Hosting Capacity of a Low-Voltage Grid
Development of a Simplified Model to be used in future Solar Roadmaps

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Abstract

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The purpose of this bachelor thesis is to assess whether it is possible to create a simplified model that estimates the hosting capacity of a low-voltage grid. The Simplified model is compared with a more elaborate model created by the Built Environment Energy Systems Group (BEESG) at Uppsala University. The Simplified model takes three easily obtainable variables into account.

The model created by BEESG allows us to observe both the amount of photovoltaic (PV) power that is installed as well as the voltages in each bus in a grid. The hosting capacity is found by gradually increasing the amount of PV power installed in a low-voltage grid until overvoltage is reached. Simulations with BEESG’s model are done for a week in July when the PV generation has its peak and the load is generally low. The Simplified model is created using linear regression with the calculated values from the BEESG’s model as a reference.

The report shows that the Simplified model will give an estimation of the low-voltage grid’s hosting capacity that is comparable to the value calculated with BEESG’s model. The results show that it is rarely the low-voltage grid that restricts the installation of PV facilities and that a high self-consumption is advantageous regarding to the grids hosting capacity.
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# Terms and Abbreviations

<table>
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<th>Term</th>
<th>Definition</th>
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<tr>
<td>Azimuth</td>
<td>The east-west orientation of the PV facility measured in degrees</td>
</tr>
<tr>
<td>BEESG</td>
<td>Built Environment Energy Systems Group</td>
</tr>
<tr>
<td>Curtailment</td>
<td>The action of limiting the output of power or electricity from a PV facility</td>
</tr>
<tr>
<td>Hosting capacity</td>
<td>The maximum amount of installed PV power, for which the distribution grid still operates according to the required power quality criteria</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>Short-circuit capacity</td>
<td>The ratio between the short-circuit power and the average annual load power</td>
</tr>
<tr>
<td>Simplified model</td>
<td>The model developed in this report, including three variables</td>
</tr>
<tr>
<td>Simplified model*</td>
<td>The Simplified model with only two of the variables</td>
</tr>
</tbody>
</table>
1. Introduction

The European Union has set climate goals to reduce the greenhouse gas emission and increase the amount of energy produced from renewable sources. In addition to this, Sweden has formulated national climate goals, with the purpose to further increase the production from renewable sources [1]. Some of these renewable energy sources, such as solar and wind power, are weather dependent, which means that the energy production cannot be adjusted to the demand. These types of energy sources can cause problems in the grid, due to their intermittent nature [2]. Therefore, one major problem in the development of a sustainable energy production is how much intermittent energy can be integrated into the grid, without decreasing the energy quality.

During the last years, European countries such as Germany have seen a quick growth in photovoltaics (PV) facilities. At the same time, Germany has also noticed problems such as stability issues in the grid [3]. In Germany, solar power accounts for around 7% of the country’s electricity mix, which can be compared to 0.1% in Sweden [4]. With a growing market, the prices for PV facilities have decreased and the rate seems to continue in this direction. This, in combination with subsidies from the Swedish government, has contributed to increasing installations of PV facilities in Sweden and this trend will most likely continue in the future [5]. Both private households and larger companies are seeing the potential of installing PV power to lower their electricity bills whilst also benefitting the environment [6].

The municipality of Herrljunga is working on a new strategy plan and they are interested in introducing more renewable energy sources, such as PV power, in their local energy mix. Herrljunga Elektriska AB, the local power company, suggested that the municipality would incorporate a solar roadmap in the strategy plan. A solar roadmap is a document containing guidelines for future investments in PV facilities, based on where it is favourable to install PV power. Because of time constraints in the municipality’s work, the solar roadmap will not be included in the strategy plan. However, according to Anders Mannikoff, the CEO of Herrljunga Elektriska AB, the municipality still wants to investigate the future potential of solar energy in the region [7].

1.1 Purpose

The aim of this project is to develop the foundation for a solar roadmap for the municipality of Herrljunga. The purpose of the roadmap is to give a clearer picture of in which regions in the municipality it is advantageous to install PV power, considering the grid stability and the consumption behaviour of the users in those regions. The amount of power that can be supplied to the grid in specific nodes, without exceeding certain power quality criteria, is limited by the grid and the local consumption. Our task is to develop a method to classify different regions by using grid data from Herrljunga Elektriska AB, from which we create a model to predict the hosting capacity. The model
can be used to predict the hosting capacity in regions both within and outside the municipality of Herrljunga. The solar roadmap is to be seen as a base from which the municipality can make further plans regarding the expansion of PV power.

1.2 Research Questions

To fulfill the purpose, we will investigate how a region can be classified and how much PV power the different regions can manage. The classification will take the following into account:

- How strong is the grid in the region?
- What is the customer density in the region?
- What is the electricity consumption behavior of the customers in the region?

From these three variables, a simplified model to predict the hosting capacity of PV power in a low-voltage grid is created.

1.3 Scope and Delimitations

The power quality criteria include the phenomenons voltage changes, over and undervoltage, transients, flicker and harmonic distortions [8]. Since voltage is the most important factor when measuring the power quality, this will be the focus for this report. Previous studies [9] have shown that overvoltage is the part that, in most cases, will set the constraints for the amount of installed PV power. Overvoltage can cause damage in apparatus, which makes it a crucial criterion of the power quality [10].

Previous work [11] has shown that harmonic distortions rarely limits the amount of PV power connected to the grid, hence this will not be considered in this report. Undervoltage will not be affected by the number of installed PV facilities, if changes are not made on the winding ratio to adjust the voltage level to allow more PV power, thus undervoltage will not be studied. The voltage changes can be both short and long term, but since our data is per hour, only long term changes will be studied. Since transients are caused by short voltage changes, they have not been investigated. Flicker is mainly caused by power consuming loads, switched on and off repetitively, and therefore not affected by PV power [10].

Almost every larger PV facility uses three phase inverters today, therefore it is assumed that all PV systems connected to the grid use this type of inverter [12]. The assumption will make the calculations less complex, since the facility will burden each phase in the same way. The report will not show the consequences in the transmission grid when installing PV power in the distribution grid. Further, we have not considered that the transformers are designed to mainly receive power from the transmission grid and may therefore not perform as well in the case of reversed power flow.
A sensitivity analysis is done on the created model, where the variable that has the least impact on the result is excluded to see whether it is needed in the model. This version of the model is denoted as the *Simplified model*.

1.4 Disposition

The report has the following structure. The background is presented in section 2. In section 3, the methodology and the data used is presented. The results are presented in section 4, which also contains the sensitivity analysis. In section 5, the results and the sensitivity analysis are discussed. The conclusions are presented in section 6.

2. Background

*In this section, the background of the report is presented. The background includes a presentation of different grids and their function, as well as the theory behind hosting capacity and power quality. Various types of micro production, with a focus on PV systems, will also be presented. In the last section of the background, the grid in Herrljunga will be described.*

2.1 The Swedish Grid

With most of the production located in the northern part of Sweden and most of the consumption in the southern part, the grid is built to transport a vast amount of electricity from north to south. The transportation is usually done through four voltage steps, leading to grids of different types. When the electricity is transported a long distance, the voltage is high to limit the distribution losses [13].

2.1.1 Transmission Grid

The transmission grid includes the main and the regional grid. The main grid in Sweden has a voltage at 220 kV or 400 kV and is owned by Svenska Kraftnät, a government body. This grid has a couple of parallel transmission lines from north to south, with the purpose to move a large amount of electricity with small losses. The grid has a total length of 15 000 km [14].

The regional grid has a voltage from 30 kV to 130 kV [15] and is mainly owned by three power companies in Sweden; Vattenfall, E.O.N and Fortum. Larger industries and energy plants can be directly connected to the regional grid [16].

2.1.2 Distribution Grid

The distribution grid includes the medium and the low-voltage grid. The medium-voltage grid has a voltage between 10-20 kV and is usually owned by smaller actors.
Consumers who use a lot of power, such as factories, may have higher input voltage to meet their demands. These customers are connected to the medium-voltage grid. The low-voltage grid has a voltage of 400 V and is mainly used by smaller consumers, such as regular households. The main way to deliver electricity to the consumers is via underground cables. For the low-voltage grid, these cables are usually a couple of hundred meters long, but in rural areas they can be up to a kilometer. In Sweden, the low-voltage grid is 306 000 kilometers; 75% of this is underground cables and the other 25% is overhead conductors. For the medium-voltage grid, underground cables are also dominating [17]. A schematic illustration of the distribution grid is shown in Figure 1.

![Diagram](image)

*Figure 1. Illustration of how the medium voltage-grid is connected to the surrounding substations, cable distribution cabinets and the consumers. Note that it is in the substation that the voltage changes from medium voltage to low voltage.*

### 2.2 Hosting Capacity

In this report, *hosting capacity* is defined as the maximum amount of installed PV peak power, for which the distribution grid still operates according to the required power quality criteria.

Hence, the hosting capacity is an upper limit for the maximal PV power penetration. If this limit is exceeded, the power quality will be affected and the grid must be strengthened to ensure the power quality. The critical moment for when overproduction may occur is when the load is at its minimum and the PV power production is at its maximum. This will most likely occur during the summer [18].

#### 2.2.1 The Strength of the Grid

A grid can be considered either strong or weak. A grid counts as strong when the voltage level is stable throughout the low-voltage grid even during events with higher
load. The strength of the grid can be determined via the short-circuit power [19]. The short-circuit power is calculated using

\[ S_{SC} = \frac{S_M}{u_{SC}}, \]  

(1)

where \( S_{SC} \) is the short-circuit power, \( S_M \) is the rated power of the transformer and \( u_{SC} \) is the short-circuit impedance voltage of the transformer in percent [20]. The short-circuit power is a theoretical value of the power when a fault occurs in a circuit. This is related to the grid’s capability to cope with changes in consumption; the higher short-circuit power, the stronger grid [21].

### 2.2.2 Customer Density

The customer density, i.e. number of customers per kilometer cable, is related to the size of the substation, which is the connection between the medium-voltage grid and the low-voltage grid. In regions where the density is low, smaller substations are the dominating type while larger ones are used in more highly dense regions [22]. Research shows [23] that voltage fluctuations can spread out better in regions with a higher customer density. Therefore, the effect of load changes on the local grid will be lessened in regions with a higher customer density.

### 2.2.3 Consumption Behavior

The customer’s load and consumption behaviour also affects the hosting capacity. Since the PV generated electricity must be used immediately, a PV electricity production that matches the local load will decrease the reverse power flow and lead to a high self-consumption [24]. Favorable consumption behaviour, according to the grid, is thus high consumption during the day, when the PV system generates the most of its electricity. An example of a grid that has high consumption during the day can be seen in Figure 2.
Figure 2. The daily load (blue line) for a grid where the main consumer is a golf course and the PV power produced (grey line). The graph to the left shows the average day load and PV power during a summer week. The graph to the right shows the average annual day load and PV power.

Figure 3. The daily load (blue line) for a grid with mainly detached houses and the PV power produced (grey line). The graph to the left shows the average day load and PV power during a summer week. The graph to the right shows the average annual day load.

The PV generated electricity depends on the location and the azimuth of the PV system. The azimuth describes the east-west orientation of the PV facility in degrees [25]. To increase the self-consumption the azimuth could be changed. For example, this would be suitable for the grid in Figure 3, where the load peaks during the evening. Further, a
consumption behaviour that peaks during the summer matches well with the performance of the PV systems. This can be seen in Figure 2, where the load is slightly higher during the summer compared to the rest of the year. With a high self-consumption, the impacts on the grid will decrease and the hosting capacity will increase.

2.3 Power Quality Criteria

The power quality criteria are a term for assessing the quality of the electricity supply. The ideal alternating current waveform has two significant features:

1) It contains no harmonic component besides the fundamental frequency

2) Its magnitude is constant over a long period

If there is a deviation from any of the criteria above, the power quality is affected. Small distortions in the AC waveforms are tolerated, however, when the distortions are large enough to affect equipment or appear disturbing to the users it is considered as a power quality problem. Most of the problems regarding the power quality is caused by customers and the problems can affect other customers connected to the same grid [26].

The power quality is mainly related to voltage and frequency. Voltage problems include voltage changes, over- and undervoltage, transients and voltage flicker. Frequency problems include harmonic distortions [10].

2.3.1 Overvoltage

Overvoltage refers to a temporary voltage rise, exceeding the nominal voltage amplitude by 10% or more. This is caused by loads disconnected or connection of new power sources. Even a small number of PV facilities connected to the distribution grid can result in overvoltage, causing damage to the connected apparatus. Also, PV facilities can trip, i.e. they disconnect, because of their overvoltage protection [10].

2.3.2 Undervoltage

Undervoltage refers to a reduction to 90% or less of the nominal voltage. This could be caused by the same reasons as overvoltage, but it does not cause as much damage as overvoltage [10].

2.3.3 Transients

Transients are used as a term for different kinds of rapid voltage fluctuations. Regarding power quality, a transient refers to a voltage spike, either positive or negative. According to definition, voltage spikes in the grid must have a duration of less than 10 ms to be referred to as a transient. For example, this could be caused by lightning.
Transients could also occur in conjunction with grid and load connection, and in relation to connection and disconnection of capacitor banks [10].

2.3.4 Voltage Flicker

Flicker can be described as fast and cyclic changes in voltage that are detected by human eyes [26]. In areas with a weak grid, or in regions with a lot of industry, problems with flicker can occur. If the power consuming loads are switched on and off repetitively, the load voltage drops in line with this, resulting in flicker [10].

2.3.5 Harmonic Distortions

The Swedish grid has a frequency of 50 Hz, but voltages and currents at different points contain harmonic distortions. A high level of harmonic distortions could cause breakdowns, damage on apparatus and an increased risk for fire. The amount of harmonic distortions has increased recently, due to the increased use of non-linear loads such as frequency converters and low energy lamps [10].

2.4 Micro Production and PV Facilities

The growth of micro production in Sweden has increased in recent years and new policies have been implemented to stimulate the growth. To be called a micro production the connecting fuse must be 63 A or less, with an effect limit of 43.5 kW for the facility. Before connecting a micro production to the grid, it must be approved by the grid owner to guarantee grid stability. If the grid owner cannot guarantee stability with the wanted installation, the grid owner must ensure to strengthen the grid to be able to handle the new production. The grid owner can place a fee for their expenses, strengthening and the connection of the facility to the grid [27].

2.4.1 Inverters

Generated solar power must be converted to a sinusoidal waveform with a frequency of 50 Hz before it could be fed into the grid. This is done by an inverter [28]. The inverters could be either single-phase or three-phase. A single-phase inverter will feed all power into one phase, which may result in an unbalanced system. Almost every larger PV facility, including rooftop facilities, use three-phase inverters today [12].

2.5 The Grid in Herrljunga

The electrical grid in the municipality of Herrljunga is a typical rural grid, including two smaller cities. There are two different medium-voltage grids at 10 kV and 337 different low-voltage grids. Herrljunga Elektriska AB is the owner of the grid and 5174 customers are connected to it. The average voltage in the grid is slightly higher than 400 V [18].
3. Methodology

In this section, the methodologies and data used for the report will be described. The creation of the Simplified model, as well as the validation of it, will also be described.

3.1 The BEESG’s Model

The Built Environment Energy Systems Group, BEESG, is a group of researchers from the Department of Engineering Sciences at Uppsala University. BEESG has previously worked on a MATLAB-script that simulates the grid in Herrljunga municipality. The script simulates both the low-voltage and the medium-voltage grid in the region. In the script, PV power can be added on roofs in different low-voltage grids to see how it impacts the voltage in the grid. The simulations in our work are conducted for one week in July, when the production of PV power has its peak and the load is at its minimum. Since the different grids will interact with each other it is important to run the script for all the grids [18].

The irradiation data used in the script comes from the meteorological model STRÅNG for 2014. Data of the load, i.e. the electricity consumption, is provided by Herrljunga Elektriska AB. The electricity consumption is measured hourly for about 5000 customers for one year and the power factor for the consumers is assumed to be 0.9 [18].

3.2 ArcGIS

ArcGIS will be used to visualize and determine different low-voltage grids. All substations and customers are marked out on a map of the municipality. Via this map one can see where the selected grid is placed and which kind of customers are connected to it.

3.3 Classification of a Low-Voltage Grid

One way to classify a low-voltage grid is through the strength of the grid. This can be done via the short-circuit power, see Equation 1, in the substations. A high short-circuit power corresponds with a large substation. The short-circuit power in each grid is divided with the grid’s average annual load. This yields a value of the short-circuit capacity, where a high short-circuit capacity is related to a high hosting capacity. The short-circuit capacity is calculated as

\[
S_{SCC} = \frac{S_{SC}}{Average \ annual \ load},
\]

where \(S_{SCC}\) is the short-circuit capacity and \(S_{SC}\) is the short-circuit power.

The classification can also be done by determining the density of customers. Table 1 shows the different classes according to a categorization done by Elforsk [22].
customer density is calculated as the number of customers per kilometer of cable. Studies have shown [23] that a high density of customers relates to small voltage fluctuations in the grid. This is because the total load is less volatile in a grid with high customer density, compared to a grid with low customer density.

Table 1. The different classes of customer density, where $D$ is the number of customers per kilometer cable.

<table>
<thead>
<tr>
<th>$D &lt;&lt; 10$</th>
<th>$D &lt; 10$</th>
<th>$10 &lt; D &lt; 20$</th>
<th>$D &gt; 20$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sparsely built area</td>
<td>Rural area</td>
<td>Mixed built area</td>
<td>Urban area</td>
</tr>
</tbody>
</table>

One further way to classify a grid is via the customer’s load and consumption behaviour. This classification considers a comparison of the load during daytime, 07:00-19:00, and a whole day, 24 hours, for an average summer day. It also includes a factor where the average load during a summer day is compared to the average annual load during daytime. The consumption behaviour, $B$, is calculated as

$$B = \frac{L_{S,\text{daytime}}}{L_{S,\text{day}}} + \frac{L_{S,\text{daytime}}}{L_{Y,\text{daytime}}}.$$ (3)

In this equation, $L_{S,\text{daytime}}$ is the daytime load during an average summer day, $L_{S,\text{day}}$ is the entire day load during an average summer day and $L_{Y,\text{daytime}}$ is the annual average daytime load.

The consumption behaviour is based on consumption data for about 5000 customers in Herrljunga municipality. The hourly data is provided by Herrljunga Elektriska AB. Data for operating voltages and transformer power are also provided by Herrljunga Elektriska AB, as well as the cable lengths and the number of customers connected to every substation.

3.4 The Simplified Model

To be able to predict the hosting capacity of a low-voltage grid, without using BEESG’s model, a simplified model is created using linear regression. Linear regression is a method used to predict a $y$-value from one or more $x$-values, the model’s independent variables. The Simplified model estimates the hosting capacity as

$$Y = \theta_1 * u_1 + \theta_2 * u_2 + \theta_3 * u_3.$$ (4)

where $Y$ is the predicted value of the hosting capacity, i.e. the maximum amount of installed PV peak power, expressed in percent of the grids average annual load. Our three different ways to classify a low-voltage grid are used as variables in the model. $u_i$ is the strength of the grid, defined by the short-circuit capacity which is defined as the
ratio between the short-circuit power and the average annual load in the grid. $u_2$ is the customer density, measured in customer per kilometer of cable. Finally, $u_3$ is the consumption behaviour, defined by Equation 3. $\theta_1$, $\theta_2$ and $\theta_3$ are the parameters of the model.

The weighting, i.e. the determination of $\theta$ in the model, is done via the least-square method. For the grid with detached houses, the coefficients are optimized with respect to a data set including twelve grids. The model is thereafter trained by using Bootstrap aggregation, bagging, where nine grids are used to train the model and the other three are used for testing. Out of the nine grids, one is picked out and $\theta$ is calculated for the remaining eight grids before it is validated on the grid that has been left out. This is repeated until all the grids in the in-sample dataset have been left out, which results in nine different sets of $\theta$. Out of these sets of $\theta$ the median set is found, which is used on the three testing grids. Another test of the model is done by applying the model to a data set composed of nine rural grids mainly consisting of farms and detached houses.

The grids used to train the model are grids located in mixed built areas in Herrljunga and Ljung, two smaller towns in the municipality of Herrljunga. The chosen grids are simulated in the MATLAB-script with the PV penetration in the other grids set to zero. From the BEESG’s model, the voltages for all the busses, the nodes, in the grid as well as the loads can be studied. The PV penetration in the grid is increased until one of the busses in the grid reaches overvoltage. Once overvoltage is reached, the hosting capacity can be calculated. This is done by dividing the PV peak power with the average annual load power. The hosting capacity is calculated in Excel for the different grids. The results from the Simplified model are compared to the previously calculated hosting capacities from the BEESG’s model. From this comparison, the normalized root mean square error (NRMSE) and the mean absolute percentage error (MAPE) are calculated. The NRMSE is calculated as

$$\text{NRMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{ny}},$$

where $\hat{y}$ is the estimated hosting capacities from the Simplified model and $y$ is the hosting capacities from BEESG’s model. The number of grids is described as $n$. NRMSE is a normalized value, which makes it possible to compare data sets with different scales. The MAPE is also a normalized value, calculated as

$$\text{MAPE} = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{\hat{y}_i - y_i}{y} \right|,$$

where $\hat{y}$ is the estimated hosting capacities from the Simplified model and $y$ is the calculated hosting capacities from BEESG’s model. The number of grids is described as $n$. MAPE is the average error expressed in percent. NRMSE is the normalized square root of the average of squared errors. This makes the NRMSE more sensitive to outliers. A low value of the NRMSE and MAPE indicates a more reliable model.
4. Results

In this section, the calculations and the results from our simulations will be presented and explained. The results from the sensitivity analysis will also be presented.

4.1 The Hosting Capacity

The Simplified model, see Equation 4, uses three variables to predict the hosting capacity. The values of the variables can be seen in table 2-4. Table 5 shows the parameters, \( \theta \), that are used in our model and Table 6 shows the product of the variables and the parameters.

Table 2. The calculated short-circuit capacity, the customer density and the consumption behaviour for the different grids with detached houses in mixed built areas.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Short-Circuit Capacity [VA/VAh]</th>
<th>Customer Density [# customers/km cable]</th>
<th>Consumption Behavior [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-116</td>
<td>7.14</td>
<td>13.61</td>
<td>1.33</td>
</tr>
<tr>
<td>T-121</td>
<td>3.64</td>
<td>11.85</td>
<td>0.97</td>
</tr>
<tr>
<td>T-123</td>
<td>2.37</td>
<td>13.98</td>
<td>0.99</td>
</tr>
<tr>
<td>T-127</td>
<td>4.13</td>
<td>12.71</td>
<td>1.01</td>
</tr>
<tr>
<td>T-128</td>
<td>6.73</td>
<td>9.77</td>
<td>1.34</td>
</tr>
<tr>
<td>T-134</td>
<td>3.72</td>
<td>15.00</td>
<td>1.43</td>
</tr>
<tr>
<td>T-135</td>
<td>11.73</td>
<td>15.54</td>
<td>1.11</td>
</tr>
<tr>
<td>T-136</td>
<td>7.67</td>
<td>10.30</td>
<td>0.96</td>
</tr>
<tr>
<td>T-143</td>
<td>2.45</td>
<td>11.01</td>
<td>1.30</td>
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</tr>
<tr>
<td>T-145</td>
<td>3.35</td>
<td>16.59</td>
<td>1.03</td>
</tr>
<tr>
<td>T-713</td>
<td>4.25</td>
<td>13.93</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Table 2 shows the values of the three variables used in the Simplified model for twelve grids with detached houses. The character of the grid is obtained from the map in
ArcGIS. The short-circuit capacity is determined as the ratio between the short-circuit power and the average annual load according to Equation 2. The customer density, the number of customers per kilometer of cable, is calculated as explained in section 3.3. The consumption behaviour is calculated according to Equation 3. According to Table 2, the short-circuit capacity for grids with detached houses varies between 2.37 and 11.73. The minimum value for the customer density is 9.77 and the maximum value is 16.59 customers per kilometer cable. According to Table 1, this indicates that the grids are located in mixed built areas. The consumption behaviour varies between 0.96 and 1.43.

Table 3. The calculated short-circuit capacity, the customer density and the consumption behaviour for the different grids in rural areas.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Short-Circuit Capacity [VA/VAh]</th>
<th>Customer Density [# customers/km cable]</th>
<th>Consumption Behavior [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-445</td>
<td>11.34</td>
<td>2.62</td>
<td>0.76</td>
</tr>
<tr>
<td>T-456</td>
<td>5.11</td>
<td>3.15</td>
<td>0.78</td>
</tr>
<tr>
<td>T-459</td>
<td>6.90</td>
<td>4.22</td>
<td>0.84</td>
</tr>
<tr>
<td>T-616</td>
<td>15.61</td>
<td>5.15</td>
<td>1.23</td>
</tr>
<tr>
<td>T-627</td>
<td>4.16</td>
<td>6.37</td>
<td>1.13</td>
</tr>
<tr>
<td>T-675</td>
<td>12.86</td>
<td>2.51</td>
<td>0.91</td>
</tr>
<tr>
<td>T-840</td>
<td>2.79</td>
<td>3.94</td>
<td>1.32</td>
</tr>
<tr>
<td>T-929</td>
<td>20.28</td>
<td>4.13</td>
<td>1.17</td>
</tr>
<tr>
<td>T-963</td>
<td>9.05</td>
<td>2.56</td>
<td>1.18</td>
</tr>
</tbody>
</table>

Table 3 shows the values of the three variables used in the Simplified model for nine rural grids mainly consisting of farms and detached houses. As shown in Table 3, the short-circuit capacity for grids in rural areas varies between 2.79 and 20.28. The customer density has a minimum value of 2.51 customers per kilometer cable and a maximum value of 6.37. According to Table 1, this indicates that the grids are located in either rural or sparsely built areas. The consumption behaviour varies from 0.76 to 1.32.
Table 4. The calculated short-circuit capacity, the customer density and the consumption behaviour for four grids with mixed load pattern, located both in rural areas and in more dense parts of the municipality.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Short-Circuit Capacity [VA/VAh]</th>
<th>Customer Density [# customers/km cable]</th>
<th>Consumption Behavior [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-111</td>
<td>4.84</td>
<td>9.82</td>
<td>0.98</td>
</tr>
<tr>
<td>T-114</td>
<td>3.71</td>
<td>12.06</td>
<td>1.06</td>
</tr>
<tr>
<td>T-122</td>
<td>11.48</td>
<td>4.48</td>
<td>0.83</td>
</tr>
<tr>
<td>T-328</td>
<td>6.67</td>
<td>5.25</td>
<td>1.56</td>
</tr>
</tbody>
</table>

Table 4 shows the values of the three variables used in the Simplified model for four grids with a consumption behavior and a location that does not match either the detached houses in mixed built areas, nor the rural grids mainly consisting of farms. For the four grids in Table 4, the short-circuit capacity varies between 3.71 and 11.48. The minimum value of the customer density is 4.48 and the maximum value is 12.06. The consumption behaviour varies between 0.83 and 1.56.

Table 5. The final $\theta$ after the training of the model, calculated for nine grids in mixed built areas consisting of detached houses. The table includes the calculated $\theta$ for the Simplified model and the Simplified model*.

<table>
<thead>
<tr>
<th>Type</th>
<th>$\theta_1$</th>
<th>$\theta_2$</th>
<th>$\theta_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified model</td>
<td>37.590</td>
<td>4.002</td>
<td>99.746</td>
</tr>
<tr>
<td>Simplified model*</td>
<td>38.360</td>
<td>-</td>
<td>150.330</td>
</tr>
</tbody>
</table>

After the training of the Simplified model, done with bagging, $\theta_{1,3}$ is conducted, which can be seen in Table 5. Table 5 also shows the values of $\theta_1$ and $\theta_3$ used in the Simplified model* where the customer density is excluded and bagging is performed again on nine grids.
Table 6. The product of $\theta$ and $u$ used in the Simplified model, calculated for nine grids with detached houses in mixed built areas.

<table>
<thead>
<tr>
<th>Grid</th>
<th>$\theta_1 \times u_1$</th>
<th>$\theta_2 \times u_2$</th>
<th>$\theta_3 \times u_3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-116</td>
<td>268.24</td>
<td>54.48</td>
<td>132.59</td>
</tr>
<tr>
<td>T-121</td>
<td>136.73</td>
<td>47.43</td>
<td>96.59</td>
</tr>
<tr>
<td>T-123</td>
<td>89.24</td>
<td>55.95</td>
<td>98.46</td>
</tr>
<tr>
<td>T-127</td>
<td>155.11</td>
<td>50.85</td>
<td>100.37</td>
</tr>
<tr>
<td>T-128</td>
<td>253.17</td>
<td>39.10</td>
<td>133.12</td>
</tr>
<tr>
<td>T-134</td>
<td>139.97</td>
<td>59.84</td>
<td>142.22</td>
</tr>
<tr>
<td>T-135</td>
<td>441.03</td>
<td>62.20</td>
<td>110.89</td>
</tr>
<tr>
<td>T-136</td>
<td>181.60</td>
<td>42.24</td>
<td>95.44</td>
</tr>
<tr>
<td>T-713</td>
<td>159.97</td>
<td>55.74</td>
<td>121.57</td>
</tr>
</tbody>
</table>

The result in Table 6 shows that the product of $\theta$ and the three variables varies according to the different variables. The product for the short-circuit capacity varies between 89.24 and 441.03. For the customer density, $u_3$, the product varies between 39.10 and 62.20 and for the consumption behaviour, the product varies between 95.44 and 142.22.

The following figures show the hosting capacity of different grids in Herrljunga, estimated with the Simplified model using the values shown in Table 2-5. As a reference, the values of the hosting capacity calculated with BEESG’s model are used.
Figure 4. The hosting capacity of nine grids with detached houses in mixed built areas, calculated with BEESG’s model and estimated with the Simplified model.

The grids in Figure 4 are the in-sample grids used to train the Simplified model with bagging. For six of the grids, the estimated value from the Simplified model is below the value calculated with BEESG’s model. The estimated value is almost equal to the calculated one for one grid. For two grids, the estimated value is higher than the calculated one. The error of the estimated value is calculated using both the NRMSE and MAPE method, with a NRMSE of 22% and a MAPE of 24%.

Figure 5. The hosting capacity of the out-sample test grids with detached houses in mixed built areas, calculated with BEESG’s model and estimated with the Simplified model.
The Simplified model with the trained parameters is tested on three out-sample grids. The result is shown in Figure 5. For one grid, the estimated value is higher than the calculated. For two grids, the estimated value is lower than the calculated one, although the difference is small for grid number T-713. The error of the estimated value is calculated using both the NRMSE and MAPE method, with a NRMSE of 17% and a MAPE of 16%.

![Figure 6](image-url)  
*Figure 6. The hosting capacity of nine grids in rural areas, calculated with BEESG’s model and estimated with the Simplified model.*

The Simplified model is tested on nine rural grids with the parameters calculated from the grids with detached houses in mixed built areas. For eight of the nine grids, the value from the Simplified model is below the calculated one. It is worth noting that, for one grid, the BEESG’s model calculates the hosting capacity to nearly 1400%, which changes the scale of the y-axis. The error of the estimated value is calculated using both the NRMSE and MAPE method, with a NRMSE of 34% and a MAPE of 31%.
Figure 7. The hosting capacity of all 25 grids used in the simulations, calculated with BEESG’s model and estimated with the Simplified model.

Figure 7 shows the hosting capacity of all the simulated grids. The grids are located in both mixed built areas and rural areas. Four grids are unspecified, including e.g. a golf course, a football field and grids with a mix of different consumers. The graph shows that the estimation from the Simplified model can be used on different types of grids, even if the parameters are trained for detached houses in mixed built areas. The error of the estimated value is calculated using both the NRMSE and MAPE method, with a NRMSE of 30% and a MAPE of 24%.

Figure 8. The voltage for a randomly selected grid, measured over a six-month period from mid-July to the last of December, when the hosting capacity is reached.

The voltage fluctuations seen in Figure 8 shows the maximum voltage per hour in one specific grid, from mid-July to the last of December. The studied grid is randomly selected since all grids will show the same trends in the behaviour. Figure 8 shows that
after September, the PV generated electricity does not affect the voltage in the grid significantly.

4.2 Sensitivity Analysis

The result in Table 6 shows that the customer density has the smallest impact on the result. The impact of the customer density is therefore tested in a sensitivity analysis, where this variable is set to zero. The new set of $\theta$ is trained in the same way as before, via bagging. The values of $\theta_1$ and $\theta_3$ are shown in Table 5. This version of the model is denoted as the Simplified model*.

![Figure 9. The hosting capacity of the out-sample test grids with detached houses in mixed built areas, calculated with BEESG’s model and estimated with the Simplified model and the Simplified model*.](image)

The estimated values from the Simplified model* are below the values from the Simplified model for all three grids seen in Figure 9. For two of the grids, this entails that the estimated value from the Simplified model* is closer to BEESG’s value compared to the Simplified model’s.

<table>
<thead>
<tr>
<th>Model</th>
<th>NRMSE</th>
<th>MAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified model</td>
<td>17.27%</td>
<td>16.37%</td>
</tr>
<tr>
<td>Simplified model*</td>
<td>16.75%</td>
<td>16.41%</td>
</tr>
</tbody>
</table>

Table 7. The calculated errors for the Simplified model and the Simplified model* when predicting the hosting capacity for the three out of sample grids.
When the Simplified model* is used on the three out-sample test grids seen in Figure 5, the estimation of the hosting capacity differs some but the error is almost the same. This can be seen in Table 7. When the Simplified model* is tested on all grids the error is smaller for the model with three variables, see Table 8.

Table 8. The calculated errors for the Simplified model and the Simplified model* when predicting the hosting capacity for all 25 grids.

<table>
<thead>
<tr>
<th>Model</th>
<th>NRMSE</th>
<th>MAPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simplified model</td>
<td>30.48%</td>
<td>23.81%</td>
</tr>
<tr>
<td>Simplified model*</td>
<td>27.24%</td>
<td>23.44%</td>
</tr>
</tbody>
</table>

5. Discussion

In this section, the results from the model and the model itself will be discussed. Improvements of the model will be further analyzed as well as the model’s area of application. Furthermore, different ways to increase the hosting capacity will be discussed and some future research directions are given.

To be able to create a solar roadmap, a method to classify different regions and their hosting capacities is needed. The BEESG’s model is a MATLAB-script containing a lot of information. Since this information is specific for the municipality of Herrljunga, the script cannot be applied to other municipalities without substantial effort. An easier classification method is desirable if more municipalities should have the desire to develop a solar roadmap. Hence, the aim with this project is to develop a simplified model to predict the hosting capacity of different regions. With the BEESG’s model as a reference, a simplified model including only three parameters is created.

5.1 The Simplified Model

As shown in Figure 7, the results from the Simplified model seem to resemble the results from the BEESG’s model for different types of grids, although the Simplified model is trained on grids in mixed built areas. The results show that it is possible to create a simplified model by classifying grids according to a few parameters. In Table 6, the values of the product show that the customer density is significantly smaller than the other two variables. This implies that the customer density does not affect the result as much as the other variables. This hypothesis is tested in the sensitivity analysis. The results from the sensitivity analysis show that the hosting capacity estimated with the Simplified model* is close to the estimated value from the Simplified model. According to the result in Table 8, the Simplified model* estimates the hosting capacity more accurate than the Simplified model. With customer density excluded there is no
significant increase of the MAPE. When the NRMSE is compared, the error is smaller with the Simplified model*, see Table 7. However, more grids must be investigated to determine if the customer density is required in the model.

In some of the simulated grids the voltage in some of the busses were remarkably more affected by the introduction of PV systems than others. These buses are limiting the hosting capacity of the specific low-voltage grid because it reaches overvoltage much sooner. This could be a consequence of the way BEESG’s MATLAB-script is constructed, where roofs with a high solar irradiation gets a lot of PV facilities which causes overvoltage in the concerned busses. Another explanation could be that the cable from a bus is too weak for a larger PV system, which results in overvoltage earlier in the concerned bus. This would limit the whole low-voltage grid. The Simplified model does not take specific busses into account, which could be an explanation to some parts of the error in the Simplified model.

The Simplified model often predicts a value below the BEESG’s. A plausible reason for this is that during the training of the model, $\theta$ is calculated with the least square method. One of the grids, T-127, has a low hosting capacity according to the BEESG’s model but the variables in the Simplified model are rather high for this grid. The least square method is compensating for this when $\theta$ is calculated and therefore, the parameter’s final value decreases. This results in that the Simplified model will underestimate the hosting capacity for most of the grids, which can be seen in Figure 7. By using more grids during the training of the model the impact from one specific grid would be less and the results would be more reliable.

Our simulations show that there is a difference in hosting capacity between grids that theoretically should have been quite similar. A possible explanation for this is that the medium-voltage grid is different for these grids. A weak medium-voltage grid will constrain the hosting capacity for the low-voltage grids connected to it. A study [18] from BEESG shows that, in most cases, the hosting capacity is limited by the medium-voltage grid. To improve our model, variables regarding the strength of the medium voltage grid can be added. In addition, one might perform studies into other variables that could aid the predictive accuracy. Furthermore, the relationship between the variables and the hosting capacity may not be linear. For this reason, the model could be expanded with polynomial variables.

5.2 Outlook

If the customers in a grid with a high hosting capacity decide to install PV systems to its maximum capacity, this might exceed the grids own momentary consumption. This will result in a reversed power flow up into the medium-voltage grid where it will be distributed amongst the other low-voltage grids. One grid can thereby lower the hosting capacity of grids nearby.
Reversed power flow could especially be a problem on the countryside, where the low-voltage grids in general have a higher hosting capacity, see figure 7. Previous studies from BEESG [3] have shown that the medium-voltage grid is often weaker on the countryside compared to more densely built regions. This, in combination with a strong low-voltage grid, makes the medium-voltage grid into a bottleneck. To approach this problem, one can think of the low-voltage grids as small virtual grids that are disconnected from each other. This means that all the produced PV electricity must be consumed or stored within this virtual grid. This will prevent the grids from affecting each other via the connecting medium-voltage grid, which will prevent a grid to lower the hosting capacity of other grids nearby. Our simulations show that the higher consumption a low-voltage grid has when the generation of PV electricity peaks, the higher the hosting capacity is.

One way to increase the hosting capacity of a grid is to maximize the self-consumption. This can be done by studying the customer’s load pattern and placing the PV system in a way that matches the electricity generation with the consumption. Since PV electricity is generated by the amount of irradiation that hits the solar panels, it peaks at midday when the sun is at its highest. During the summer months, this peak can be significantly higher than the rest of the year. By restricting the maximum allowed PV electricity production, the installed PV power can be increased without reaching overvoltage. This is referred to as curtailment. Another possible solution is to change the consumption behavior so that more electricity is used during the peak hours.

The hosting capacity of a grid could be increased in other ways too. The voltage in most of the studied grids is quite high, often around 410 V. A high nominal operating voltage is a way to lower the risk of undervoltage for customers who are located at the end of the grid, but simultaneously, it also lowers the grid’s hosting capacity since the operating voltage is closer to the limit for overvoltage. By lowering the output voltage in the substations, the grid’s hosting capacity can be increased. However, if the nominal operating voltage is lowered, the risk for undervoltage increase since the impact from the PV systems are negligible during the winter months. This could theoretically be compensated by alternating the nominal operating voltage emitted from the substations depending on the seasons, with a higher voltage during the winter months than during the summer months. In reality this is too expensive and time consuming to be seen as a viable solution with today’s technology. A further and more in depth analysis with alternatives to increase Herrljunga’s hosting capacity is presented in BEESG’s report [18].

To be able to create a solar roadmap for the municipality, a method to classify different regions or users must be developed. The Simplified model is a step towards achieving this and by improving the model it could be used in the compilation of a solar roadmap. Recommendations for customers regarding the electricity consumption behaviour and the azimuth angle are something that could be added in the roadmap, since this affects the hosting capacity for both the low-voltage grid and the medium-voltage grid.
6. Conclusions

It is possible to estimate the hosting capacity of a grid with a simplified model including only three variables. The Simplified model is useful even when one variable, the customer density, is excluded. Our results indicate that the low-voltage grid is not the limiting factor in the expansion of PV power in Herrljunga. The model can be improved by e.g. adding the strength of the medium-voltage grid as a variable. With some adjustments, the Simplified model can be used in Herrljunga as well as in other municipalities to estimate the hosting capacity and classify different regions. This is the first step in the work towards a complete solar roadmap.
7. References


