shows a pi-model of a cable. The inductive elements are more dominant in an overhead line than in a cable, due to that the long distance between the conductors allows a stronger magnetic field. The long distance between the conductors also gives a lower E-field and therefore a lower capacitance. The distance between the conductors is small in a cable, which gives lower magnetic fields and inductances while the E-fields and capacitances are higher. [2] Each type of cable has its own impedance that depends on the materials and constructions and can be found in data sheets. The impedances in the cables are used to calculate the active and reactive losses in the cables.

The three-phase active and reactive power in a system are

$$P = \sqrt{3} U I \cos(\varphi) \tag{2.5}$$

$$Q = \sqrt{3} U I \sin(\varphi), \tag{2.6}$$

where P and Q is the 3-phase active and reactive power and U is the line-to-line voltage.

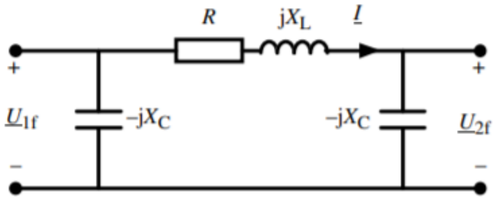

Figure 2.6: A PI-model of a cable.

The active and reactive power are related as

$$\overline{S} = P + jQ = \overline{U}\overline{I}^{*} \Rightarrow \overline{I} = \frac{P - jQ}{\overline{U}} \tag{2.7}$$

Since the reactive power consumption isn't known at all customers it is assumed that the power factor, $\cos(\varphi)$, is equal to 0.9 where the measurements are lacking. Equation (2.5) and (2.6) gives the relationship between the active and reactive power as

$$Q = P\frac{\sin(\varphi)}{\cos(\varphi)} \tag{2.8}$$

The currents is then used to calculate the losses in the grid. The active power losses depend on the resistance and the current through the cable as shown in Equation (2.9), while the reactive losses depend on the inductance in the cable and the current through it as shown in Equation (2.10). The capacitive reactive power from the cable is calculated in (2.11).

$$P_R = R \cdot |I|^2 \tag{2.9}$$

$$Q_L = X_L \cdot |I|^2 \tag{2.10}$$

$$Q_C = \frac{|U|^2}{X_C} \tag{2.11}$$

2.5 Cost for Losses

The cost for the losses in the grid depends on the magnitude of the losses and the price for the lost electricity. Table 2.1 shows the average price for the electric losses in the grid for 2020 and the estimated average price for 2021, according to GENAB.

Table 2.1: Price for losses in the grid.

	2020 (excl. moms)	2021 (excl. moms)
Price for loss energy	41 öre/kWh	37 öre/kWh

2.6 Cost for Energy and Power

The local grid has fees towards the regional grid. The fees are divided into a fixed fee for the connection, a fee for the transferred energy and a fee for the highest transferred power during the year. The prices depend on the location, at which voltage the connection is made and the owner of the regional grid. The local grid in Gothenburg is connected to Vattenfall's and Ellevio's regional grid. Table 2.2 shows the prices for transferred energy and the connection to Vattenfall's regional grid for 2020 [9] and 2021 [10]. Table 2.2 also shows the annual power fee for customers with multiple connection points to Vattenfall's regional grid and a local high-voltage grid that is connected in a loop to enable aggregation of the power [11], as in the case of the local grid in Gothenburg. The high load time for the energy fee in Table 2.2 is defined as weekdays 6-22 between November-March with the exception for holidays on weekdays [11].

Table 2.2: Vattenfall regional network tariffs for connections to the 130kV regional grid in southern Sweden.

	2020 (excl. moms)	2021 (excl. moms)
Fixed fee	400 000 kr	400 000 kr
Annual power fee	30 kr/kW	30 kr/kW
Energy fee, high load time	8.3 öre/kWh	8.4 öre/kWh
Energy fee, low load time	1.1 öre/kWh	0.9 öre/kWh

2.7 Solar Energy

There is atomic fusion, where hydrogen atoms are merged to one helium atom, occurring in the sun at all times. The energy that is released during this process is emitted as radiation in space. The radiation can be converted into other types of energies. The power density(irradiance) of the radiance that reaches the atmosphere of the earth is called the solar constant and has the value of $1367 W/m^2$. The amount of irradiance that is reaching the surface on the earth depends on the angle to the sun, which gives the distance that the radiation has to travel inside the atmosphere. One way to use the solar radiation as a renewable energy source is to use photovoltaic (PV) cells to convert the energy to electric energy. The solar energy that can be converted to electric energy is varying, depending on how much irradiation that reaches the surface of the earth. During cloudy and/or dark winter days, less solar energy reaches the surface of the earth, and less energy can be converted into electric energy. This results in that even with a large amount of installed solar panels, there is still a high need for reserve power stations that can step in when the solar power generation is low.[3]

2.7.1 Solar Panels

Solar panels consist of several connected PV cells. PV cells are made of monocrystalline or polycrystalline silicon or thin film. The semiconductors in the cells are doped to get p-n junctions, which generates an electrical field. Charge carriers are released from the bindings and starts to move due to the electrical field. The result of this is a DC voltage over the cell. By connecting many solar cells in series, a solar panel with higher DC voltage is obtained. [3]

Multiple solar panels can be connected in series and mounted on, for instance, a roof. The panels are connected to the intern electric grid in the house as well as the local feeding grid through an inverter that changes the DC power to AC power.

2.8 Effects of Distributed Energy Resources

Some of the main problems with the integration of solar power production units in the local grid concerns voltage deviations, system losses, bi-directional power flow and current limits. The hosting capacity in the grid describes how much solar power that can be installed without violating the operating limits for current and voltage. The hosting capacity depends on the connected equipment, the location in the grid and the consumption and production patterns. [12]

2.8.1 Voltage

One problem related to the voltage in a grid with a high level of solar power penetration is a possible overvoltage at instances with high production and low demand [13]. The overvoltage issue is related to an increased amount of solar power production units and can limit the hosting capacity in the distribution grid. [14]

The overvoltage occurs because the peak generation often does not coincide with the peak demand and that the generation varies due to the irregular sun radiation. The problems with the varying voltages can be reduced with various methods. One technique that can be used is energy storage. Energy storage can help reduce the increased voltage during the peak generation as well as the voltage drop at high load times, since the excess energy can be stored until the demand is high. [14]

One easy way of reducing the overvoltage could be to turn off the production unit when the upper voltage limit is reached at the terminal of the production unit [15]. This could lead to unfairness among the facility owners, since one customer's production facility can be turned off more often than others. It is also bad from the sustainability point of view to force the renewable power production units to be turned off.

Other ways of limiting the overvoltage are to use active or reactive power control, reinforcing the grid or to use tap changers[16]. The idea of the method of reinforcing the grid is to reduce the series resistance in the cable. This is, however, expensive and impacts both the protection devices and the short circuit currents [15]. The use of a tap changer regulates the voltage at the transformer rather than at the customer connection points, which would give uneven voltages at the customers, depending on if there are production units installed in their specific feeder or not. An active and reactive power control method in the production facility can be, for instance, to control the power factor in the power electronics connected to the solar panels. This would provide active power injection while the voltage is being regulated [15].

2.8.2 Current

The injected current has to be within the capacity limits of the cables and the transformers. A coincidence factor is usually used to dimension the grid. The coincidence factor is based on the assumption that several connected loads will not have a peak consumption simultaneously. These assumptions are not valid with the solar power production, since it can be assumed that the solar panels that are connected to the same cables will experience peak irradiance and maximum production at the same time [15].

2.9 Technical Limits

The capacity is usually determined by the thermal limits in the grid, which in turn gives a current limit [17]. The current limits for cables are differing with different types of installations, insulation and number of conductors. There are some recommendations regarding the loading capacity for cables with different technical characteristics from SEK Svensk Elstandard (Swedisch Electricity Standard) that intends to ensure a proper lifetime for cables with a continuous current. There are different tables that gives the maximum continuous lading current in different cases.[18]

3
Methods

The benefit that the facilities provides to the grid and the financial value of it will be assessed with respect to the change in fees and cost for losses that are related to the production units. The first step is to review the laws and regulations regarding compensation to facility owners, in order to reach a result that corresponds to the law. A comparison of the financial compensation that the grid owners in the close surroundings are offering is also done.

3.1 Estimation of the Change in Energy Fees

The reduction in fees towards the overlaying grid is assessed based on hourly energy measurements of the produced energy together with the fee agreements that GENAB has with the overlaying grid. Measurements of active and reactive power are gathered from a software called Generis, which GENAB uses to handle measurement data. The fee depends on the time of the injection in the grid (high- or low load time), the hourly measurements for the entire year 2020 is therefore gathered together with the timestamps for the measurements. The fee reduction is calculated each hour, based on the quantity of energy that is injected, at which time it is injected and if it is high or low load time that hour. The total sum of the fee reduction is then divided with the total amount of produced energy, to get an averaged fee reduction per produced kWh. The calculations are made in MATLAB.

3.2 Estimation of the Change in Power Fees

The power fee depends on the highest withdrawal over the year. The gathered hourly energy measurements gives an hourly averaged power. The hourly averaged produced and consumed power are used to see how much power the production units produce at the time of the highest consumption, and if it helps reduce the highest withdrawn power from the overlaying grid. The grid owner can reduce their subscribed power if the production facilities can ensure a certain production at the peak consumption.

3.3 Estimation of the Changes in Costs for Losses

The change in the losses depends on the topology in the grid, the equipment that is included and the load profile. The changes in the losses are calculated in MATLAB according to the steps described below.

Step 1: Calculate the local losses between the cable cabinets and each customer
Each customers energy measurements (Wh/h) is used to get the hourly averaged current between the cable cabinet and the customer with

$$\overline{I} = \frac{P - jQ}{\sqrt{3}\overline{U}} \tag{3.1}$$

where P is the hourly averaged active power, U is the voltage and Q is the hourly averaged reactive power ($Q = P\frac{\sin(\varphi)}{\cos(\varphi)}$ and $\cos(\varphi) = 0.9$ is used everywhere where the reactive power measurements are lacking)

The current is calculated for all cables between the customers and the cable distribution cabinets. The current in each cable is used together with the cable data to get the local active and reactive power losses. The distances between the cable cabinet and the customers that are connected to it are averaged for simplicity, since the local variations are insignificant compared to the distances to the substation and the receiving station. The sum of the losses in all lines connected to the cable distribution cabinet and the customers consumption and production gives the total local output in the cabinet. Figure 3.1 shows a sketch of a cable distribution cabinet with 3 customers. I in the Figure indicates the resulting current from the customers consumption (or production). P_loss shows the losses in the line between the customer and the cable distribution cabinet. P_line shows the sum of the consumption and the losses related to all customers that are connected to that cabinet. I_line shows the current that goes to (or from) the cabinet, as a result of the consumption (or production).

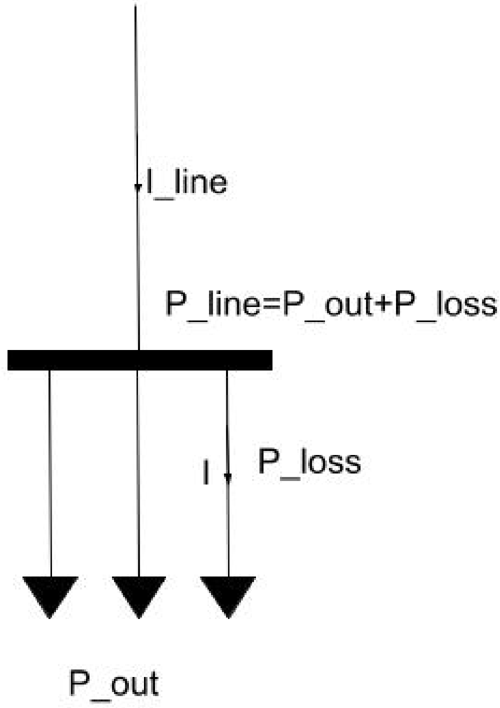

Figure 3.1: A sketch over a cable distribution cabinet and its connected customers. I indicates the current that corresponds to the production or consumption. P_loss shows the losses in the line between the customer and the cable distribution cabinet. P_line shows the sum of the consumption and the losses related to all customers that are connected to that cabinet.

Step 2: Calculate the losses between the cabinet and the next overlaying node

The transformer in the substation has multiple outgoing lines. Each of the lines have multiple cable distribution cabinets connected, some in series and some are radial fed. The part of the series connected lines that is closest to the transformer is loaded with all the consumption at the cabinets, all the local losses between the cabinets and the customers as well as all the losses in the line between the transformer and the cabinets. Figure 3.2 shows 2 series connected cabinets. It is shown that the upper line is loaded with the current to both cabinets, but the lower line is only loaded with the current to the lower cabinet. To determine the total load at each part of the line it is necessary to start with the part of the line that is furthest away from the transformer, since the losses are accumulated along the line.

The current in the line to the cabinet at the end of the series connected lines (the lower cabinet in Figure 3.2) is determined by

$$P_{line1} = P_{out} + P_{loss} \tag{3.2}$$

The power in the line is used to get the current, which is then used together with the cable data to get the losses. To get the losses in the next part of the line the same calculation is repeated for that cabinet, except that P_{line1} and $P_{line1,loss}$ are added to the equation as in

$$P_{line2} = P_{out} + P_{loss} + P_{line1} + P_{line1,loss} \tag{3.3}$$

This is repeated until the entire line is covered and the total loss in the line is obtained. This is done for all the lines that are connected to the transformer to cover the losses in the entire area.

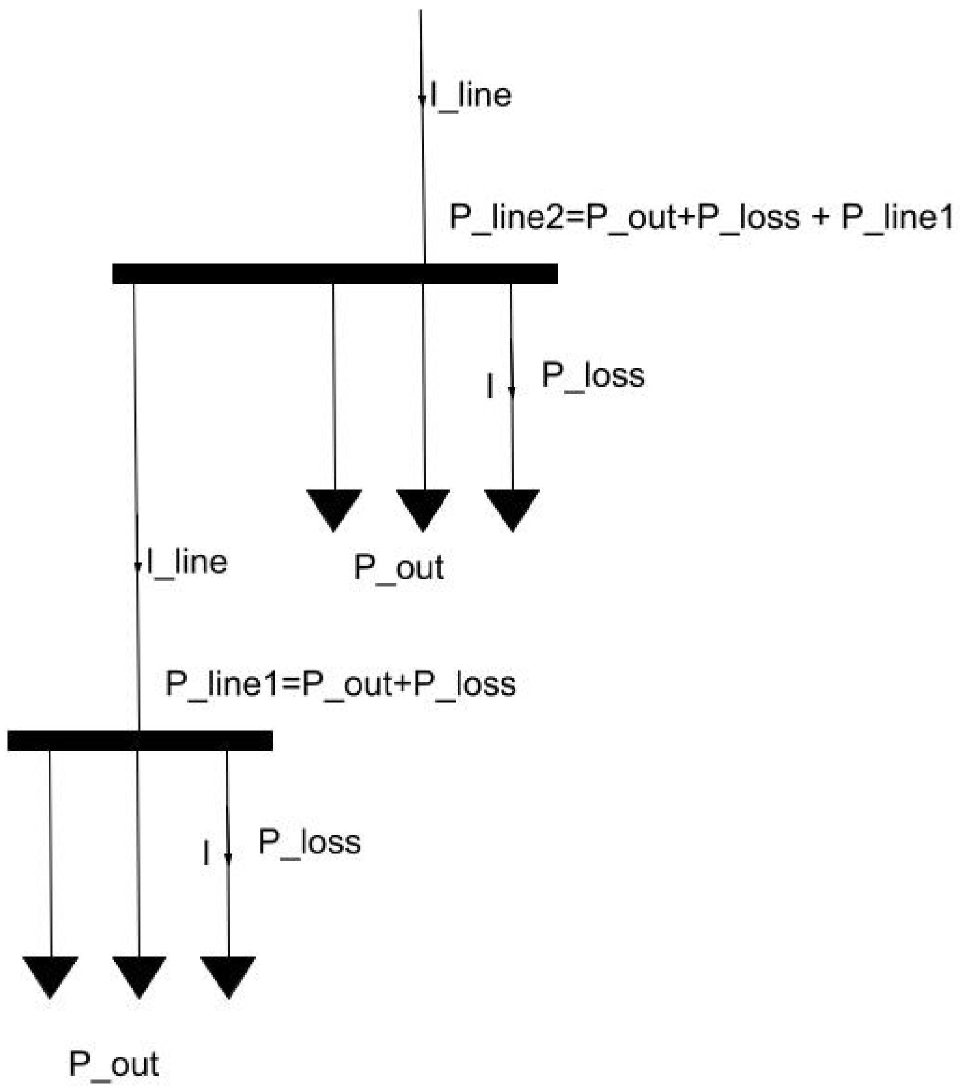

Figure 3.2: A sketch over two series connected cable distribution cabinets and their connected customers. I indicates the current that corresponds to the production or consumption. P_loss shows the losses in the line between the customer and the cable distribution cabinet. P_line shows the sum of the consumption and the losses related to all customers that are connected to that cabinet.

Step 3: Calculate the losses in the transformer in the substation
The transformer parameters are determined from the nominal power, voltage and losses that are specified on the plate on the transformer. The total current that goes

through the transformer is used to get the load losses and the voltage at the high voltage side is used to get the no-load losses.

Step 4: Calculate the losses in the line between the substation and the receiving station
The losses in the high voltage cable are determined by the cable data and the current through it, which is determined by the total load, losses in the low voltage cables and the losses in the transformer. Only the current that is related to the investigated area is used.

Step 5: Calculate the part of the losses in the transformer in the receiving station that comes from the area in question
The transformer losses are determined as in step 3, but with different transformer parameters

Step 6: Get the cost for the losses
The total losses for each hour is added and multiplied with the cost for the loss energy.

Step 7: Change the amount of solar power in the area
Production units are added, one by one, at the customer connection points and the calculations are remade with different amounts of installed power, in order to see how the amount of installed power affects the electrical losses and the cost that is related to it. The number of installed units is increased until the losses has increased above the initial value.

3.4 Estimation of the Impact of the Capacity

The current limits in the grid depends on the specifications of the cables and the protection system. The currents that are obtained when the losses are calculated are used to see if any limits are violated.

The micro-production module in dpPower is used to analyse the impact different levels of production has on the voltage in the area. More solar power production facilities are successively added into the grid between each calculation.

4
Results

The results consist of calculations of losses, cost for losses and cost for energy and how they vary with different amounts of solar powers installed in the investigated area. There is also a comparison with the grid benefit compensation that other grid owners offers their customers with a production facility.

4.1 Comparison With Other Grids

The compensation that the grid owners in the near surroundings offer are of interest since the conditions for sun ought to be similar. A comparison between the financial compensations that are offered could give a rough estimation of the benefit that the micro-scaled solar power production gives to the grid in the area. The total grid benefit compensation (including reduction in power fees, energy fees and cost for losses) in different grids in the surroundings are shown in Table 4.1. It is noticed that the compensation differs a lot between the different grids, with a span from 2.9 öre/kWh to 10 öre/kWh. The big difference probably depends on the different topologies in the different grids and that the agreements towards the overlaying grid might differ. It is observed that GENAB today has among the highest compensations today in this comparison.

Table 4.1: Comparison of different compensation from different grids in the surroundings.

Grid owner	öre/kWh(incl moms)
Vattenfall distribution[19]	10
Mölndal energi nät ab [20]	4
Borås elnät [21]	2.9
Ellevio, high load time[1][22]	5.4
Ellevio, low load time [22]	4.5
Härryda energi [23]	4.6
E.ON [24]	3.65
Göteborg Energi nät ab [25]	6

[1]Ellevio's high load time is defined as 6-22 between 1 November-31 March, all other time is viewed as low load. With exception for holidays, which always is low load

4.2 A Brief Description of the Investigated Area

The investigated area is located in Torslanda in Gothenburg and is fed from a substation with a 10kV/0.4kV transformer. The area consists of mostly one-family houses, a few multifamily houses and a few business buildings. As can be seen in Table 4.2, there are 103 connected consumption facilities in the area. Initially, 3 of the customers also have production facilities connected to the grid, with a total power of 7+7+16.77 = 30.77kW. The losses and fees related to the area are investigated by changing the configuration in the area by adding more production units, one by one, until the final configuration shown in Table 4.3 is reached. The connected units are divided into 17 cable distribution cabinets. The distances between each cable cabinet and the related connection points are averaged for simplicity. Figure 4.1 shows a cable distribution cabinet, its feeding cable, and the cables to the customers. It is noticed that the cable length difference is small. The distance from the substation in the area to the receiving station that is connected to the regional grid is measured to approximately 1200m.

Table 4.2: Initial configuration in the area

Distance from substation to receiving station	1206 m
Number of consumption units	103
Number of production units	3
Total installed power	30.77 kW
Total production in one year	16.8 MWh
Number of cable distribution cabinets	17

Table 4.3: Final configuration in the area

Distance from substation to receiving station	1206 m
Number of consumption units	103
Number of production units	75
Total installed power	812 kW
Total production in one year	520 MWh
Number of cable distribution cabinets	17

Figure 4.1: Overview of a cable distribution cabinet and the related cables and connection points. The house in the upper left also has a solar power production unit installed, as indicated by the small sun that is connected to the red dot. Cu 10 shows that the cable is a copper cable with a conductor area of $10mm^2$

4.3 Power Fees

The power fees are based on an annual maximum power withdrawal from the region grid. Figure 4.2 shows the total energy consumption and production when all 75 production units in Table 4.3 are used. The Figure shows that the peak consumption occurs during the winter while the peak solar production occurs in the summer. This means that the solar power production units do not contribute towards lower power fees. The power fee is therefore not a part in the grid benefit compensation and no further analyses are made on the power fees.

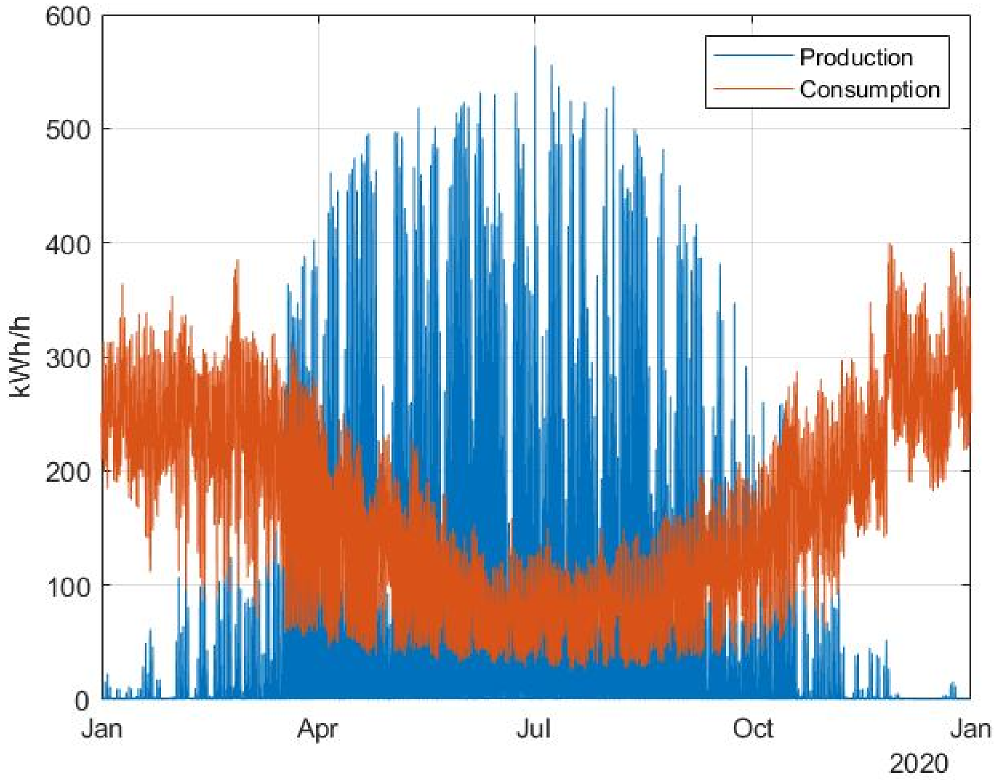

Figure 4.2: Graphs over the consumption and production during one year when 75 production units are integrated.

4.4 Energy Fees

The high and low load times are defined in Section 2.6. It is stated that there are some days that are counted as low load time, even if they occur on a weekday. Most of these exception days occur during December and January. The average solar energy production, with all 75 units in Table 4.3, is calculated with Equation (4.1) as 6.7 kWh per day, which is a very small part of the total production of 520 MWh during one year, as can be seen in Equation (4.3). The impact of viewing those days as high load time if they occur during weekdays is thus assumed to be negligible.

$$\frac{\sum_{i=1}^{n} Production(i)}{x} = 6.7kWh\ per\ day \tag{4.1}$$

$$E_{tot,year} = \sum_{i=1}^{n} Production(i) = 520MWh \tag{4.2}$$

$$\frac{E_{avg,march}}{E_{tot,year}} = 0.0013\% \tag{4.3}$$

where n is the number of hours in the month, i is the hour, x is the number of days in the month and *Production(i)* is the production in kWh at hour i.

There are also exceptions from the high load time during 3 days in the Easter week. Easter normally occurs in March or April, and the entire month of April is already defined as low load time. There will only be an impact of these exception days when Easter occurs in March. The impact is calculated with the average energy production in March and the total energy production during a year with Equation (4.4) - (4.6). The average production is 16.9kWh per day in March. The total energy production during the year is 520 MWh. This gives that each day in March only contributes to 0.078% of the total energy production. The impact of ignoring the Easter-days as low load time is therefore assumed to be negligibly small.

$$E_{avg,march=}\frac{\sum_{i=1}^{n} Production(i)}{x} = 405kWh \tag{4.4}$$

$$E_{tot,year} = \sum_{i=1}^{n} Production(i) = 520MWh \tag{4.5}$$

$$\frac{E_{avg,March}}{E_{tot,year}} = 0.078\% \tag{4.6}$$

where n is the number of hours in the month, i is the hour, x is the number of days in the month and *Production(i)* is the production in kWh at hour i.

4.4.1 Current Scenario

The reduction in energy fees in the current situation based on the production from 2020 is calculated with Equation (4.7)-(4.9). The total energy is obtained in (4.7). The reduction in energy fees for each hour is calculated in (4.8), where the energy for each hour is multiplied with the cost to the regional grid at that hour. The average reduction in energy fees per produced kWh is calculated in (4.9) by dividing the total reduction in fees with the total energy production.

$$E_{tot} = \sum_{i=1}^{n} E_{prod}(i) = 14.48MWh \tag{4.7}$$

$$C_{tot} = \sum_{i=1}^{n} E_{prod}(i) \cdot C_{energy}(i) = 172kr \tag{4.8}$$

$$C_{per\ kWh} = \frac{C_{tot}}{E_{tot}} = 1.19\text{öre/kWh} \tag{4.9}$$

where n is the number of hours for the year, $E_{prod}(i)$ is the produced energy at hour i and $C_{energy}(i)$ is the fee towards the regional grid at hour i (high- or low load hour).

4.4.2 Energy Fees at Different Amounts of Installed Power

The amount of energy that needs to be imported from the overlaying grid is reduced when more production units are introduced in the area. The fee depends on the amount of energy that is injected into the grid and if the injection takes place at high- or low load time. Figure 4.3 shows the total produced energy from all 75 production units at each hour on the right y-axis, and the energy fee towards the overlaying grid at each hour on the left y-axis. Figure 4.4 shows a zoom in on a week in March.

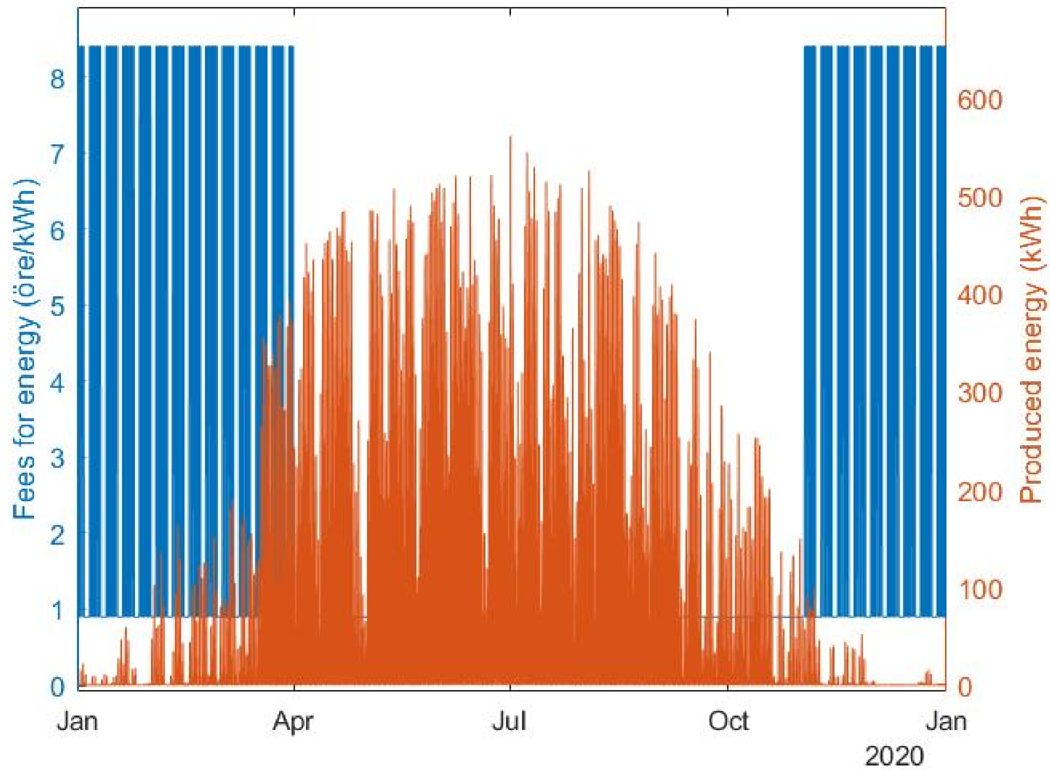

Figure 4.3: The left y-axis show the fee with respect to high and low load time while the right y-axis shows how much energy that is produced from the 75 production units each hour of 2020.

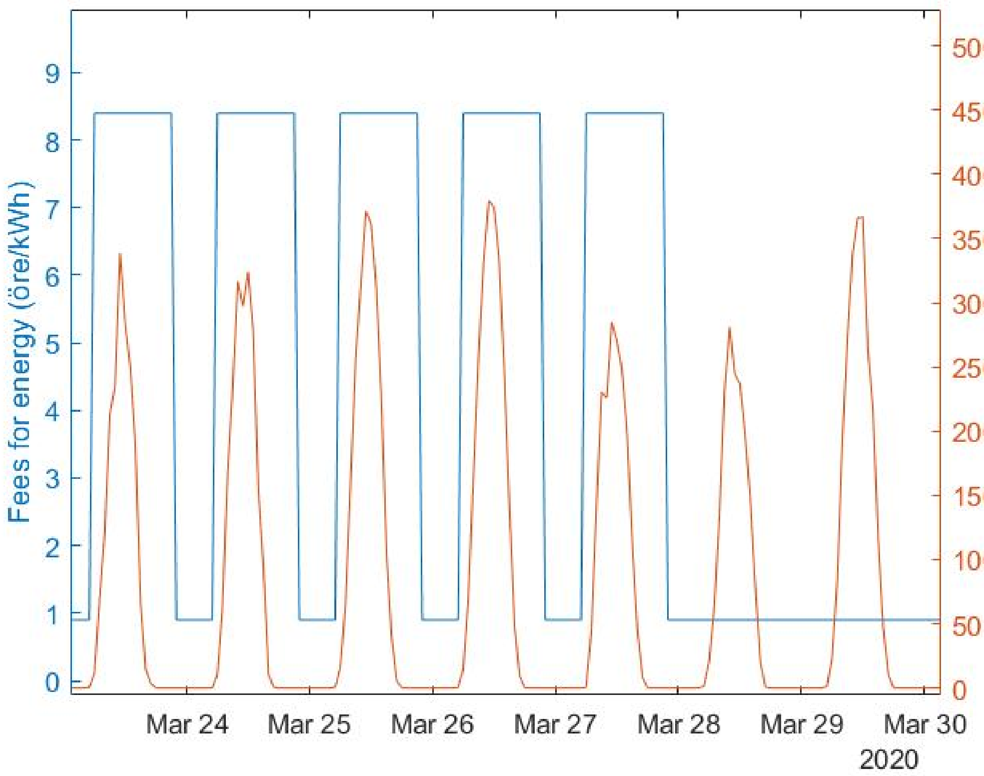

Figure 4.4: The left y-axis show the fee with respect to high and low load time while the right y-axis shows how much energy that is produced from the 75 production units each hour of 2020.

Equation (4.7) - (4.9) are performed for all cases between 0 and 75 installed units to see how different amounts of installed units impacts the fees, and the results are shown in the blue line in Figure 4.5. The Figure doesn't show a complete linear relationship between the reduction in fees and the installed units since the change in fee does not depend on the number of production units or how big they are. The only thing that matters is if every kWh is produced on high- or low load time.

If the energy that is injected from all 75 production units is used instead, an averaged value that is less dependent on one single unit (which could have been out of use for a couple of days due to, for instance, maintenance). The average reduction in energy fee per produced kWh is then calculated as 1.43 öre/kWh with Equation (4.10)-(4.12). The fee reduction that is calculated from the averaged values is presented in the orange line in Figure 4.5, which has a linear relationship with the produced energy.

$$E_{tot} = \sum_{i=1}^{n} E_{prod}(i) = 520MWh \tag{4.10}$$

$$C_{tot} = \sum_{i=1}^{n} E_{prod}(i) \cdot C_{energy}(i) = 7445kr \tag{4.11}$$

$$C_{per\ kWh} = \frac{C_{tot}}{E_{tot}} = 1.43\text{öre/kWh} \tag{4.12}$$

where n is the number of hours for the year, $E_{prod}(i)$ is the produced energy at hour i and $C_{energy}(i)$ is the fee towards the regional grid at hour i (high- or low load hour).

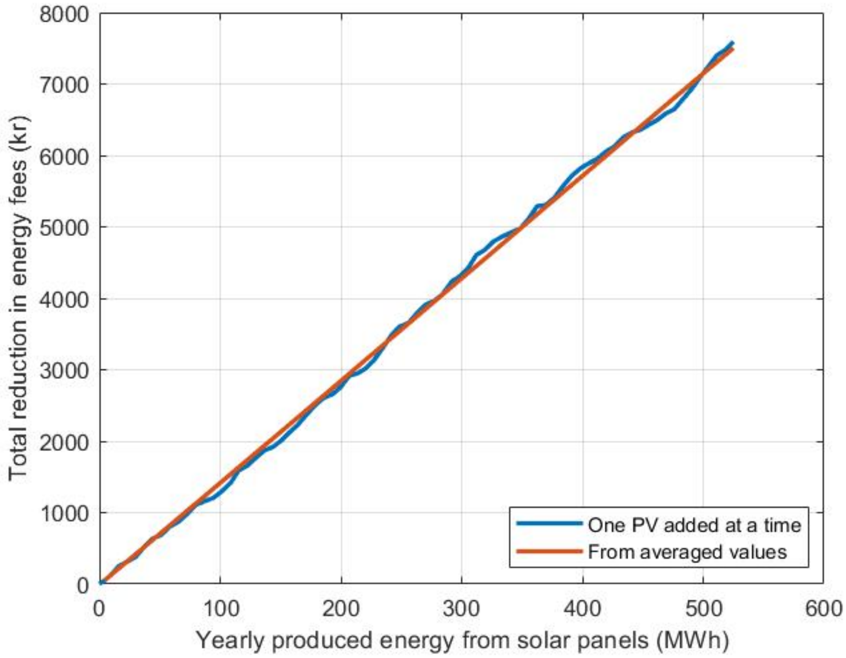

Figure 4.5: Graph over the change in fee for different amount of produced power.

4.5 Losses

The losses related to the area are calculated in the current scenario and for all scenarios with 0-75 production units. All values contains the total losses between the overlaying grid and each customer in the area. An equation that shows how the losses vary with the amount of installed power is also presented. The change in cost for the losses at different amount of installed power is also calculated.

4.5.1 Current Scenario

The losses related to the investigated area (from the customer to the overlaying grid) in the current scenario for 2020 are shown in Figure 4.6. The total lost energy during the year 2020 is calculated as 20.9 MWh. The total price for the losses is calculated by multiplying the losses each hour of the year with the assumed price for the energy. The total price for the losses in 2020 is then calculated as

$$C_{tot} = \sum_{i=1}^{n} E_{loss}(i) \cdot C_{electricity} = 8567.9kr \tag{4.13}$$

where n is the number of hours for the year, $E_{loss}(i)$ is the loss energy at hour i and $C_{electricity}$ is the price for the lost energy.

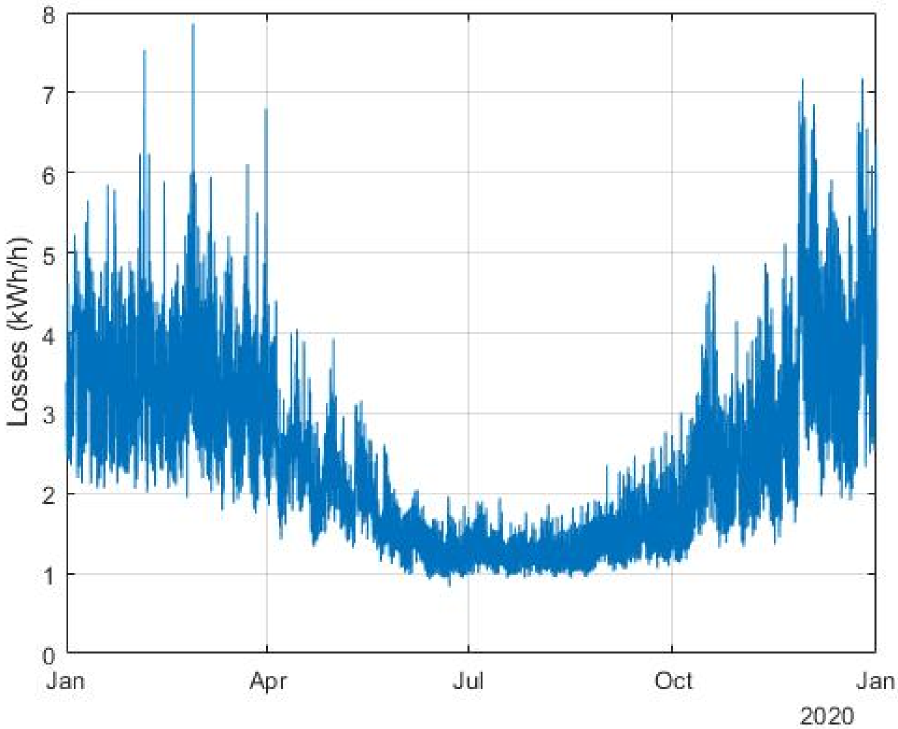

Figure 4.6: A graph that shows the calculated losses over year 2020.

4.5.2 Scenario without Solar Panels

The measurements from the meters do not show the actual consumption or production in a household with a production unit. The measurements only show the amount of energy that is imported or exported to the grid in the physical point where the meter is installed. Some of the energy that is produced will be used locally and is therefore not measured, but the grid is not burdened with the locally produced energy. The losses will therefore be lowered, even though no energy is injected to the grid from the solar power. An estimation of the consumption in the case without solar panels is made by using consumption measurements from before the production units was installed for the connection points where there now are production units. The total losses is then estimated as 21.3 MWh during one year. The total cost for losses in the case without solar power installed is calculated as

$$C_{tot} = \sum_{i=1}^{n} E_{loss}(i) \cdot C_{electricity} = 8745.7kr \tag{4.14}$$

4.5.3 Losses at Different Amounts of Installed Power

The losses vary with the amount of installed power production units. How much the losses are changing depends on the unit's rated power and where they are placed in the grid. The consumption is changed when a production unit is installed since some of the produced power is consumed locally. Measurements from both production and consumption are therefore changed in order to analyze the impact that the different amounts of installed power have on the losses related to the area. Figure 4.7 shows how the losses change when all 75 production units are placed, one by one, at a randomized customer in the grid, in a randomized order. The graph shows that the losses tend to be reduced until approximately 400 kW is installed. The losses are higher than the initial value at 700 kW installed power. The procedure of placing production units randomly in the grid is repeated to get a average value that is less dependent on where in the grid it is installed, and in which order which unit is installed. Figure 4.8 shows how the losses looks like in 100 randomized placements of the 75 production units. By taking the mean of the installed power and related losses for each number of installed units, the graph in Figure 4.9 is obtained. The averaged losses are decreasing until 310 kW installed power and are increased from the initial value at 650 kW installed power.

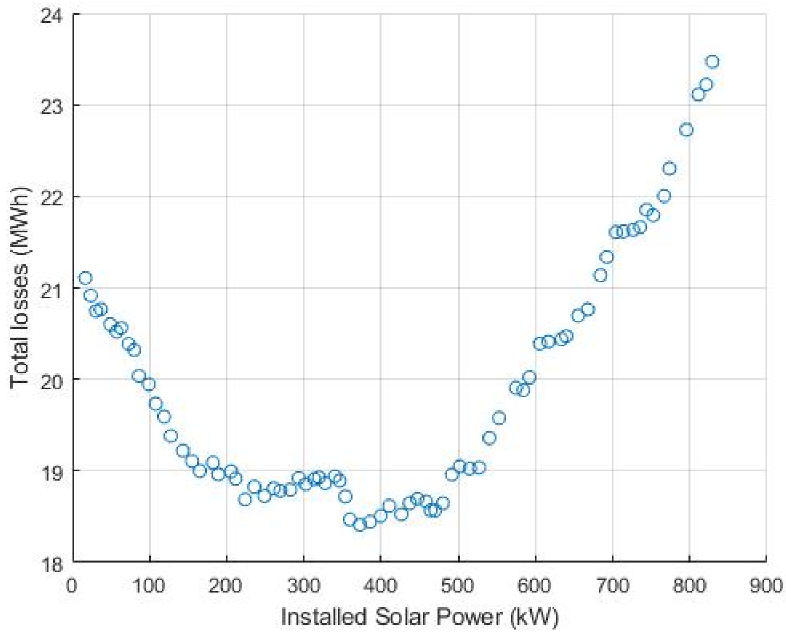

Figure 4.7: Graph over how the losses are changed with more production units in the grid.

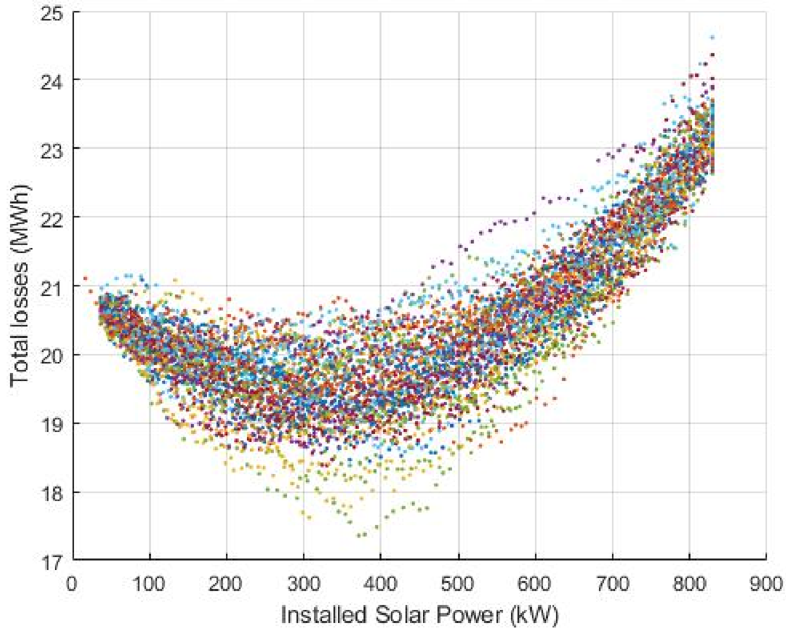

Figure 4.8: The trends for the losses are varying a lot with the different outcomes from the randomized order and placement.

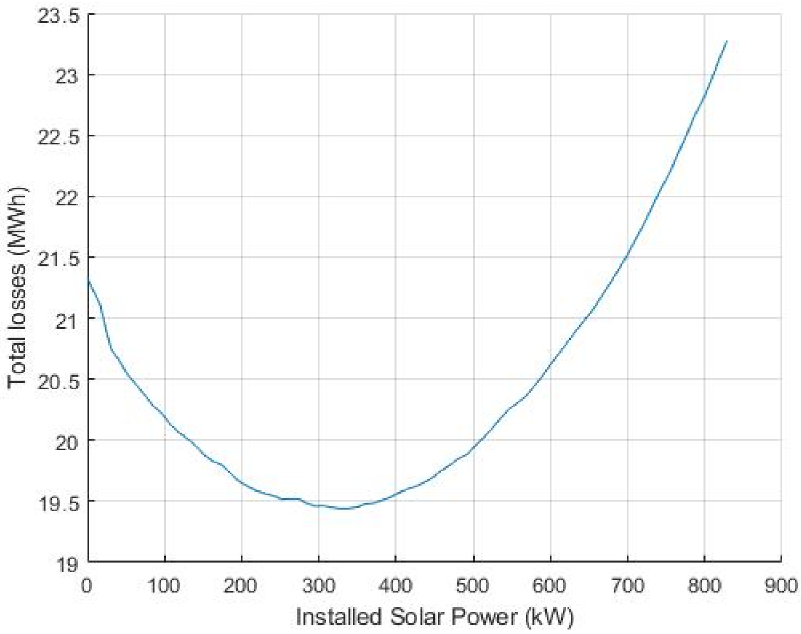

Figure 4.9: Graph over how the mean of the losses from Figure 4.8 are changed with the installed power.

4.5.4 Loss Coefficient

The relationship between the losses and the installed power in Figure 4.9 can be approximated with the curve fit tool in MATLAB. The equation that is obtained from the curve fit tool is presented in Equation (4.15). Equation (4.15) shows how the losses in the area are changed with the installed power. The derivative in Equation (4.16) shows how the losses are changed with each installed kW of production. Figure 4.10 shows the calculated and approximated curve while Figure 4.11 shows the derivative. It is seen that the losses are linearly decreasing until approximately 320 kW (31 units) solar power production is installed in the area. The losses are then increased again. At approximately 652kW (58 units) installed solar power, the losses are reaching the same losses as the initial value.

$$P_{loss} = 15.1 \cdot P_{inst}^2 - 9860 \cdot P_{inst} + 2.1 \cdot 10^7 \tag{4.15}$$

$$\frac{\Delta P_{loss}}{\Delta P_{inst}} = 30.2 \cdot P_{inst} - 9860 \tag{4.16}$$

where P_{loss} is in Wh and P_{inst} is in kW.

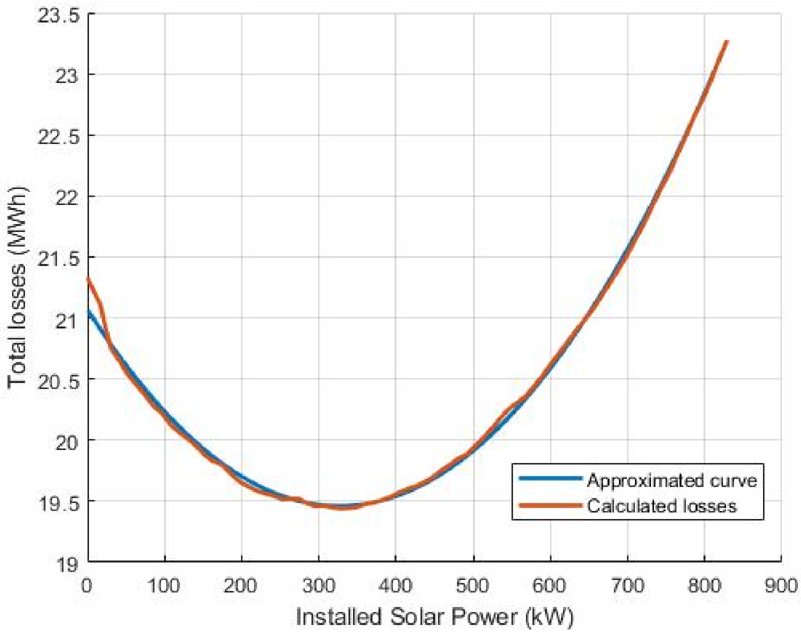

Figure 4.10: Graph over how the losses are varying with the installed power.

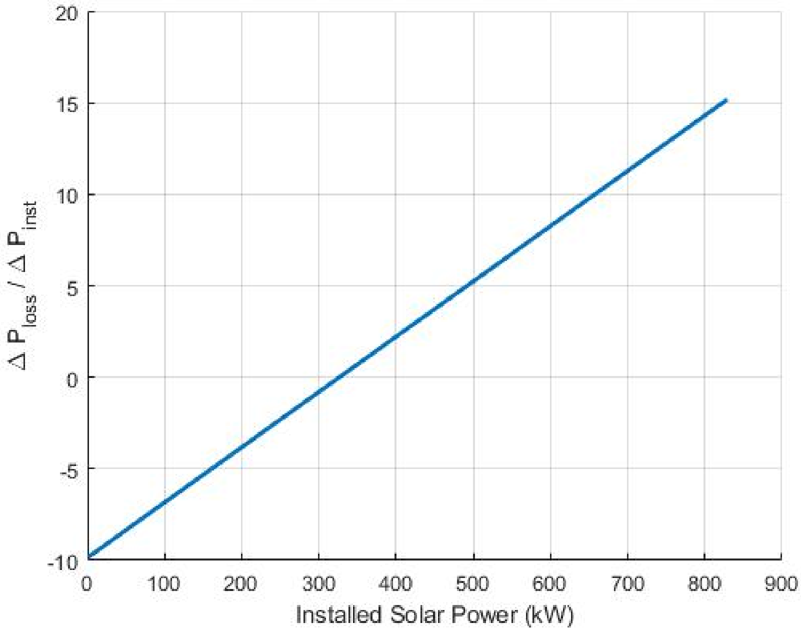

Figure 4.11: The derivative of the approximated curve in Figure 4.10.

4.5.5 Cost for Losses

The curve for the averaged losses at different amount of installed power in Figure 4.8 is used to estimate the change in cost for the losses at different amounts of installed power. A price of 0.41 öre/kWh (excl. moms) for the losses is assumed. The graph over the total cost for losses related to the area in Figure 4.12 is obtained by multiplying the cost for the losses with the total losses for each number of installed power. Figure 4.13 shows the average change in cost for losses per produced kWh at different amounts of installed power. Also, here it is noticed that the cost for the losses is decreased until 650 kW solar power is installed.

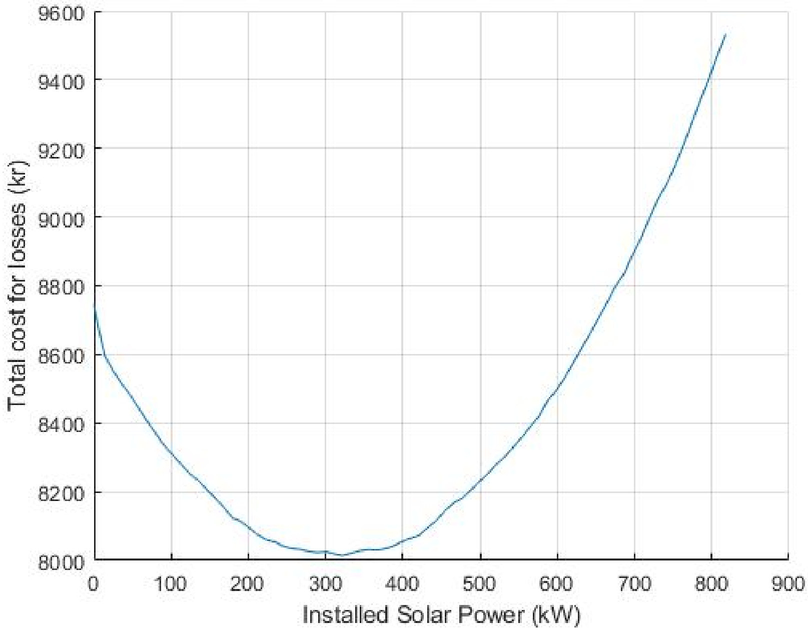

Figure 4.12: Graph over how the mean of the cost for losses are changing with installed power.

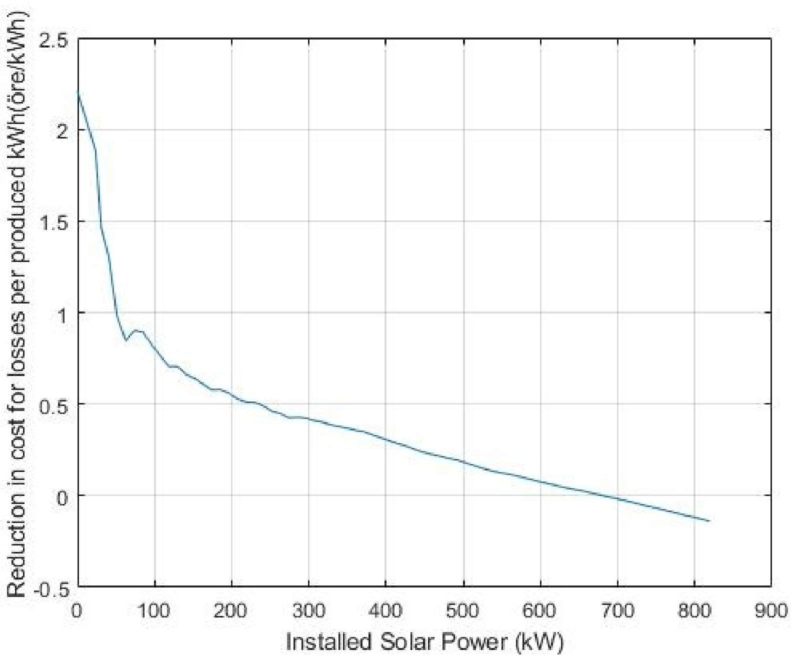

Figure 4.13: Graph over how the change in cost for the losses per produced kWh is changed with more production in the area.

4.6 Total Impact on the Cost for Different Amounts of Installed Power

The total change in cost that the different amounts of installed solar power production units consists of both the change in energy fees and the change in the cost for the losses. According to EI, each part of the grid benefit compensation (the change in fee for energy and power and the change in the cost for losses) should be greater than or equal to zero before they are added into the total grid benefit compensation, as described in Section 2.1. The graph in Figure 4.13 is therefore changed to zero at all points where the reduction in cost for the losses is less then zero (i.e. when the cost for the losses is higher than the initial value). The result is shown in Figure 4.14. When the change in fees for energy and the change in cost for losses are added the result in Figure 4.15 is obtained. The initial value is 3.6 öre/kwh (excl. moms) , which is then reduced to 1.43 öre/kWh (excl. moms) when all 75 production units are installed.

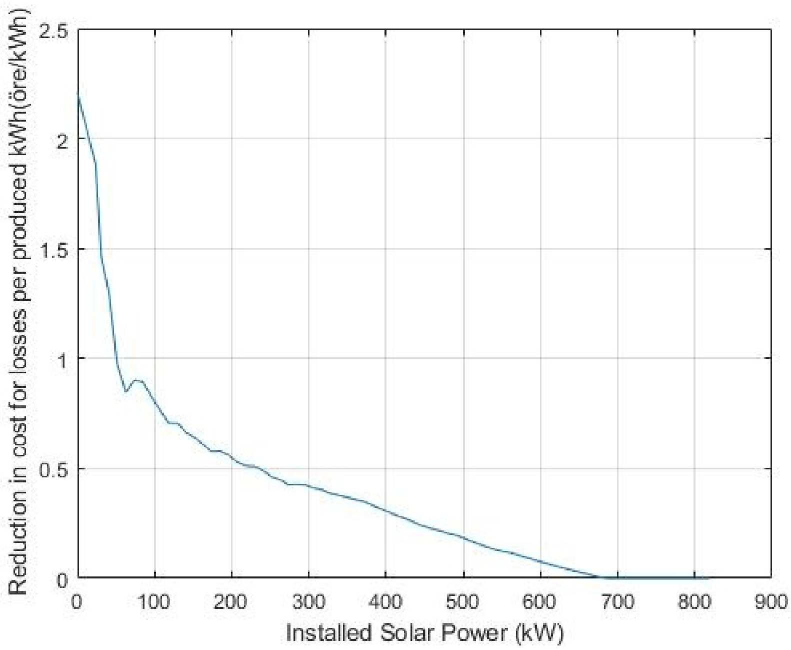

Figure 4.14: Graph over how the change in cost for the losses per produced kWh is changed with more production in the area. Any value that is less than zero is changed to zero.

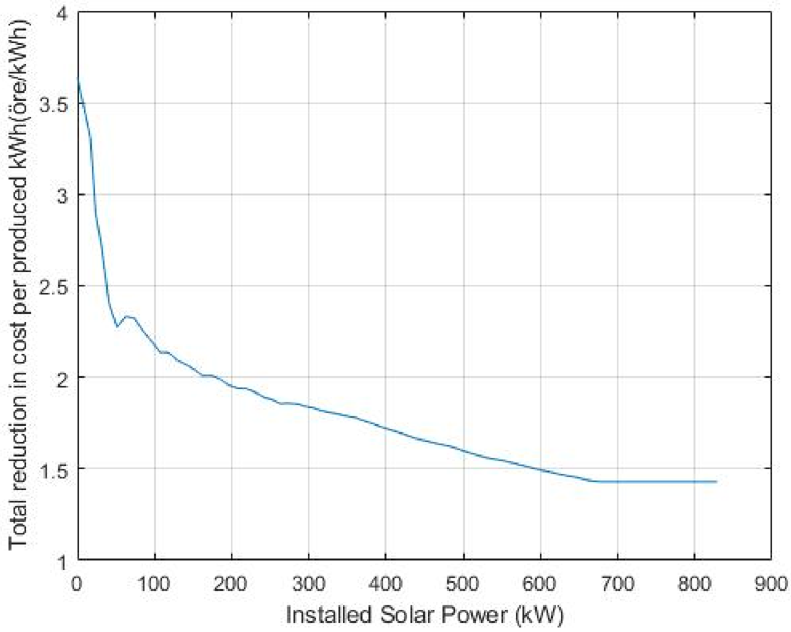

Figure 4.15: Graph over how the total change in cost for the losses and fees for the energy per produced kWh is changed with more production in the area.

When the curve fitting tool in MATLAB is used Equation (4.17) is obtained. Figure 4.16 shows how the approximation from the curve fitting tool looks like compared to the calculated graph.

$$Cost_{total\ reduction} = 1.51e^{(-0.03 \cdot P_{inst})} + 2.198e^{(-6.06 \cdot 10^{-4} \cdot P_{inst})} \tag{4.17}$$

where P_{inst} is the total installed power in kW.

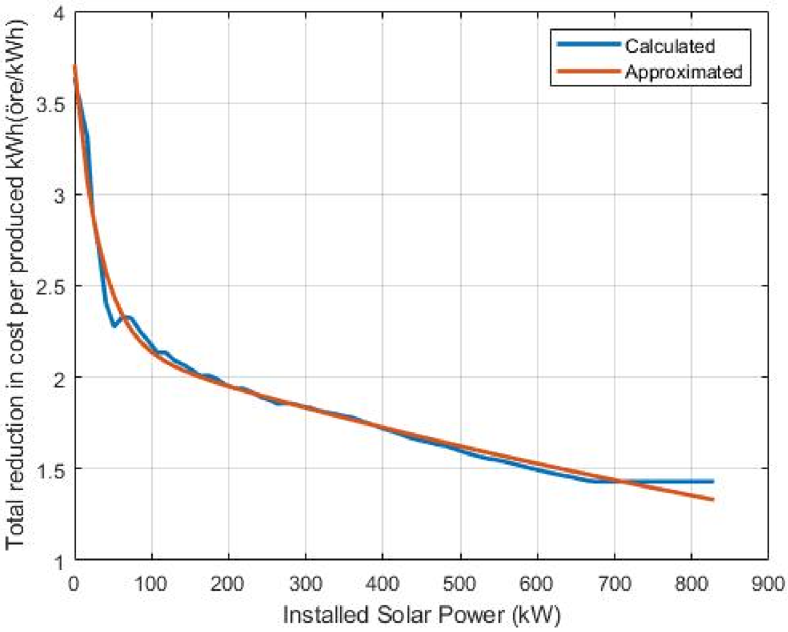

Figure 4.16: A graph over the reduction in cost per produced kwh at different amounts of installed power. The orange line shows the calculated reduction in cost and the blue line shows a approximation made with the curve fitting tool in MATLAB.

4.7 Impact on the Capacity

The capacity in the grid, in terms of voltage and current limits are investigated at different levels of power production in the grid.

4.7.1 Currents in the Area

The grid in the area is connected to the substation through feeding 7 cables (with dimensions 4x240mm^2). Each of the cables have multiple cable distribution cabinets connected in series, as shown in Figure 2.2. The cables between the cabinet and the customers are mainly 4x10mm^2. The currents that are used to calculate the losses (based on the hourly energy production and consumption) are used to analyze if the current limits in the grid are violated when all the 75 production units are connected to the grid. The maximum current in the different feeding cables is between 64.4 A and 179.3 A when all 75 production units are connected. Figure 4.17 shows the current magnitude in the feeding cable with the highest current magnitude. The maximum current, when all 75 production units are connected is 179.3 A in July. The peak production current (in the summer) is higher than the peak consumption current (in the winter) when all 75 production units are connected, which indicates that a grid with a high amount of solar power production facilities will experience more stress during the summers than during the winters.

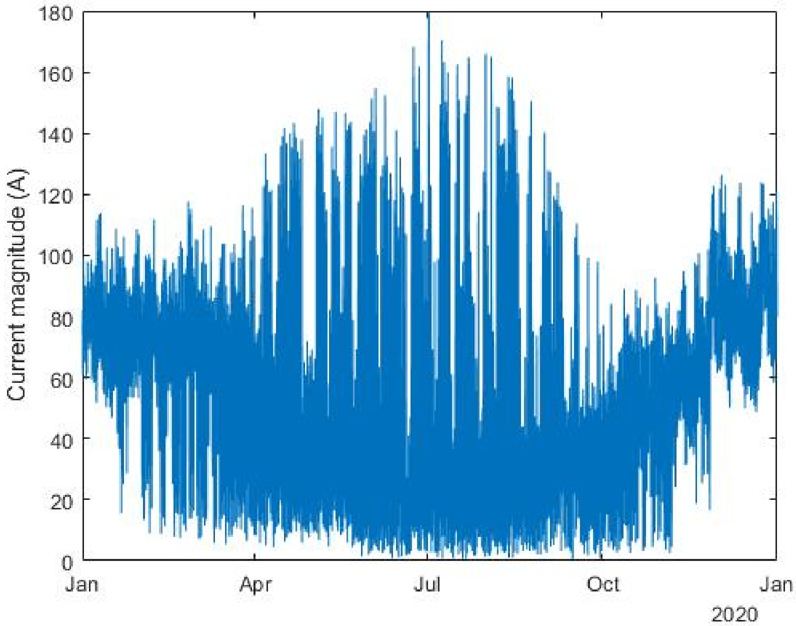

Figure 4.17: The current magnitude in the feeding cable with the highest current in the area when all 75 production units.

The cables between the customers and the cable distribution cabinets are mainly of the dimension 4x10mm^2. The highest hourly averaged current between a customer and a cable distribution cabinet is calculated as 21A.

4.7.2 The Fuses in the Area

The current limit in a cable depends on the cable specifications and the configuration of the protection. A sample of the rated currents in the fuses in the area is done to see how much current that the grid can manage with the current fuse and cable configuration. The fuses in the area are taken from the grid documentation in dpPower. Table 4.4 shows some samples of the fuses at cables with the dimensions 4x240mm^2 and 4x10mm^2. The fuses at the 4x240mm^2 cables are checked at the substation and the fuses at the 4x10mm^2 cables are checked at the connection point to the customer. It is seen in the Table that most fuses at the 4x240mm^2 cables have a rated current of 250 A, which means that the highest current of 179.3 A is well below the limit. If a lot of production units are to be connected to the cable with the fuse of 100 A, it has to be investigated if the fuse should be replaced with a fuse with higher rating. The fuses at the 4x10mm^2 cables are of various sizes. Most of them are larger than the highest production current of 21A. In the cases where the fuse is smaller, it might have to be changed if the customer wants to connect a production unit.

Table 4.4: A table over the fuses at different cable types. The fuses can be seen in the small yellow dots in Figure 2.2.

Position	Cable dimension (mm^2)	Rated current (A)
Substation	4x240	250
Substation	4x240	250
Substation	4x240	100
Substation	4x240	250
Substation	4x240	250
Substation	4x240	250
Substation	4x240	250
Customer	4x10	50
Customer	4x10	16
Customer	4x10	20
Customer	4x10	25
Customer	4x10	50
Customer	4x10	35
Customer	4x10	50
Customer	4x10	35
Customer	4x10	50
Customer	4x10	20
Customer	4x10	25
Customer	4x10	50

4.7.3 Voltages in the Area

The voltages in the low-voltage part of the investigated area at different levels of power production is analyzed with the micro-production module in dpPower. The maximum phase voltages at all nodes in the grid in the current situation is shown in Figure 4.18. The red lines in the Figures symbolizes the allowed ±10% change in voltage. It is seen that the voltage in most parts of the grid in the current situation is 229 V. At some points it is increased to maximum 234 V. Figure 4.19 shows the phase voltages in the area when 300 kW power is installed (which corresponds to the point where the losses are minimized in Figure 4.9). It is seen that the maximum voltage is slightly increased at all nodes in the area. Figure 4.20 shows the maximum phase voltage in the area when all production units are installed. The maximum voltage is increased at all nodes, but it remains below the limit of 253 V.

Figure 4.18: The voltages at all nodes in the investigated low-voltage grid, in the current configuration, are shown in the black line. The red lines symbolizes ±10% change in voltage.

Figure 4.19: The voltages at all nodes in the investigated low-voltage grid, with 300 kW installed power, are shown in the black line. The red lines symbolizes ±10% change in voltage.

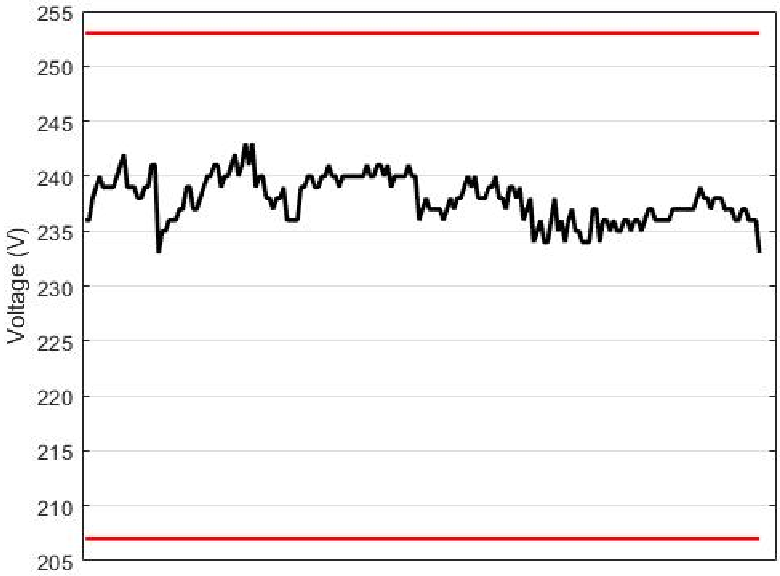

Figure 4.20: The voltages at all nodes in the investigated low-voltage grid, when all 75 production units are connected, are shown in the black line. The red lines symbolizes ±10% change in voltage.

4.8 Technical Limits

The technical limits that are investigated are the voltage and current capacity in the grid in the area. The current limits depends on the type of cable, its thermal ratings, how it is installed and what type of insulation it has. The voltage limits in the cables depends on the rated voltage in the cables. The technical limits in the transformers depends on the rated voltage and the rated power. The power capacity obtained in this chapter is the peak power production that the grid withstands with the assumed voltage and power factor.

The tables for loading capacity in cables in the Electrical Installation Rules are used to estimate the current capacity[18]. It is assumed that the cables are installed in a cable channel in the ground, with an ambient ground temperature of $20°C$.

4.8.1 Cable to the Customers

The cables between the cable distribution cabinets and the customers in the area are mainly of the type N1XV-U 4x10. These cables have a rated phase voltage of 600 V. The voltages at the nodes in the area were seen in section 4.7.3, where it was noted that the voltage never went above the limit of ±10%. ±10% gives a voltage span of 207-253V. This limit is lower than the technical voltage limit of the cable. The limiting factor regarding the voltage in the area is therefore not the technical voltage limit of the cable, but rather the power quality requirement.

The current through a cable is limited by the thermal limit of the cable. This cable has a thermal limit of $90°C$. A cable with that thermal limit, dimensions and aluminum conductors that are PEX-insulated and is installed in a cable channel in the ground has a loading capacity of 46 A. If a power factor of 0.9 and a phase voltage of 230V is assumed, this gives an active three-phase power capacity, with respect to the thermal limits, of

$$P = 3UI\cos(\varphi) = 3 \cdot 230 \cdot 46 \cdot 0.9 = 28.6kW. \tag{4.18}$$

where U is the phase voltage, I is the current and $\cos(\varphi)$ is the power factor.

4.8.2 Feeding Cables

The cables between the substation and the cable distribution cabinets are of the type N1XV-AS 4x240. These cables have a rated phase voltage of 600 V, and voltage limit of ±10% will be reached before the technical limit is reached. The technical voltage limit of the cable is therefore not the limiting factor.

The current through a cable is limited by the thermal limit of the cable. This cable has a thermal limit of $90°C$. A cable with that thermal limit, dimensions and aluminum conductors that are PEX-insulated and is installed in a cable channel in the ground has a loading capacity of 253 A. If a power factor of 0.9 and a phase voltage of 230V is assumed, this gives an active three-phase power capacity, with respect to the thermal limits, of

$$P = 3UI\cos(\varphi) = 3 \cdot 230 \cdot 253 \cdot 0.9 = 157kW. \tag{4.19}$$

where U is the phase voltage, I is the current and $\cos(\varphi)$ is the power factor.

4.8.3 10/0.4 kV Transformer

The voltages at both sides of the transformer will be within the nominal values if the voltage in the connected cables are within the ±10%.

The transformer in the substation has a rated power of 500 kVA. If the power factor is assumed to be 0.9 this gives a maximum active three-phase power capacity of

$$P = S \cdot \cos(\varphi) = 500kVA \cdot 0.9 = 450kW \tag{4.20}$$

where S is the three phase apparent power and $\cos(\varphi)$ is the power factor.

4.8.4 10 kV Cable

The medium voltage cable between the substation and the receiving station that is connected to the overlaying grid has a nominal phase voltage 14kV. The maximum phase voltage in the cable is 6.7kV if the voltage is within the ±10% limit in the low voltage area, which is well below the nominal voltage.

The current through a cable is limited by the thermal limit of the cable. This cable has a thermal limit of $90°C$. A cable with that thermal limit, dimensions and aluminum conductors that are PEX-insulated and is installed in a cable channel in the ground has a loading capacity of 253 A. If a power factor of 0.9 and a phase voltage of 10kV is assumed, this gives an active three-phase power capacity, with respect to the thermal limits, of

$$P = 3UI\cos(\varphi) = 3 \cdot 10 \cdot 10^3 \cdot 253 \cdot 0.9 = 6.8MW. \tag{4.21}$$

where U is the phase voltage, I is the current and $\cos(\varphi)$ is the power factor.

4.8.5 130/10 kV Transformer

The high voltage transformer has a rated power of 40MVA. With an assumed power factor of 0.9, this gives an active three-phase power capacity of

$$P = S \cdot \cos(\varphi) = 40MVA \cdot 0.9 = 36MW \tag{4.22}$$

where S is the three-phase apparent power and $\cos(\varphi)$ is the power factor.

5
Discussion

This section includes a discussion about the methods used and the results obtained and some sustainable and ethical aspects that are related to the thesis topic. What further research that can be done within the topic is also discussed.

5.1 The Change in Fees

The change in energy fees depends, as already mentioned, on when the energy is produced and if that hour is counted as high- or low load. The obtained result of 1.43 öre/kWh is based on when the average reduction in fees when all 75 units are connected in the area. The method is therefore sensitive for if some units were, for instance, disconnected during some time periods. The method is also based on historical production measurements. The sun conditions might not be the same during the high- and low load hours next year. This way, however, is simple, both for the customer and the grid owner. The customer knows beforehand how the grid compensation will turn out and the grid owner can easily calculate how the financial compensation should look with solely the measurement values (no time stamps are needed).

One way to get a result that is less dependent on historical events would be to differentiate between high- and low load time for the energy part of the grid benefit compensation. The grid benefit compensation would in that case be more correct, and each unit that injects energy in the grid during the high load time would get compensated for the actual contribution. One disadvantage by differentiating between high- and low load time could be that it is more unclear for the customer what financial compensation that they can count on. The grid owner would have to analyze the production measurement together with a time array to calculate the correct compensation, depending on if it is high- or low load.

The investigated power production facilities in this case covers solar power exclusively. As seen in Figure 4.3, most production occurs during low load time. With that in mind, it is not motivated to complicate the calculations of the grid benefit compensation by differentiating it between high- and low load times.

5.2 The Calculated Losses

The method used to calculate the losses is based on several assumptions that might impact the final result. The measurements of production and consumption that are used in the loss calculations are hourly energy measurements (kWh/h). The power that is obtained from the hourly energy is a hourly averaged power. The actual power is probably not constant the entire hour. Since the losses depends on the square of the current, the losses will be significantly higher if the power is much higher during some instances of the averaged hour.

The method of calculating the losses is based on hourly energy measurements. A customer with a connected production facility can be a producer and consumer during the same hour. The calculation method of summing all the production and consumption (together with all the local losses) at each cable distribution cabinet will probably lead to lower losses than in reality. Each cable distribution cabinet acts like an "hourly energy storage" with this method. If a production facility is injecting a total of 10kWh into the grid at one hour and the neighbour consumes a total of 10kWh the same hour, it is not safe to say that this will occur at the same moment. There will be no further losses in the grid above the cable distribution cabinet if the 10 kWh goes straight to the neighbour. If the energy instead is produced ten minutes after the neighbour consumes it, there will be losses in the higher grid related to both the 10 kWh that is produced and the 10 kWh that is consumed. The total losses that are calculated with this method will therefore probably be lower than if the calculations were made with a higher time resolution.

The loss calculations are only valid within this specific investigation area. An area with a different topology might get a different result. This area is relatively close to the overlaying grid. An area that is situated further away from the overlaying grid will have more losses in the high voltage cable due to the longer transportation of power. Such an area might benefit even more from locally produced energy since the transportation distance is decreased.

The calculated losses in the area are a bit lower than the known average losses (according to GENAB) in the local grid in Gothenburg. The lower losses probably depends on the assumptions that were made on a constant voltage and power factor and the method used to calculate the losses. The changes in the losses at different amounts of installed power is, however, showing an interesting trend, since they are calculated and compared with the same presumptions.

5.3 The Current and Voltages in the Area

The currents in the area are obtained in the method of getting the losses. The currents are probably a bit higher in reality, since the method doesn't take into consideration that there could be production and consumption at different times during the hour, with the same reasoning as in Section 5.1.

It was noticed that the fuses at the cables with the same types of cables are different. The size of the fuse depends on the amount of power that the customer has subscribed to. If a customer wants to connect a production unit, the subscribed power and the fuse might have to be changed. Each case needs to be investigated separately since the size of the fuse depends on each production units rated power. It is also important to make sure that the fuses are operating safely during the times where the customer only is a consumer. Also, the entire protection scheme has to be designed to be able to handle bi-directional power flow.

Even though the voltages at all nodes were within the allowed limits, it is still significantly increased from the initial values. It was shown that the voltage will be higher with production facilities integrated in the grid. The voltage at the customer point in the grid in a solar power dense area might differ a lot between a sunny day during the summer with high production and a cloudy winter day with high consumption. The voltage drop between the transformer and the customer is higher when the consumption is high while the voltage will increase at the customer when the production is high. These voltage variations could be limited with some voltage regulating strategy.

The production exceeds the consumption by over 4 times during some months in the summer when all 75 units in the calculations are used, as seen in Figure 4.2. This will not cause any problem if it is only one smaller area that have this high density of production units. The excess energy in the area can be transferred to an area close by. But if the density of production units is very high in a larger area, the excess energy won't be needed anywhere close and consequently has to be transferred longer distances to where it is needed or stored in some kind of energy storage.

5.4 Technical Limits in the Grid in the Area

The calculations in Section 4.8 are based on a worst case scenario where the production facilities are producing their peak power while there are no power demand in the area. The grid can probably withstand a higher installed power than the obtained results, due to the fact that the peak power production in a facility only occurs during optimal conditions, that almost never exist. Some of the power will probably be used locally, and the grid will then withstand higher power production since the current won't go throgh the entire system.

The maximum current capacity in the cables is calculated as if there are no other power cables nearby. It has to be reduced if other cables are installed close surroundings, since the heat in the ground might be increased in that case.

The voltage in the area is assumed to be within the allowed limit of $\pm 10\%$. It is therefore assumed that some kind of voltage regulation is applied in the area if there are a high amount of installed power, to make sure that this limit is not exceeded.

If the $\pm 10\%$ limit is violated, there are other problems than those related to the grids capability to withstand the voltage level. The customer might, for instance, have sensitive equipment that could break at a to high voltage level.

5.5 Sustainability

The sustainable aspects are of great relevance within this topic. Both environmental as well as social and economic sustainability are considered.

5.5.1 Environmental Sustainability

Micro produced solar power is an environmentally friendly source of energy. It is therefore beneficial to integrate this energy source in the power grid. By doing so, the use of more emission heavy energy sources can be reduced. It is important to keep developing the power grid to keep up with technical developments and possibilities for more climate friendly power production. Even though no voltage or current limits seem to be violated even with 75 production units, it could be useful to take a high amount of micro production facilities into consideration when planning for future investments and grid reinforcement, to make sure that every customer that wants to install micro production facilities can do that.

Another way of reducing the emissions related to energy production is to reduce the energy usage. One way of doing that is to reduce the losses in the system. It is shown that it is possible to reduce the electrical losses in an area with more locally produced energy. But it is also shown that the losses start to increase again once the installed power reaches a certain point.

It is only the local grid in Gothenburg that is within the scope of this thesis, but locally produced energy impacts the entire grid. The losses in the overlaying grid are also reduced when the energy is locally produced and consumed.

If the locally produced energy is higher than the local demand, the losses will increase since much power has to be transferred through the low voltage grid, and through the transformers and on to the regional grid. In such a case it could be beneficial to somehow store the energy locally, so that it can be used when there is a local demand.

5.5.2 Social Sustainability

Electrical energy is a cornerstone in a modern society. More locally produced electrical energy will help reduce the congestion in the power grid between the northern and southern parts of Sweden and to ensure power supply to society. It is therefore of great importance to make sure that customers are encouraged to install production units in their facilities.

A power production without emissions gives cleaner air, healthier humans, and a healthier climate that society can thrive in. It is important to have a fair economical compensation to encourage more emission-free power production.

5.5.3 Economical Sustainability

Many industries are dependent on reliable power supply. It is important for the economic well-fare that all industries are economically sustainable by ensuring them power supply. Companies that can show that their products are made with green energy can gain likability and customers based on their wish to strive for a better climate. Even though the main goal for the company might be economic growth, it has a positive side-effect on the climate as well.

A fair financial grid benefit compensation gives an economic incentive for the customer to install a micro production facility. But the big economic incentive in installing micro production units is rather to be more eclectically self-sustaining, and to buy less energy from the big companies.

5.6 Ethical Aspects

The financial grid benefit compensation is a payment from the grid company to a production facility owner. The economic value of the compensation should correspond to the reduced costs that the company experiences due to the integration of the production facility. It is an ethical aspect to make sure that the financial compensation is reasonable. Partly because the production facility owner should get the compensation that is rightfully theirs according to the law. But a to high grid benefit compensation will in the long run increase the grid owner's expenses. When the expenses are increased, someone has to pay. In this case it is all the customers without production facilities that will have to pay for a compensation towards the customers with production units. It is therefore important to make sure that the compensation is fair for all parties, so that it is ethically defensible.

6

Conclusions and Future Work

All the research questions in Section 1.3 got an answer during the investigation. The questions and their answers are provided in this section.

The first research question was if the power and energy fees where impacted by more solar power production in the area. It was found that the power fees remains the same, no matter how much solar power that was installed. The energy fee is reduced when more energy is produced locally. The energy fee is reduced by 1.43 öre per produced kWh in average.

The second research question was related to the losses in the grid and how they are changing with different amounts of solar power. The losses in an area can be expected to decrease when more production units are installed, but they will start to increase again once the installed power reaches a breaking point. From an environmental point of view, it could be good to investigate a strategy on how to limit the increase of the losses with more power production units in the grid.

The third research question treats the capacity in the grid, and if the grid in the area can tolerate large quantities of solar power production. The grid in the investigated area will manage a large amount of locally produced energy, without any violations on the voltage or current limits. The voltage will however be increased in the area, and it could be wise to investigate the possibilities of voltage regulations in areas where it is suspected that the installed amount of power production units will increase rapidly. The fuses in the area might need to be changed in order to handle the currents from the production units.

The fourth research question was how a reasonable financial for the grid benefit a production facility provides looks like. The cost for the losses is changed at the same rate as the losses itself, while the cost for the power fees remains the same and the cost for the energy fees is decreasing with more production units. The total change in cost is decreasing until the cost for the losses is reaching the initial value again, then the grid benefit compensation only consists of the reduction in energy fees, since each part of the grid benefit compensation should be greater than or equal to zero. The financial value of the benefit that a production facility in the area today is around 3.5öre/kWh + moms. The value of benefit is then decreasing when more production units are installed in the area, until it only consists of the change in energy fees.

6.1 Future Work

Some further research within the area could be done to get results that are valid in other parts of the grid as well.This study only covers one area with 103 connected customers, which is a very small part of the total customers in the local grid in Gothenburg. The losses, and the changes in losses with more production units, are very dependent on the topology of the grid. It could therefore be of interest to widen the area of investigation to get a result that is consistent in a bigger part of the grid.

A more thorough power flow analysis could be of interest, to get a result that is not based on hourly averaged energy measurements. A result based on instantaneous power, current, voltage and losses would give a better understanding of how the solar power impacts the grid, although it would demand large quantities of measurements and grid data.

An inclusion of energy storage in the grid could increase the benefit of local micro-production of energy since the peak production doesn't coincide with the peak consumption. Short term energy storage, where the customer can use the electrical energy that was produced during the day at the evening when the family are home from work, would give less variations in the power consumption during the day. Long term and large-scale energy storage could be used to reduce the long term variations between the high production time during the summer and the high consumption time during the winter. This would give even more benefits to the grid from the micro produced electrical energy.

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A
dpPower

dpPower is a network information system that is used for, for instance, handling grid documentation, grid models and planning of the grid.

A micro-production module in dpPower is used for specific calculations related to the effects of micro-production. It is made for both micro scaled wind and solar power production. The module makes calculations based on the reports MIKRO and AMP from the Swedish Energy, in order to calculate the impact the micro-production has on the power quality in the grid. The result that is obtained from the calculations for micro scaled solar power includes the maximum and minimum voltages at different operating modes, the difference between the maximum and minimum voltages and voltage imbalances. The maximum voltage is calculated based on the operating mode where there is low consumption and maximum production in the area. It is this maximum voltage when all solar panels are producing 100% of their rated power that is presented in the result in Section 4.7.3. Figure A.1 and A.2 shows the windows in dpPower where the micro-production settings are entered. [26]

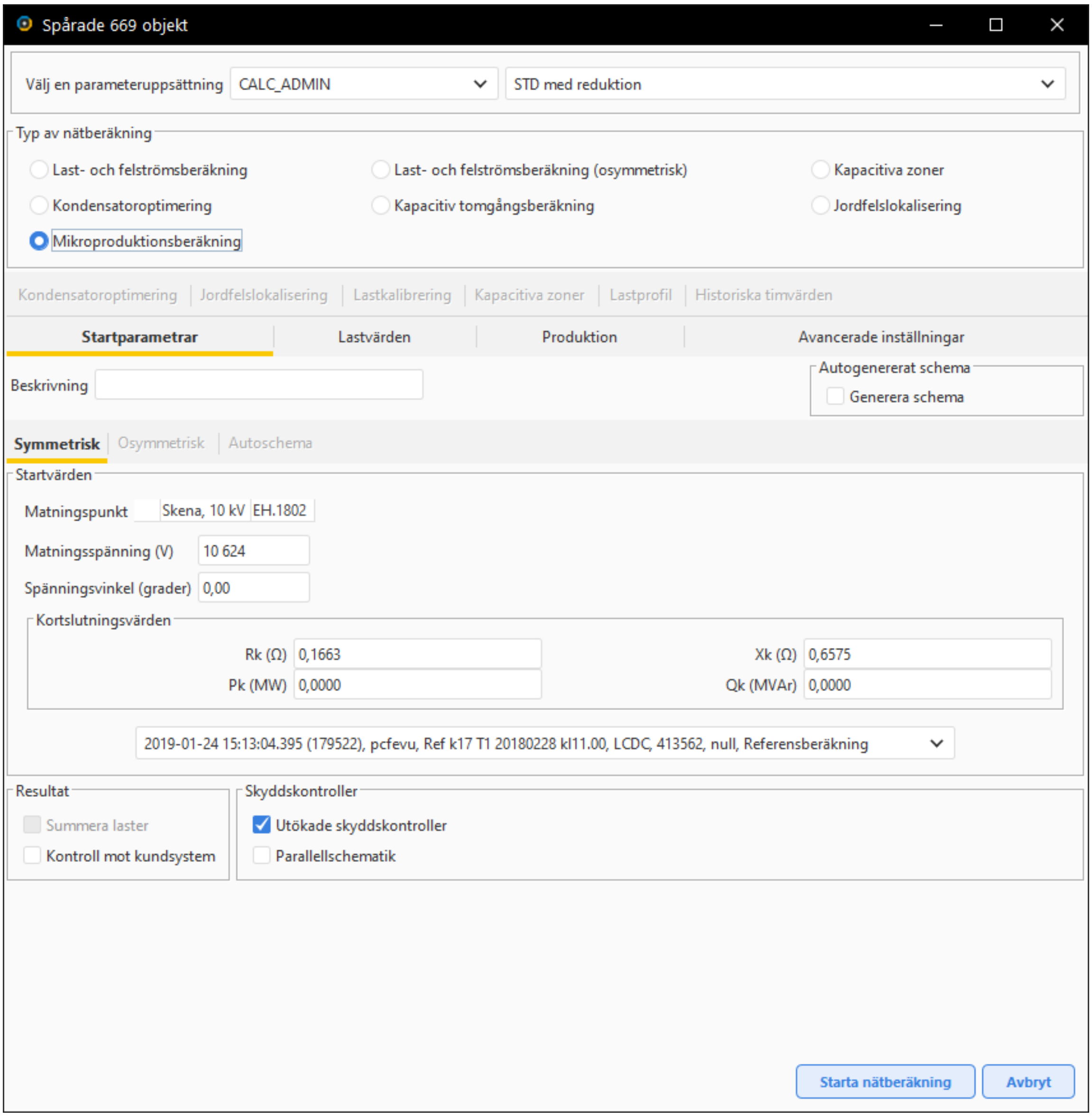

Figure A.1: The command window where the micro-production module is chosen.

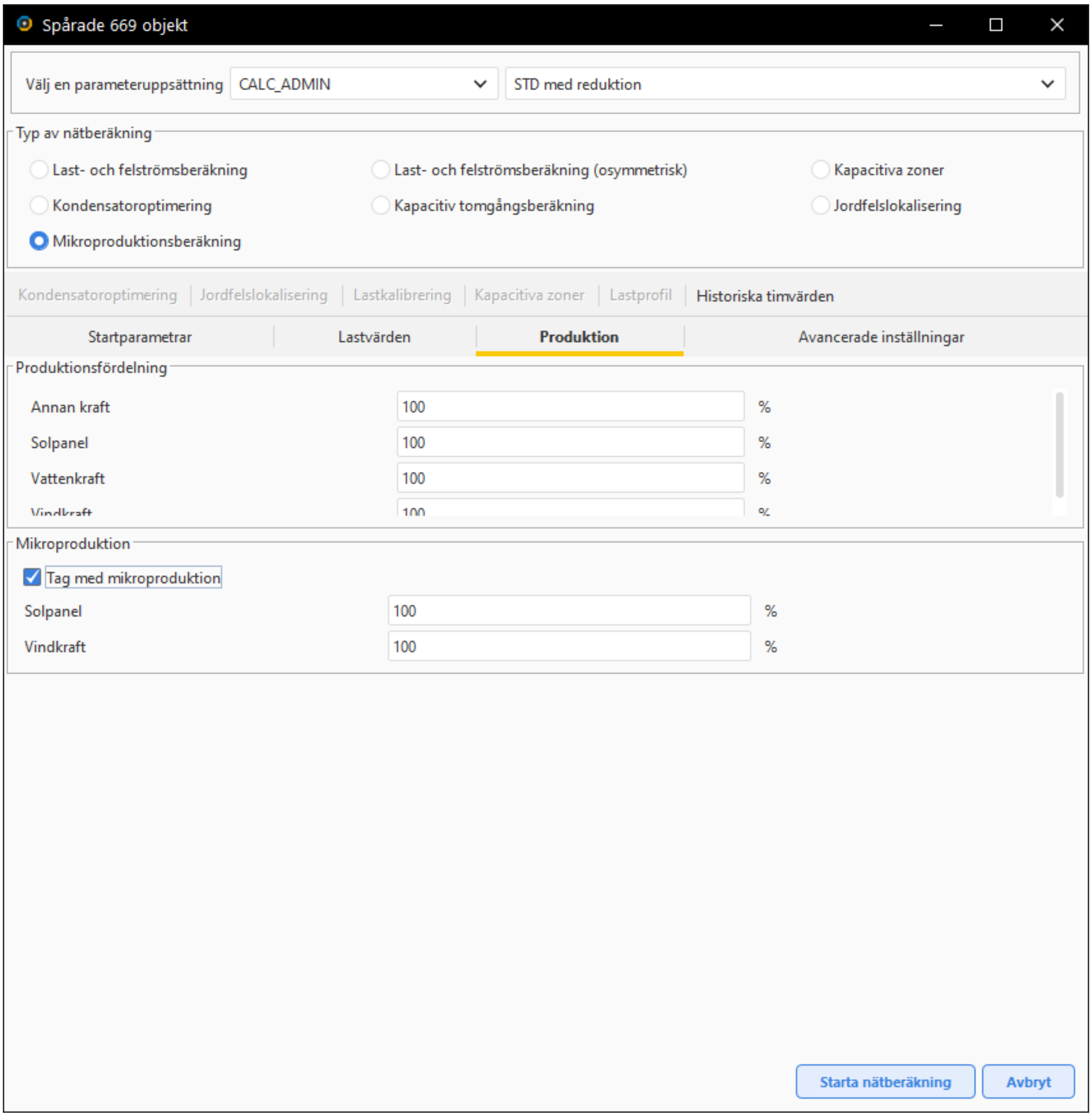

Figure A.2: The command window where 100% of the rated power is chosen for the micro-production.

B

Cable Data

The cable data for the most common cables in the area that are used in the calculations for the losses in the cables are shown in Table B.1.

Table B.1: Cable data for the most common cables in the area

Cable type	Resistance	Inductance	Capacitance
N1XV-AS 4x240	0.125 Ω/km	0.23 mH/km	0.14 μF/km
N1XV-U 4x10	1.83 Ω/km	0.026 mH/km	0.08 μF/km

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