Degree Project Thesis
*Bachelor of Science in Engineering*

**Simulation Tool for Design of Multiple Photovoltaic Systems**

**Estimation of System Sizes, Grid Interaction, and Area Requirements**

Author: Maria Björklund  
Supervisors: Désirée Kroner, Ewa Wäckelgård  
External supervisor: Jon Persson  
Company: Research Institutes of Sweden (RISE)  
Examiner: Johan Heier  
Subject/main field of study: Energy technology  
Course code: EG2004  
Credits: 15  
Date of examination: 6 June 2021

At Dalarna University it is possible to publish the student thesis in full text in DiVA. The publishing is open access, which means the work will be freely accessible to read and download on the internet. This will significantly increase the dissemination and visibility of the student thesis.

Open access is becoming the standard route for spreading scientific and academic information on the internet. Dalarna University recommends that both researchers as well as students publish their work open access.

I give my/we give our consent for full text publishing (freely accessible on the internet, open access):

Yes ☒  
No ☐
Abstract

Photovoltaic solar power is an increasing source of energy and part of the renewable energy generation which is needed in the near future to achieve the set climate goals. When planning new photovoltaic installations, parameters which affect the design are both local conditions (e.g. weather) and system parameters such as tilt and azimuth angles. Commercial areas often have high loads during the day when solar power is available and are therefore interesting for photovoltaic installations. In order to make a quick estimation of photovoltaic power potential in an area, a simulation tool which handles load profiles from multiple buildings would be desirable. The aim of this thesis project is therefore to create a tool which can simulate multiple photovoltaic systems and for each of them estimate system sizes, grid interactions, and area requirements. The simulation tool is based on Python programming with the aid of System Advisor Model, a simulation software for photovoltaic and other renewable energy technologies. Optimization of orientation angles was made for clear sky with the goal of high load-generation match. Different system sizes were estimated and simulated based on different degrees of self-sufficiency, net-zero consumption, and the existing transfer capacity of the building in question. When the simulation result was compared to a detailed photovoltaic design project, some agreements between the results were found, as well as further development needs such as refining area estimation. To further develop the usability of the tool, a more user-friendly interface is needed. Other improvements could be to enable simulations of multiple direction systems and integration of the local grid structure and limitations.

Keywords: Photovoltaic system, simulation, design, system size, orientation, tilt, azimuth, grid interaction, roof-installation
Acknowledgement
I would like to extend my thanks to my main supervisor Jon Persson at Research Institutes of Sweden (RISE), who has given me great support, feedback, and inspiration during the process of this thesis work. I would also like to thank my supervisors at Dalarna University, Désirée Kroner and Ewa Wäckelgård for your valuable input in order to improve the thesis report, and thanks to Sarah Ramsay for helpful feedback regarding academic writing.

If not stated otherwise, the figures in this report are produced by the author.

Maria Björklund
6 June 2021 Borlänge, Dalarna
### Concepts and/or abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>EPW</td>
<td>EnergyPlus Weather (weather file format)</td>
</tr>
<tr>
<td>GCR</td>
<td>Ground Coverage Ratio</td>
</tr>
<tr>
<td>JSON</td>
<td>JavaScript Object Notation</td>
</tr>
<tr>
<td>NZC</td>
<td>Net-zero consumption</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable Energy Source</td>
</tr>
<tr>
<td>SAM</td>
<td>System Advisor Model (software)</td>
</tr>
<tr>
<td>SC</td>
<td>Self-Consumption</td>
</tr>
<tr>
<td>TMY</td>
<td>Typical Meteorological Year</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>Meaning</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>Tilt angle</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Azimuth angle</td>
</tr>
<tr>
<td>( \beta_{\text{start}} )</td>
<td>Start value of azimuth angle</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Solar inclination angle</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Time for normal distribution peak</td>
</tr>
<tr>
<td>( \phi_{\text{sc}} )</td>
<td>Rate of self-consumption</td>
</tr>
<tr>
<td>( \phi_{\text{sc,end}} )</td>
<td>Desired rate of self-consumption</td>
</tr>
<tr>
<td>( \phi_{\text{ss}} )</td>
<td>Rate of self-sufficiency</td>
</tr>
<tr>
<td>( A_{\text{diff}} )</td>
<td>Difference between ( A_{\text{roof}} ) and ( A_{\text{syst}} )</td>
</tr>
<tr>
<td>( A_{\text{mod}} )</td>
<td>Module area</td>
</tr>
<tr>
<td>( A_{\text{roof}} )</td>
<td>Roof area</td>
</tr>
<tr>
<td>( A_{\text{syst}} )</td>
<td>PV system area</td>
</tr>
<tr>
<td>( c )</td>
<td>Constant</td>
</tr>
<tr>
<td>( d_{g} )</td>
<td>Ground row distance</td>
</tr>
<tr>
<td>( d_{\text{pv}} )</td>
<td>Height of PV module</td>
</tr>
<tr>
<td>( E_{\text{grid}} )</td>
<td>Total export to grid per year</td>
</tr>
<tr>
<td>( f_{\text{load}} )</td>
<td>Optimization ratio 1 / mean(r)</td>
</tr>
<tr>
<td>( f_{\text{sc}} )</td>
<td>Absolute difference between ( \phi_{\text{sc}} ) and ( \phi_{\text{sc,end}} )</td>
</tr>
<tr>
<td>( \text{GCR} )</td>
<td>Ground coverage ratio</td>
</tr>
<tr>
<td>( L )</td>
<td>Load</td>
</tr>
<tr>
<td>( L_{\text{min}} )</td>
<td>Lowest load</td>
</tr>
<tr>
<td>( M )</td>
<td>Self-consumption</td>
</tr>
<tr>
<td>( n )</td>
<td>Scaling factor in size calculations</td>
</tr>
<tr>
<td>( P )</td>
<td>Generation</td>
</tr>
<tr>
<td>( P_{\text{AC}} )</td>
<td>Output power (AC)</td>
</tr>
<tr>
<td>( P_{\text{AC2}} )</td>
<td>Output power (AC) for system 2</td>
</tr>
<tr>
<td>( P_{\text{mod}} )</td>
<td>( P_{\text{peak}} ) of single module</td>
</tr>
<tr>
<td>( P_{\text{peak}} )</td>
<td>Installed peak power (DC)</td>
</tr>
<tr>
<td>( P_{\text{peak2}} )</td>
<td>Installed peak power (DC) for system 2</td>
</tr>
<tr>
<td>( P_{\text{peak, start}} )</td>
<td>Start value of installed peak power (DC)</td>
</tr>
<tr>
<td>( r )</td>
<td>The ratio of AC power output ( (P_{\text{AC}}) ) to load ( (L) )</td>
</tr>
<tr>
<td>( S )</td>
<td>Power transfer between building and grid</td>
</tr>
<tr>
<td>( S_{\text{max}} )</td>
<td>Maximal power transfer between building and grid</td>
</tr>
<tr>
<td>( t_{1} )</td>
<td>Start time of period</td>
</tr>
<tr>
<td>( t_{2} )</td>
<td>End time of period</td>
</tr>
</tbody>
</table>
# Table of Contents

## 1 Introduction

1.1 Solar power ................................................................. 1
1.2 Grid impact ................................................................. 2
1.3 Scenario ........................................................................ 2
1.4 Aim ............................................................................. 3
1.5 Limitations .................................................................... 3
1.6 Structure of report .......................................................... 3

## 2 Theory

2.1 Self-consumption .............................................................. 4
2.2 Net-zero consumption ......................................................... 6
2.3 Maximal transfer capacity ..................................................... 6
2.4 PV design parameters .......................................................... 7
2.4.1 Local conditions .............................................................. 7
2.4.2 PV system .................................................................... 8
2.4.3 Ground coverage ratio ....................................................... 9
2.4.4 Tilt and azimuth ............................................................. 10
2.4.5 Load-match .................................................................. 10
2.5 Previous design study: Roof based PV system ......................... 11

## 3 Method

3.1 Orientation optimization ...................................................... 13
3.2 Simulation of PV system ....................................................... 14
3.3 Size calculation ................................................................. 16
3.3.1 Self-consumption ............................................................ 16
3.3.2 Net-zero consumption ....................................................... 17
3.3.3 Within existing maximal transfer capacity ......................... 17
3.4 Grid interaction ................................................................. 17
3.5 Area calculation ................................................................. 17
3.6 Result comparison to reference ............................................ 18

## 4 Description of Simulation Tool

4.1 Input ............................................................................. 20
4.2 Tilt and azimuth optimization .............................................. 21
4.3 Ground coverage ratio ......................................................... 22
4.4 SAM simulation ............................................................... 22
4.5 System size optimization ...................................................... 22
5 Comparison to Reference Study

6 Discussion

6.1 Results discussion .................................................................27
6.2 Method discussion .................................................................27
6.2.1 Input .................................................................27
6.2.2 Simulation .................................................................28
6.2.3 Comparison to reference study ...........................................29
6.3 Applicability of this thesis project .........................................29
6.4 Future work ..........................................................................29

7 Conclusions

Appendices

Appendix

Appendix 1. Python code overview ........................................(1 page)
Appendix 2. Overview of result output ......................................(1 page)
1 Introduction

In 2016, five of the parliamentary parties in Sweden made an environmental agreement to achieve 100% production of electricity from renewable energy sources (RES) by 2040 at the latest [1]. This means that the nuclear power plants which in 2019 delivered 39% of the electricity in Sweden [2] should be replaced by RES in the near future. Apart from nuclear power, electricity generation in Sweden in 2019 originated from hydropower (39%), wind power (12%), solar power (0.4%), and combined heat and power plants (10%) which are partly driven by fossil fuels, see Figure 1.1 [2].

![Source of electricity Sweden 2019 (based on data from SCB [2])](image)

Figure 1.1 Source of electricity Sweden 2019 (based on data from SCB [2])

To achieve the goal of 100% RES, the Swedish energy system needs great changes. To show how this could be achieved, the Swedish Energy Agency has developed three different scenarios – the wind, solar and cogeneration scenarios [3]. All of them consist of a high share of wind power, but also an increased share of solar power. According to the Swedish Energy Agency, solar power has the potential to generate 3-14% of the electricity needed in Sweden in 2040, depending on which scenario is studied [3]. Looking at the solar scenario, 14% of the electricity generated in Sweden in 2040 could come from the sun. This would require an installed capacity of 25-30 GW [3] which is about 23-28 times the capacity of solar power plants installed in 2020 (1090 MW) [4].

1.1 Solar power

Solar power includes mainly two technologies to produce electricity to the grid, thermal solar power and photovoltaic solar power (PV), where PV accounted for 98% of the world’s generation of solar power in 2018 [5]. Thermal solar power uses concentrated solar radiation to heat a fluid to steam which is then converted to electricity by a steam turbine [6, p. 2]. PV, on the other hand, converts solar radiation directly to electricity within the PV cell [6, p. 2]. The power output from a PV module varies depending on the time of day and time of year, and can therefore not provide electricity all day and all year round [6, p. 31], [7, pp. 12–13]. To enable usage of solar energy in a power system, the solar energy must either be stored or mixed with other energy sources to create a balance between load and generation [6, p. 13]. Although technologies for energy storage already exist, e.g. pumped hydro and batteries, storage is still a major challenge because of costs and losses related to these technologies [8]. When integrating large amounts of intermittent RES into an energy system, it will affect the power grid which will briefly be described in Section 1.2. Although PV has its challenges, it also has advantages.
Apart from being an endless energy source, Bollen [7, pp. 30–33] claims that the required land area in the Nordic countries per generated kWh during one year is less for PV than for wind power if the total park area is considered, 80 kWh/m²/year versus 30 kWh/m²/year. In addition, PV modules are easy to mount close to consumption which thereby decreases the need for power transmission [7, pp. 30–33].

1.2 Grid impact

As mentioned above, there are challenges related to the integration of large-scale PV in a power system which also includes other intermittent RES e.g. wind power. Some of the transitions of the world’s power grids due to integration of RES are that [7, pp. 84–86]:

- Generation is connected to the distribution grid instead of transmission grid, which was not initially built for two-way transmission
- The different power plants are built by different owners, who have their own economic interest in the generation and thereby do not often build their power plant in the optimal location from a power grid perspective
- The grid balance between load and generation is complicated by the different actors involved in the grid operation and the intermittent generation patterns

Rapid changes of generation, grid, and consumption increase the complexity of analysis in order to estimate the effects of the above mentioned changes [7, p. 85]. However, possible effects described in the literature are, among others, risks of transformer and feeder overload, dysfunction of the grid’s protection system, and power quality problems e.g. over or under voltage, frequency instability and harmonics [7, p. 87], [9], [10]. Due to these challenges, it is important to plan and simulate which impact new installations will have on the power grid.

1.3 Scenario

As the expansion of PV systems is escalating, there is an increased need for planning tools to find optimal solutions for today’s complex cities, e.g. while planning large commercial areas or town districts. The installation of multiple PV systems close to each other leads to possible grid challenges, as indicated in Section 1.2. By coordination of installation projects within an area, a local grid owner would have an increased possibility to make wise decisions concerning the future power grid. One goal of the Research Institutes of Sweden (RISE) is to create an energy simulation tool to assist decision-making for urban district energy planning. A natural part of the tool would be simulation of multiple PV systems and their interaction with the grid. The tool would provide an initial estimation of the PV potential which can be followed by a detailed design study of individual systems. To enable interconnection to other parts of the tool, i.e. import and export of simulation data, the use of a flexible programming language which works in many fields is required; thus Python language has been chosen for this tool.

There are three commercial areas in southern Sweden which have an interest in PV as part of their future power system, and where RISE are involved. These areas contain multiple industries or businesses which have most of their electricity need during the day, when solar power is available. These will act as test scenarios during development of the simulation tool for PV installation, and provide this thesis project with historical hourly load data.
1.4 Aim
The aim of this thesis project is to create a Python based PV simulation tool which can be used as part of a future energy simulation tool for urban district energy planning. The tool should be able to size a large number of PV systems based on hourly load data and with different sizing goals: a certain degree of self-consumption (SC), net-zero consumption (NZC), or to stay within the existing transfer capacity. For each of these systems, an estimation of grid interaction and area requirements should be made.

1.5 Limitations
This thesis project does not include simulation of the power grid connected to the load, but solely estimates the power transferred over the point of connection between grid and building. The process of size calculations for the PV systems is based on available hourly load data for each building and not primarily available roof area or orientation of the actual building. The simulation tool is developed based on the assumption of flat roofs. Financial evaluation related to the installation of PV systems is excluded from this thesis project.

1.6 Structure of report
The report continues with six main sections. Section 2 “Theory” presents important concepts of the thesis project as well as relevant theory and a presentation of a reference study with which the result will be compared. In Section 3 “Method”, the design choices of the simulation tool are presented which include built-in functions, assumptions, and values of base parameters. A description of the comparison between simulation tool and reference study is presented in Section 2.5. The, for this thesis project, final version of the simulation tool is presented with its functions and input requirements in Section 4 “Description of Simulation Tool”. Section 5 “Comparison to Reference Study” presents some key values for comparison between the simulation tool and data from the reference study. The simulation tool and design choices will be discussed in Section 6 “Discussion” and lastly Section 7 “Conclusions” will highlight the main results and recommendations for future development.

A pre-study to this thesis project was conducted within the Sustainable Energy Systems course (10 credits) [11]. Parts of the following sections are transferred as a whole or partly rewritten from [11]: 1 Introduction, 2.4.4 Tilt and azimuth, and 2.4.5 Load-match.
2 Theory

As described above, it is a challenge to integrate large amounts of energy from RES into the power system with respect to power grid limits and power quality [7, p. 87], [9], [10]. For this reason it could be beneficial to consume the power locally i.e. in the building where it is generated, which means the power will never enter the grid. To consume the power at the time of generation is the meaning of SC [12]. This makes the degree of SC an interesting goal of PV system design. Another goal could be to generate the same amount of energy which the building uses for a certain period of time and thus be a net-zero consumer within that period [13]. One problem with NZC in Sweden is the low power generation during wintertime, see example in Figure 2.1 for two sunny days where a shows the generation on 9 July and b the generation on 28 December for a system designed for yearly NZC (based on data from this thesis project). The installed capacity must be enough to generate most of the energy during summertime, which leads to large overproduction in this period as shown in Figure 2.1a. This will likely lead to expensive upgrades of the transfer capacity between the building and the grid e.g. new cables. To avoid such costs, the scenario to stay within the existing transfer capacity could be important and therefore included as a possibility in this thesis project. The definitions of these different scenarios are presented below as well as a literature review of other design parameters to match load and generation and thereby increase SC and decrease the transfer capacity needed.

Figure 2.1 Difference of daily generation between a sunny day in the summer (9/7) (Figure 2.1a) and in the winter (23/1) (Figure 2.1b), where the PV system is sized for yearly NZC. Figures are based on load data used in this thesis project.

2.1 Self-consumption

Luz et al. [12] define SC as the electric power which is consumed at the same time and location as its generation. The system border for SC in this thesis project is the connection point between the building and the grid, and every load for the building is thereby seen as part of the SC. The term SC is illustrated in Figure 2.2 where field $A+C$ represents the load, field $B+C$ the generation, and field $C$ the SC (based on load data from this thesis project). The rate of SC ($\phi_{sc}$) is often used to relate SC to the total local power generation as shown in Equation 2.1 [14]. SC should not be confused with the term self-sufficiency, which represents the share of load $(A+C)$ covered by the instantaneous generation of the building $(C)$, see Equation 2.2 [14].
Figure 2.2 Illustration of SC and NZC where A+C is the load, B+C is the generation, and C is the SC. For NZC (described in Section 2.2) A=B. Figure is based on load data used in this thesis project.

\[ \phi_{sc} = \frac{C}{B + C} \]  \hspace{1cm} 2.1

where
\( \phi_{sc} \) is the rate of SC (\( \cdot \) )

\[ \phi_{ss} = \frac{C}{A + C} \]  \hspace{1cm} 2.2

where
\( \phi_{ss} \) is the rate of self-sufficiency (\( \cdot \))

Luthander et al. [14] use two equations which describe SC and are thus used in this thesis project. Equation 2.3 shows the SC in kW and Equation 2.4 shows the degree of SC during a certain time period, \( t_1 \) to \( t_2 \).
\[
M(t) = \min\{L(t), P(t)\}
\]
\[
\phi_{SC} = \frac{\sum_{t=t_1}^{t_2} M(t)}{\sum_{t=t_1}^{t_2} P(t)}
\]

where

\(L(t)\) is the load at time \(t\) (kW)

\(M(t)\) is the SC at time \(t\) (kW)

\(P(t)\) is the generation at time \(t\) (kW)

\(t_1\) is the start time of the intended time period (h)

\(t_2\) is the end time of the intended time period (h)

### 2.2 Net-zero consumption

In this thesis project, NZC is simply defined as the balance between the total amount of locally generated energy (\(P_{AC}\)) and total consumption (\(L\)) over a certain time period, \(t_1\) to \(t_2\). Unlike SC, it is the energy and not the power which is important, since it is not necessary to use the power at the same time as it is generated. This can be visualized by the use of Figure 2.2 where \(A\) should be equal to \(B\). A review [13] concerning net-zero energy buildings highlights three important parameters to attain NZC: energy infrastructure, RES, and energy efficient measures. This thesis project will focus on the RES, but nevertheless measures to increase energy efficiency and reduce the need for energy are very important actions to consider before integrating PV systems. One reason to size the system for NZC is the future possibility of electric self-sufficiency aided by daily and seasonal energy storage. This could additionally serve as a competitive advantage if customers choose to support companies which use energy from RES for production or services.

### 2.3 Maximal transfer capacity

In Sweden, most of the industries and larger electricity consumers have an agreement with the local grid operator which states the maximum acceptable power consumption (kW). A customer subscribes and pays for the appropriate level of power, which is dependent on the power needed and where the company is connected to the power grid i.e. to the high, medium, or low voltage grid [15]. Technical equipment and electrical infrastructure in the area e.g. fuse size, cables, and transformers are dimensioned to match the power usage. Since an expansion of existing power infrastructure is costly, it could be desirable to install PV systems without the need to increase the transfer capacity. During the development of distributed generation, generation connected to the distribution grid, the concept of hosting capacity has emerged, which basically indicates how much distributed generation can be connected at a specific point in the power grid with maintained acceptable power quality [7, pp. 88–89]. To estimate the hosting capacity a simplified calculation for safe hosting capacity can be used, given there are no previous power quality issues, see Equation 2.5 [7, p. 105].

\[
S_{\text{max}} = P_{\text{peak}} - L_{\text{min}}
\]

where

\(L_{\text{min}}\) is the lowest load (kW)

\(P_{\text{peak}}\) is the maximal power generation (kW)

\(S_{\text{max}}\) is the maximal safe power transfer (kW)
Based on this simplified calculation of hosting capacity, the maximal PV system size to stay within existing maximal transfer capacity can be calculated according to Equations 2.6 and 2.7, where the hosting capacity is calculated for each hour and the system can then be designed for the largest power transfer. Figure 2.3 illustrates the maximal transfer capacity based on data used in this thesis project.

\[ S(t) = P(t) - L(t) \]  
\[ S_{\text{max}} = \max \{S(t)\} \]

where
\( S(t) \) is the transferred power to the grid at time \( t \) (kW)

![Figure 2.3 Illustration of generation limit a summer day with low load where the black dashed line shows the limit of allowed PV generation. Figure is based on load data used in this thesis project.](image)

### 2.4 PV design parameters

According to an International Energy Agency report [16] there are two forms of design parameters for a PV installation:

- Local conditions such as latitude, longitude, altitude, etc.
- System parameters such as type of inverter, type of module, number of modules, cable types, tilt, azimuth, reflectivity from the surroundings, risk of shading, etc.

Other types of parameters described when optimizing a PV system are: available area, financial limitations, and electric energy needed [17].

#### 2.4.1 Local conditions

The amount of solar irradiance at a specific location depends mainly on the time of day and the time of year as well as the weather. Which local time the sun is exactly positioned in the south depends on the local longitude angle where every longitude angle within a time zone has a unique time when the solar azimuth is 180° (south) [18, p. 30]. The path of the sun is also affected by the latitude, where there is a well-known seasonal variation when the solar altitude (height over horizon) is lower during wintertime [18, p. 27]. The solar movement over the sky,
including daily and yearly variations, is easy to forecast, however PV generation is highly affected by cloud coverage which complicates the prediction of power output [7, pp. 31–32], see example of variation in Figure 2.4 (based on generation data from this thesis project).

![Figure 2.4 Example of generation variations during a summer’s day for one of the systems simulated in this thesis project.](image)

To enable simulation of PV power on a specific location, a historical weather data file could be of great help to take a normalized cloud coverage into consideration [7, p. 44]. In climates with considerable snowfall, this will also affect PV power output during wintertime. The snow losses depend mainly on the climate, if the snow can slide off the modules, and the tilt angle of the modules. Snow losses have been estimated to less than 10% during a full year, but as high as 90-100% during the winter period [19], but are for simplicity not considered in this thesis project.

2.4.2 PV system
A PV system is built from several components, mainly [20]:

- PV modules
- Mounting system
- Inverters

PV modules are built from PV cells which normally generate below 5 W [18, p. 49]. To attain power of 400 W, i.e. the size of some commercially available modules [21], PV cells are connected to each other in series where each cell increases the voltage by 0.5 V and thereby also increases the power [18, p. 49], see Figure 2.5. In order to reach PV system sizes of hundreds of kW or even MW, the modules are also connected in series, known as a PV array, adding up in the same way as the PV cells [18, pp. 49–50].
There are different methods when mounting a PV system on a roof. The choice of mounting system depends on the type and roof inclination. For flat roofs, which are assumed in this thesis project, the use of a ballast system is the most common, which keeps the PV systems in place mainly by use of weight and friction [22], even though fixation by some anchor points could be necessary [18, pp. 216–217]. Inverters are other important components in the PV system, which convert the DC power generated by the PV cells into AC power which can be used to power electrical equipment. There are different types of inverters, which have different e.g. output ranges, efficiencies, and degrees of harmonics distortion.

2.4.3 Ground coverage ratio
The distance between the rows of PV modules affects how much internal shading the modules are exposed to, and thereby the shading losses. There is however a conflict between avoidance of internal shading and the utilization of available roof space, as increased row distance will decrease the installed capacity per area; described by the ground coverage ratio (GCR). This is illustrated in Figure 2.6 and defined by Equation 2.8 [23]. The value of \( d_g \) is calculated by the law of sines, see Equation 2.9. In Sweden, the common practice is to choose the minimal solar inclination angle (\( \gamma \)) for unshaded modules to between 12° and 20° [24].

Figure 2.5 PV modules consists of series connected PV cells, where one single PV cell generate less than 5 W [18, p. 49].

Figure 2.6 Illustration of parameters used in the calculation of GCR, see Equation 2.8 and 2.9 (based on [23]).
\[ GCR = \frac{d_{pv}}{d_g} \]

\[ d_g = \frac{\sin(180° - \gamma - \alpha)}{\sin(\gamma)} \cdot d_{pv} \]

where

- \( d_g \) is the ground distance between the modules (m)
- \( d_{pv} \) is the height of the PV module (m)
- \( GCR \) is the ground coverage ratio (\(-\))
- \( \alpha \) is the tilt angle of the PV modules (°), see Figure 2.6
- \( \gamma \) is the minimal solar inclination angle (°)

### 2.4.4 Tilt and azimuth

The optimal tilt angle differs between locations and Cheng et al. [25] conclude that 98.6% of the PV power plants studied had an optimal tilt angle equal to the local latitude, where optimal tilt was defined as the tilt resulting in the highest total yearly output. However, it has been shown that at higher latitude the optimal tilt could be lower than the latitude angle [26]. To achieve the highest energy generation from a PV plant per year in the Northern Hemisphere, normally a tilt of 90% of the latitude and modules oriented towards the south will be used [18, p. 130]. In addition, there is seasonal variation of the optimal tilt angle, i.e. a higher tilt is preferred in winter [27]. For flat roofs (< 5° inclination) however, the common practice is to use a tilt angle of 10°-20° [22].

Regarding azimuth angle, some studies suggest that the optimal azimuth angle is about 180° (south) for commercial buildings [28], others imply ±20° deviation from south does not significantly affect yearly production [18, p. 133]. However most studies are conducted on residential buildings, where south-west oriented systems are purposed to increase SC [28], [29].

### 2.4.5 Load-match

A study conducted in 2009 in Stockholm, Sweden, investigated the impact of orientation, electrical storage and demand side management to increase the share of solar power and to decrease electricity exported to the grid [30]. The results showed that orientation played a minor role in a load-generation match, whereas storage was implied to be the most important factor for high solar power share. However, according to the same study, storage appeared to have a small impact on peak shaving, unless the storage was large enough or designed to handle the peaks; whereas demand side management was indicated to have a large impact on the possibility of peak shaving. A review from 2015 supports the possibility of increased self-sufficiency by usage of storage and demand side management [14].

Other authors state that a change in tilt and azimuth could increase the match between load and generation [18, p. 130], [28], [29]. Messenger and Abtahi [18, p. 130] point out that the yearly generation could decrease when facing the modules deviated from the south, although the load-generation match would increase. Most of the studies regarding PV systems are focused on smaller scale installations on residential buildings. Litjens et al. [28], e.g., found that for residential buildings in the Netherlands, the optimal orientation of the PV system varied depending on the goal. A south oriented system, azimuth between 181° and 188°, resulted in a maximum power output whereas an orientation towards south-west resulted in a higher match between load and generation [28]. Presenting similar results, Awad and Gül [29] studied two
types of grid-connected single family houses in Canada with an installed PV capacity ($P_{\text{peak}}$) of 5-9 kW and saw that a south-west orientation could increase the match between load and generation, and that a tilt of the latitude ± 10° gave the best match between load and generation in residential single-family houses. In addition, they saw that if the load was higher in the winter than in the summer, an increased tilt could be advantageous. Similarly, Mehleri et al. [31] suggested that, if possible, the tilt could be changed between seasons to increase the yearly output.

As previously indicated, not many studies were found regarding the match between load and generation for commercial buildings. However, as Litjens et al. [28] studied PV systems in the Netherlands connected to commercial buildings, which in contrast to residential buildings have relatively high energy demands at noon, they saw that azimuth would preferably face south. In addition, they found that commercial operation could gain from a lower tilt angle, in this case 17°, compared to the optimal tilt for residential buildings (26°) to generate a more even power curve during the day. By optimizing the orientation with regards to a high load-match, SC could increase by 2.7 % compared to maximizing the yearly power output [28].

2.5 Previous design study: Roof based PV system

As described in Section 1.3 there are three commercial areas in southern Sweden which are areas where PV is currently being considered. For this reason 11 load profiles from these areas are available to RISE and will be used as test profiles during the development of the simulation tool for this thesis project. Prior to this thesis project a detailed design study for installation of PV was carried out for one of the buildings in question, with the goal of maximizing the total installed capacity with regards to roof geometry, orientation, and roof top obstacles, which will be referred to as the reference study throughout the report. Simulations for the reference study were made in PVSOL, and the main design result is presented in Table 2.1 [32]. The roof area was not entirely flat but mainly with low inclination, and the final PV system orientation varied between east, south, and west, following the roof. The modules used in reference study were of the type “Sunpower SPR-MAX3-400” with the following data [21], [32]:

- $P_{\text{peak}}$: 400 W
- Height: 1.05 m
- Length: 1.69 m
- Efficiency: 22.6 %
- Temperature coefficient: -0.27 %/°C

<table>
<thead>
<tr>
<th>Installed capacity (kW)</th>
<th>1 260</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly generation (MWh)</td>
<td>1 120</td>
</tr>
<tr>
<td>Roof area used (m²) *</td>
<td>10 600</td>
</tr>
<tr>
<td>GCR (-) **</td>
<td>0.53</td>
</tr>
<tr>
<td>Tilt (°)</td>
<td>10-45</td>
</tr>
<tr>
<td>Azimuth (°)</td>
<td>46-226</td>
</tr>
</tbody>
</table>

Table 2.1 Presentation of relevant results from the reference study. *Area includes inter row spacing. ** GCR was calculated by the author of this thesis project according to Equation 2.10.
\[ GCR = \frac{P_{\text{peak}}/P_{\text{mod}}}{A_{\text{roof}}/A_{\text{mod}}} \]

where

- \( A_{\text{mod}} \) is the active module area (m\(^2\))
- \( A_{\text{roof}} \) is the roof area used (m\(^2\))
- \( P_{\text{mod}} \) is the module power (kW)

The result from the reference study includes hourly simulated values of generation, see example of different weeks during the year in Figure 2.7.

Figure 2.7 Example of generation for four different weeks from the reference study by [32], a) 13-19 March, b) 7-13 July, c) 19-25 September, and d) 25-31 December
3 Method

To simulate multiple PV systems based on the buildings load profiles, a Python based simulation tool with the aid of System Advisor Model (SAM) version 2020.11.29 [33] was developed. The choice of Python is motivated as a necessity to enable integration with the energy simulation tool introduced in Section 1.3. SAM is one of many simulation tools for design of single PV systems, and was selected due to its compatibility with Python, and is used in this thesis project to simulate reasonable values of PV generation as described below. All other calculations are performed through the Python code developed during this thesis project.

During the development, 11 load profiles from southern Sweden (presented in Section 1.3) were used to test and evaluate the simulation tool. The load profiles were selected by convenience as data from commercial facilities were available. The measurements were made in 2019 and 2020 and measured hourly by the grid owner. To handle leap years, the data from 29 February (by orientation optimization) or 31 December (by size calculation) were deleted.

The goals with the simulation tool were to find:
- An optimal orientation for each load profile
- The system size which would result in user defined degree of SC (e.g. 50 %, 70 %, or 90 %), NZC, and maintained maximal transfer capacity
- The size of grid interaction
- The required roof area and to compare that to the actual available area

To achieve these goals, the following simulation steps were identified:
- Orientation optimization
- Simulation of PV system
- Size calculation
- Grid interaction
- Area calculation

3.1 Orientation optimization

As the simulation tool was developed for flat roof installations, a tilt angle limitation was set to 15° according to the mounting standard on flat roofs presented in Section 2.4.2 [22]. Since several studies show that the optimal azimuth angle is about 180° the span of allowed azimuth angles was set between 90° and 270° [18, p. 133], [28].

To optimize the orientation i.e. tilt and azimuth angle, a simulation using clear sky was used, which means solely the solar position was used to optimize tilt and azimuth in relation to the load, based on coordinates and time zone [29]. In order to match load and generation, the hourly output of the clear sky simulation \( P_{AC} \) was compared to the hourly load \( L \), see Equation 3.1.

\[
 r(t) = \frac{P_{AC}(t)}{L(t)} \tag{3.1}
\]

where
- \( P_{AC}(t) \) is the power generated at time \( t \) (kW)
- \( r(t) \) is the ratio between \( P_{AC} \) and \( L \) at time \( t \) (-)
When the instantaneous generation (P<sub>AC</sub>) is greater than the load (L), the ratio is set to 1, which indicates no electricity is bought from the grid, see Equation 3.2.

\[ r(t) > 1 \rightarrow r(t) = 1 \]  

3.2

In order to optimize the orientation parameters, the mean value of \( r \) should be as close to 1 as possible. Therefore, a function using tilt and azimuth angles as input was used to minimize \( f_{\text{load}} \), and thereby find the optimal angles, see Equation 3.3.

\[ f_{\text{load}} = \frac{1}{\text{mean}\{r(t)\}} \]  

3.3

where
\( f_{\text{load}} \) is the optimization ratio (-)

This optimization function needs an initial estimation of tilt and azimuth angles. The tilt angle (\( \alpha \)) was set to 10° which was an arbitrary value within the limits of 0° to 15°. To find a start azimuth angle (\( \beta_{\text{start}} \)), an analysis of the load was made. For the period used in the simulation, a mean day of load was created, for which a normal distribution curve was drawn, see Figure 3.1.

![Figure 3.1 Example of mean day with normal distribution curve to estimate start azimuth angle (\( \beta_{\text{start}} \)).](image)

The maximal value of the curve was set to represent the azimuth angle according to Equation 3.4.

\[ \beta_{\text{start}} = \frac{\mu}{24} \cdot 360 \]  

3.4

where
\( \beta_{\text{start}} \) is the start value of azimuth (°)
\( \mu \) is the time for the normal distribution curve peak (h)

### 3.2 Simulation of PV system

To simulate the P<sub>AC</sub> based on local weather conditions, GCR, and optimized orientation, the simulation software SAM was used. The software has different models dependent on the level
of detail desired. Within the scope of this thesis project, the simplified model PVwatts for commercial owners was used which excludes choice of specific PV module and inverter, external shading e.g. from surrounding trees and buildings, and the possibility to choose the arrangement of PV modules and inverters [23].

As a base for the simulations, a template with start values was created in JavaScript Object Notation (JSON) format, see Table 3.1.

Table 3.1 System design parameters in SAM template, weather data file not shown. *Defined below.

<table>
<thead>
<tr>
<th>Base values</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System parameters</strong></td>
<td></td>
</tr>
<tr>
<td>System capacity (P_{\text{peak, start}})</td>
<td>500 kW (DC)</td>
</tr>
<tr>
<td>Module type</td>
<td>Premium* -</td>
</tr>
<tr>
<td>DC to AC ratio</td>
<td>1.2 -</td>
</tr>
<tr>
<td>Rated inverter size</td>
<td>416.67 kW (AC)</td>
</tr>
<tr>
<td>Inverter efficiency</td>
<td>96 %</td>
</tr>
<tr>
<td><strong>Orientation and tracking</strong></td>
<td></td>
</tr>
<tr>
<td>Array type</td>
<td>Fixed open rack -</td>
</tr>
<tr>
<td>Tilt</td>
<td>20 °</td>
</tr>
<tr>
<td>Azimuth</td>
<td>180 °</td>
</tr>
<tr>
<td>GCR</td>
<td>0.4 -</td>
</tr>
<tr>
<td><strong>Losses</strong></td>
<td></td>
</tr>
<tr>
<td>Total loss</td>
<td>20.95 %</td>
</tr>
<tr>
<td>Soiling</td>
<td>2 %</td>
</tr>
<tr>
<td>Shading</td>
<td>3 %</td>
</tr>
<tr>
<td>Snow</td>
<td>0 %</td>
</tr>
<tr>
<td>Mismatch</td>
<td>2 %</td>
</tr>
<tr>
<td>Wiring</td>
<td>2 %</td>
</tr>
<tr>
<td>Connections</td>
<td>0.5 %</td>
</tr>
<tr>
<td>Light-induced degradation</td>
<td>1.5 %</td>
</tr>
<tr>
<td>Nameplate</td>
<td>1 %</td>
</tr>
<tr>
<td>Age</td>
<td>0 %</td>
</tr>
<tr>
<td>Availability</td>
<td>3 %</td>
</tr>
<tr>
<td>Total system losses</td>
<td>14.08 %</td>
</tr>
</tbody>
</table>

The base values were assigned as follows. An arbitrary value was selected as system capacity, denoted \(P_{\text{peak, start}}\) and the default values were used for the DC to AC ratio, rated inverter size, and inverter efficiency. The module type was set to “premium” which in SAM is defined as a crystalline silicon module with anti-reflective glass coverage and has the following characteristics [23]:

- Efficiency: 20.1 %
- Temperature coefficient: -0.35 %/°C
- Fill factor: 80.1 %

Orientation and tracking input were also kept at their default values in the template but tilt, azimuth, and GCR were changed during simulation by the Python program. Since the PV systems in this thesis project are assumed to be installed on flat roofs, the array type “fixed open rack” was selected as the most suitable option; i.e. the modules are not mounted directly on the roof, and the simulation will include the cooling effect from wind as well as internal shading between the modules [23]. Default values were also applied for the losses. In the model PVwatts for commercial owners there is a financial model included although this was not used in this thesis project. The weather file format included in the SAM template was EnergyPlus Weather
When testing the simulation tool, weather data from a typical meteorological year (TMY) for the local area in question was used from [34] and [35].

3.3 Size calculation

As described above, the size was calculated for different scenarios: user defined degree of SC, NZC, and maintained maximal transfer capacity. During the development process the main degrees of SC simulated were 50 %, 70 %, and 90 %. All size calculations were based on the assumption that there is a linear relationship between system size ($P_{peak}$) and output power ($P_{AC}$) described in Section 2.4.2. From this assumption it follows that a new system size ($P_{peak2}$) can be calculated if one system size ($P_{peak}$) and its AC output ($P_{AC}$) is known as well as the desired AC output ($P_{AC2}$) of the new system, see Equation 3.5, 3.6, and 3.7.

\[
P_{AC} = c \cdot P_{peak} \tag{3.5}
\]

\[
P_{AC2} = c \cdot P_{peak2} \tag{3.6}
\]

\[
\rightarrow P_{peak2} = \frac{P_{AC2} \cdot P_{peak}}{P_{AC}} \tag{3.7}
\]

where

c is a constant (-)

$P_{AC2}$ is the AC output for system 2 (kW)

$P_{peak2}$ is the installed capacity for system 2 (kW)

In the following sections, each system size calculation method is presented based on the definitions shown in Section 2.1, 2.2, and 2.3. The goal of SC and NZC could be limited to a user defined time period, $t_1$ to $t_2$. All system sizes were calculated based on hourly load data and generation data from the 500 kW PV system simulated in SAM.

3.3.1 Self-consumption

The instantaneous SC is defined according to Equation 2.3 and the degree of SC for a certain time period is defined in Equation 2.4 [14]. During the optimization process $P(t)$ was calculated according to Equation 3.8, where $P(t)_{AC}$ was a list of hourly generation limited to the user defined period, simulated by SAM. $n$ was the scaling factor which was optimized by the use of a minimizing function where the SC ($\phi_{sc}$) should be equal to the desired SC ($\phi_{sc,end}$) according to Equation 3.9.

\[
P(t) = P(t)_{AC} \cdot n \tag{3.8}
\]

\[
f_{sc} = abs\{\phi_{sc} - \phi_{sc,end}\} \tag{3.9}
\]

where

$f_{sc}$ is the absolute difference between $\phi_{sc}$ and $\phi_{sc,end}$ (-)

$n$ is the scaling factor (-)

$\phi_{sc,end}$ is the desired degree of SC (-)

As $n$ was found, the calculation of the system size was carried out as shown in Equation 3.10.
\[ P_{\text{peak}} = P_{\text{peak,start}} \cdot n \]  \hspace{1cm} (3.10)

where
\( P_{\text{peak,start}} \) is the start value of the PV system, 500 (kW)

### 3.3.2 Net-zero consumption

The system size for NZC was calculated based on Equation 3.7 performed according to Equation 3.11, where the selected time period was considered.

\[ P_{\text{peak}} = \frac{\sum_{t_1}^{t_2} \{L(t)\} \cdot P_{\text{peak,start}}}{\sum_{t_1}^{t_2} P_{AC}(t)} \]  \hspace{1cm} (3.11)

### 3.3.3 Within existing maximal transfer capacity

The goal of this calculation was to find a system size which did not increase the existing maximum transfer capacity. Unlike the size calculations for SC and NZC, this system size did not consider the user-selected time period but was calculated to stay within the transfer limit for the entire year. The power transferred through the grid connection point was calculated according to Equation 3.12, where \( n \) is the scaling factor found from an iterative optimization process similar to the one used for SC. The maximal transferred power was then calculated according to Equation 3.13 and 3.14. The maximal system size was calculated by usage of Equation 3.10, where \( n \) was found from Equation 3.12, given that \( S_{\text{max}} \) is equal to the maximal power transfer capacity, which is given from the power agreement of the building.

\[ S(t) = P(t)_AC \cdot n - L(t) \]  \hspace{1cm} (3.12)

\[ S(t) < 0 \rightarrow S(t) = 0 \]  \hspace{1cm} (3.13)

\[ S_{\text{max}} = \max \{S(t)\} \]  \hspace{1cm} (3.14)

### 3.4 Grid interaction

The hourly interaction with the grid was calculated during an entire year according to Equation 3.15 and summarized as the total amount of energy exported to the grid for one year, see Equation 3.16.

\[ S(t) = P(t)_AC - L(t) \]  \hspace{1cm} (3.15)

\[ E_{\text{grid}} = \sum_{1}^{8760} S(t) \text{ if } S(t) > 0 \]  \hspace{1cm} (3.16)

where
\( E_{\text{grid}} \) is the total export of electric energy to the grid in one year (kWh)

### 3.5 Area calculation

To enable a comparison between the area of the theoretical PV system and the assumed available roof area, a simplified estimation was made. The PV modules used as size reference was the same as the ones in the reference study [32] with a dimension of 1.69 \cdot 1.05 \text{ m}^2 and a peak power of 0.4 kW [21]. The system area was calculated according to Equation 3.17.
where

\[ A_{\text{syst}} = \frac{P_{\text{peak}}}{P_{\text{mod}}} \cdot \frac{A_{\text{mod}}}{GCR} \]  

18

\[ A_{\text{diff}} = A_{\text{roof}} - A_{\text{syst}} \]  

17

\[ A_{\text{diff}} \] is the difference between \( A_{\text{roof}} \) and \( A_{\text{PV}} \), where negative value indicates lack of space (m²)

The roof areas were measured from maps available at Lantmäteriet [36], a land surveying governmental agency in Sweden, exemplified in Figure 3.2. The roofs were not further evaluated if suitable for PV installations with regards to e.g. inclination, ventilation units or chimneys. When comparing the \( A_{\text{syst}} \) and the roof area, see Equation 3.18, the modules were assumed to fit perfectly on the roof and the orientation of the building was also considered optimal.

3.6 Result comparison to reference

In order to examine the validity of the simulation tool, part of the result was compared with data from the reference study which was performed in detail as described in Section 2.5. As the reference study had a different goal than this thesis project, the result from the simulation tool was scaled to fit a system size of 1 260 kW, the resulting size in the reference study. Following this resize, there was no possibility to compare the system sizes. However, the following parameters were compared:
• Used roof area
• GCR
• Tilt
• Azimuth
• Yearly generation

Used roof area means the area of the PV system which includes row distance. GCR was not calculated in the reference study but to enable a comparison, it was calculated within this thesis project according to Equation 2.10.

Except for a detailed study of the roof and multiple module orientations in the reference study, another difference is the weather file used which was not available for this thesis project. Instead another TMY weather file for the same location was used. To support a fair comparison between the simulation tool and reference study, sunny days were chosen for this purpose. Even though the weather files were different, the total amount of energy generated per year was compared. Since TMY data was used, the files should be similar to each other.
4 Description of Simulation Tool

The aim of the thesis project was to generate a simulation tool which could be used to make an initial simulation during the design process of one or preferable several PV systems. The result is presented in this section.

The simulations are based on hourly load data from the buildings which the user is interested in as well as local weather data. Individual simulations for each building are conducted and generate optimized tilt and azimuth angles, GCR based on tilt angle, calculated system sizes, grid interaction, and area requirements for each scenario.

The simulation tool written in Python is aided by the software SAM as described in Section 3.2. Figure 4.1 provides an overview of the simulation process of the tool. All steps will be further described in the same order as they appear in the program code. A more detailed diagram of the program is presented in Appendix 1.

4.1 Input

Input data to the simulation tool is:

- Hourly load data set
  - Start: 1 January 00.00
  - End: 31 December 23.00
  - Unit: kWh/h
  - Number of measurement points: 8760 (8784 if leap year)

- Location of PV systems
  - Coordinates
  - Time zone
JSON-file generated from SAM which includes:
  - Start values of SAM simulation (see Section 3.2)
  - Local TMY weather file (format EPW)

User choices
  - Time period to simulate (e.g. 1 April to 30 September)
  - Three levels of SC rate (e.g. 50 %, 70 %, and 90 %)

If the load data is measured for a leap year, the data from 29 February is deleted when optimizing orientation and during size calculations, i.e. the first 365 day’s data is used.

4.2 Tilt and azimuth optimization

The optimization of tilt and azimuth angle is based solely on solar position in the sky, which is affected by user input of coordinates, and does not include parameters such as shading from nearby obstacles or weather conditions. For simulation of solar position, the Python package pvlib is used. Optimization of tilt and azimuth is done for each individual load profile added as input to the tool, where an azimuth angle of 180° is defined as south.

As input to the orientation optimization a start value of tilt and azimuth is needed, where the azimuth angle is decided from an analysis of the load data input. The load data is reorganized into an intensity map, see Figure 4.2, where the time of the day is presented on the y-axis and the date on the x-axis. The difference in color represents the amount of electric energy used at a certain time of the year, where white/orange is the highest load and black/purple the lowest.

From the intensity map, a mean value for each time of the day is created and presented as a histogram, see Figure 4.3. A normal distribution curve is added based on the mean day energy distribution and the azimuth angle is calculated according to Equation 3.4, where μ is the peak time for the normal distribution curve; in the example shown in Figure 4.3a this is at 11.49 which results in an azimuth start angle (β_{start}) of 177°. As the time period analyzed can be changed by the user, the intensity map and thereby the mean day graph and β_{start} can vary, see the slight difference between a and b in Figure 4.3. The start value of the tilt angle (α_{start}) is by default set to 10°. The value of P_{peak} for the orientation optimization is also set from the normal distribution curve as the maximal value.
4.3 Ground coverage ratio

To enable simulation of self-shading in SAM, the GCR is calculated based on the optimized tilt angle according to Equation 2.8 and 2.9. As described in Section 2.4.3 the minimal solar inclination angle \( \gamma \) which does not result in internal shading is set to 15°, see Figure 2.6. The value of GCR is exported to SAM for the PV system simulation.

4.4 SAM simulation

In the next step, a simulation of a 500 kW peak power PV system \( (P_{\text{peak,start}}) \) with an optimized orientation and calculated GCR is conducted. The local weather file and values of a number of other system design parameters presented in Section 3.2 are imported by calling a JSON file, which is generated manually in the SAM software. The output of the SAM simulation are hourly values of the AC power output \( (P_{\text{AC}})(\text{kWh/h}) \).

4.5 System size optimization

The returned hourly values of \( P_{\text{AC}} \) act as a base for further calculation in the Python program, where the system size is scaled to fit the requirements described in Section 3; three user defined degrees of SC (0 % to 100 %; Equations 2.3, 2.4, 3.8, 3.9, and 3.10), NZC (Equations 3.5, 3.6, 3.7, and 3.11), and power transfer limited to existing transfer capacity (Equations 3.12, 3.13, and 3.14). The NZC and SC scenarios are calculated for the user defined time period, whereas the scenario for power transfer limitation is calculated for the whole year, since this limit is fixed.

4.6 Grid interaction and area calculation

To indicate the grid interaction for each building, the simulation tool presents the hourly power transfer of the different scenarios as presented in Section 3.4 and calculated according to Equations 3.15 and 3.16 as well as the total yearly energy export (Equation 3.16). Hourly transmission to the grid is also visualized, see Figure 4.4a for full year view and Figure 4.4b for an excerpt of one spring week from the same data. Lastly, the tool presents an estimation of the roof area needed as well as a comparison to the roof area measured from aerial photos as described in Section 3.5.
Figure 4.4 An example of hourly grid interaction graphs, where Figure 4.4a presents 50% yearly SC and Figure 4.4b shows an excerpt of one spring week (13-19 March) from the same data (note that the value on the y-axis differs between a and b). Positive value indicated export to grid and negative value import from grid.

4.7 Output

The output from the simulation tool is optimized orientation, estimation of system sizes, grid interactions, and areas which is exported to an Excel file (Result.xlsx) and the graphs to a folder named Figures. The Excel file contains an overview as well as detailed data. The overview sheet present key values for each of the profiles analyzed, see example in Figure 4.5 and a complete list of the key values in Appendix 2.

![Figure 4.5](image)

Figure 4.5 Screenshot from part of the result overview in the Excel file, presenting main values from the simulations. See a complete list in Appendix 2.

The detailed data is presented individually for each building and contains hourly load, generation, and grid interaction for each scenario to enable further processing of the data. See an excerpt of values in Figure 4.6 for building A, where the data from NZC, 50% of SC, and 70% of SC is visible.
Figure 4.6 Screenshot to show an excerpt of hourly output values for some scenarios from building A.

Some key parameters from the simulation result of the 11 load profiles included as test profiles are presented in Table 4.1 for the full year of 2019, and Table 4.2 for the period of 1 April to 30 September. The reasonability of these values is discussed in Section 6.1.

### Table 4.1 Full year 2019. *Low or no load during periods of the year.*

<table>
<thead>
<tr>
<th>Building</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>I</th>
<th>J *</th>
<th>K</th>
<th>L *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt (°)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>6</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Azimuth (°)</td>
<td>179</td>
<td>172</td>
<td>178</td>
<td>181</td>
<td>177</td>
<td>179</td>
<td>176</td>
<td>179</td>
<td>180</td>
<td>174</td>
<td>173</td>
</tr>
<tr>
<td>GCR (%)</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>73</td>
<td>52</td>
<td>52</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Building</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>I</th>
<th>J *</th>
<th>K</th>
<th>L *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tilt (°)</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>6</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Azimuth (°)</td>
<td>177</td>
<td>163</td>
<td>175</td>
<td>181</td>
<td>174</td>
<td>178</td>
<td>178</td>
<td>179</td>
<td>180</td>
<td>161</td>
<td>185</td>
</tr>
<tr>
<td>GCR (%)</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>52</td>
<td>73</td>
<td>52</td>
<td>60</td>
</tr>
</tbody>
</table>
5 Comparison to Reference Study

The simulation results were compared to the results of the reference study, presented in Section 2.5. As described above, the system size and thereby power output \( P_{AC} \) was rescaled to fit the system size of the reference study. Some key values for comparison are presented in Table 5.1.

Table 5.1 Key result for building E. *Scaled to match reference study. **10\(^\circ\) for east-west installation and 20\(^\circ\) for south installation.

<table>
<thead>
<tr>
<th></th>
<th>Simulation tool</th>
<th>Reference study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed capacity (kW)</td>
<td>1 260*</td>
<td>1 260</td>
</tr>
<tr>
<td>Yearly simulated generation (MWh)</td>
<td>950*</td>
<td>1 120</td>
</tr>
<tr>
<td>GCR</td>
<td>0.52</td>
<td>0.53</td>
</tr>
<tr>
<td>Tilt ((^\circ))</td>
<td>15</td>
<td>10-20**</td>
</tr>
<tr>
<td>Azimuth ((^\circ))</td>
<td>177</td>
<td>46-226</td>
</tr>
</tbody>
</table>

To compare the hourly generation values between the simulation of the tool and the reference study, three sunny days were chosen and presented in Figure 5.1.

![Figure 5.1](image)

Figure 5.1 Examples of sunny days as comparison between hourly generation from simulation tool and the reference study.

As described in Section 3.5 and shown in Figure 3.2, the roof area with which the system area was compared in the simulation tool was measured in a simplified way, where obstacles, etc. were neglected. This area was compared to the roof area of the same building which was found usable in the reference study, see Table 5.2.
Table 5.2 Roof areas measured in a simplified way (simulation tool) and by detailed study of the roof (reference study).

<table>
<thead>
<tr>
<th>Available roof area (m²)</th>
<th>Simulation tool</th>
<th>Reference study</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28 700</td>
<td>10 600</td>
</tr>
</tbody>
</table>
6 Discussion

In this section the results and method of this thesis project will be put into context in order to evaluate if the simulation results are reasonable and simulation tool is usable.

6.1 Results discussion

Findings from the test simulations show that most of the simulated scenarios result in a tilt angle which is as high as possible with the limit of 15° and the azimuth angle is close to 180° for all full year scenarios, a range of 172°-181°, while the azimuth range for summer optimization ranges from 161° to 185°. The full year result is in line with the literature which describes an optimal tilt angle similar to the local latitude angle [18, p. 130], [25], [26], [28] or around 20° for commercial buildings [28], which in this case is higher than the set tilt limit. For the azimuth angle researchers suggest that the optimal azimuth angle for commercial buildings is around 180° [28] but a ± 20° deviation from south does not significantly affect the yearly production [18, p. 133]. Two of the profiles had an optimal azimuth angle of about 160° for the summer period, which deviates from the values found in the literature. Possibly the long summer days enable a greater flexibility to adjust the azimuth angle to match the load. Profile J and L deviated from the others regarding GCR, and J also regarding tilt angle. A possible explanation for this is the low or no load during certain periods of the year.

According to [22] the roof area per installed kW peak is about 10-12 m² for flat roofs, which gives a GCR of about 40 % if each 1.69·1.05 m² module has a P_peak of 0.4 kW. Using the simulation tool, the GCR is calculated to 52 % in most cases, see Table 4.1 and Table 4.2. This means the area of the system would need to be even larger than calculated to achieve 10-12 m² per installed kW peak. The roof area was in most scenarios too small for the installation as presented in Appendix 2. When key parameters of building E were compared to the reference study, only 37 % of the roof area measured (via Lantmäteriet [36]) was in fact useful for PV installations. The assumed area was the greatest difference between the results shown in Table 5.1 and Table 5.2. The yearly simulated generation was 18 % higher for the reference system after P_peak adjustments, which partly could be due to the difference in weather data. GCR was approximately the same between the studies, 52 % versus 53 %, which indicates that a solar inclination angle of 15° for unshaded modules was an acceptable assumption compared to a real installation case. In Figure 5.1 a tendency for a broader generation curve for the reference study can be seen, possibly a result of installations facing both east and west. Otherwise, the generation profiles are similar, except the power peak difference of 22 July where the difference is about 100 kWh/h. Some possible explanations for this are the different weather files used, different inverter efficiencies, or differences between the simulation tools used (SAM in this thesis project and PVSOL in the reference study). The weather data could e.g. include temperature differences. The tilt angles are in general similar between the cases, around 15°, and would thereby not influence the result.

6.2 Method discussion

The input values, simulation choices, and the comparison with the reference study will be discussed below with regards to strengths and weaknesses of the method.

6.2.1 Input

As the base for simulations hourly load profiles were used, the most common way to measure electrical load in buildings. According to [37] the resolution of hourly values (kWh/h) is not enough to receive reliable results of SC when an individual building is studied, which means
the outcome of the developed simulation tool should be seen as an estimation. Error levels of between 0 % and 80 % have been shown by [38] when the resulting SC was compared between time-resolution of 1 minute and 1 hour; and when the load and weather data on minute level had frequent spikes, the error was higher compared to more even load or generation. This is likely to also affect the calculation made for transfer capacity, since this is also in reality based on instantaneous values, and not hourly as assumed in this thesis project. The calculation of NZC, however, should not be affected in the same way regarding the load as it is the energy and not power which is considered in this case. The hourly weather data will however still generate some errors. Although the data resolution could result in misleading values, the use of hourly data increases the usability of the tool since power transmission is normally measured hourly.

In order to always have 8760 load data measurements, data from one day was deleted if the load data came from a leap year (e.g. 2020). For convenience, this was done in two different ways at different places in the code. When the orientation was optimized, 29 February was simply deleted; whereas when the systems were sized, the 365 first days were used. This was considered to have little impact on the result and therefore acceptable.

The roof areas were measured manually via Lantmäteriet’s map service [36], which could lead to some small errors based on how thorough the person measuring the areas is and the complexity of the building’s geometry. The author of this report took three different measurements of a building; if rounded to whole square meters, the result was the same so the risk of measurement errors is probably negligible. During area measurement, no consideration was taken to whether the roof was suitable for PV, e.g. slope, orientation, and obstacles, etc. the effect of which is exemplified in Section 6.2.3 below.

6.2.2 Simulation

For the SAM simulations the simplified version of PVwatts was used as the detail level was considered enough at this stage of the design process; i.e. the choice of exact products, e.g. PV-modules and inverters, or to design of the PV system layout, e.g. number of inverters and arrangement of module strings, was not necessary. When the SAM template was generated, the losses were not changed from default values. Since the tool is not developed for a specific location, this seemed reasonable. However, the tool is developed in Sweden and will probably first and foremost be used here, therefore one can question why the snow losses are set to 0 %. Further work with the simulation tool can be done to examine how snow losses could be included, which according to [19] are generally estimated to less than 10 % but up to 90-100 % during wintertime. To have weather data files which include snow data could be helpful.

The optimization of tilt and azimuth angles was made for clear sky, which means it is assumed that there are on average not more clouds during one period of the day compared to another. The clear sky simulation takes coordinates and time zone into consideration, which both could affect the optimal azimuth angle [18, p. 30]. The maximal transfer capacity was calculated according to Equations 3.12-3.14, which is a simplified safe transfer calculation, where reactive power is not considered.

The calculation of roof area needed for the PV system was simplified and should be seen only as an indication. It was assumed that the PV modules would cover the whole roof in perfect rows with no distance to the roof edges. Following this, the buildings are assumed to be optimally orientated towards the optimal azimuth angle.
6.2.3 Comparison to reference study

The results from the reference study [32] was compared to those using the simulation tool by usage of the same load profile for a single facility in both cases. Since the simulation tool output is only compared with a single detailed study from one facility, this comparison should be seen as an indication of the validity of the simulation tool. Another circumstance which complicates this comparison is the use of different weather data files. The one used in the reference study was not available for this thesis project. Instead another TMY weather file from the same location was used. To enable comparison of hourly generation data, sunny days was selected as demonstration (as shown in Figure 5.1).

The aims of the studies were different, where the reference study focused on installation of as much capacity as possible on the available roof area, whereas the simulation tool simulates systems from the load perspective. To enable a comparison between the systems, the system generated by the tool was scaled to the same size (kW) as in the reference study, which should not affect the result of the comparison as scaling the installed power was the way the systems were sized in the first place.

6.3 Applicability of this thesis project

The aim of this thesis project was to create a tool for estimation of PV systems, which means the tool should be used as a first simulation to obtain an idea of the possibility of several systems in an area. This should then be followed by a detailed study including roof evaluation and other site restrictions before installation. The comparison to the literature and the reference study shows that in multiple ways the simulation tool gives an idea of a future simulation, although the data resolution risks the reliability of the results and the area measurement needs further development to better show the useful roof area. It is however a first step towards simulation of multiple loads together for an aggregated result.

6.4 Future work

This thesis project has resulted in a first version of a simulation tool to estimate system sizes, grid interaction, and area requirements. Further development to simplify the user interface, input as well as output, is already planned as a continuation of this thesis project. One idea is that a user would just mark the building of interest on a map, drag and drop the load data, and the areas would then be measured automatically, and thereafter simulation could be run. A future goal is that the simulation tool of this thesis project could be integrated into an energy simulation tool for urban district planning.

Other possible developments of the tool are to integrate the possibility to optimize the PV systems with modules oriented in two directions, e.g. east and west, which is mentioned as a possible solution for flat roofs [22]. In addition, the possibility of increasing the tilt angle could be investigated further.

The addition of grid simulation and possibly the effect of energy storage and its mitigation effect on transmission would also strengthen the simulation tool.

An important aspect not included in this thesis project is the financial aspect which would be interesting to integrate in the future.
7 Conclusions

The aim of this thesis work was to develop a first version of a simulation tool to estimate system sizes, grid interaction, and area requirements. Based on mainly hourly load and weather data, a Python based simulation tool was written to size PV systems with optimal orientation with regards to high load-match. The program returns hourly values of load, grid interaction, and PV generation, which could be used for further and more detailed calculations. One drawback with the tool is the use of hourly load data, which risks giving a misleading indication of SC and maximal power transfer due to its low resolution. However, hourly load data increase the usability of the tool, since hourly load data is the most common form to register load. The tool can give an indication of the system sizes needed for a certain goal e.g. NZC. When compared to a detailed reference study and the available literature, the optimized orientation and calculated GCR seems reasonable. However, there is a need for adjustments to refine the available roof area assumption, as well as a function to enable east-west oriented modules as an optimization option to match load and generation, since this can possibly result in a wider generation curve which could match the load better and increase the SC. To increase the usage of grid interaction data, a local grid model would be a natural addition to the simulation tool, as well calculations of energy storage to mitigate power transfer.
References


Appendices

Appendix 1. Python code overview

![Diagram of Python code overview]
Appendix 2. Overview of result output

(The values in the table refers to calculations for the entire year. Headings in the left hand column refer to the dimensioning goals)

<table>
<thead>
<tr>
<th>Overview</th>
<th>Time period for dimensioning</th>
<th>2019-01-01</th>
<th>2019-12-31</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Building A</td>
<td>Building B</td>
<td>Building C</td>
</tr>
<tr>
<td>Transfer capacity [kW]</td>
<td>1 300</td>
<td>500</td>
<td>1 125</td>
</tr>
<tr>
<td>Roof area [m²]</td>
<td>14 400</td>
<td>5 500</td>
<td>12 400</td>
</tr>
<tr>
<td>Total load [kWh/year]</td>
<td>5 046 854</td>
<td>819 248</td>
<td>2 902 329</td>
</tr>
<tr>
<td>Tilt [degree]</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Azimuth [degree]</td>
<td>179</td>
<td>172</td>
<td>178</td>
</tr>
<tr>
<td>GCR [%]</td>
<td>52%</td>
<td>52%</td>
<td>52%</td>
</tr>
<tr>
<td>Installed capacity [kW]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>7 625</td>
<td>1 028</td>
<td>3 656</td>
</tr>
<tr>
<td>SC 50 %</td>
<td>5 054</td>
<td>672</td>
<td>2 539</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>3 581</td>
<td>361</td>
<td>1 355</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>1 979</td>
<td>123</td>
<td>388</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>2 275</td>
<td>756</td>
<td>1 710</td>
</tr>
<tr>
<td>Total generation [kWh/year]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>6 046 854</td>
<td>819 248</td>
<td>2 902 329</td>
</tr>
<tr>
<td>SC 50 %</td>
<td>4 808 765</td>
<td>535 450</td>
<td>2 015 235</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>2 840 017</td>
<td>287 436</td>
<td>1 075 306</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>1 569 249</td>
<td>98 115</td>
<td>308 295</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>1 804 950</td>
<td>602 857</td>
<td>1 357 633</td>
</tr>
<tr>
<td>Self-consumption [kWh/year]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>2 557 205</td>
<td>304 683</td>
<td>1 128 246</td>
</tr>
<tr>
<td>SC 50 %</td>
<td>2 404 383</td>
<td>267 725</td>
<td>1 007 618</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>1 988 012</td>
<td>201 205</td>
<td>752 714</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>1 412 324</td>
<td>88 303</td>
<td>277 466</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>1 559 791</td>
<td>278 893</td>
<td>852 829</td>
</tr>
<tr>
<td>Degree of self-consumption [%]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>42%</td>
<td>37%</td>
<td>39%</td>
</tr>
<tr>
<td>SC 50 %</td>
<td>50%</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>70%</td>
<td>70%</td>
<td>70%</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>86%</td>
<td>46%</td>
<td>63%</td>
</tr>
<tr>
<td>Export to grid [kWh/year]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>3 489 649</td>
<td>514 565</td>
<td>1 774 083</td>
</tr>
<tr>
<td>SC 50 %</td>
<td>2 404 382</td>
<td>267 725</td>
<td>1 007 618</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>852 005</td>
<td>86 231</td>
<td>322 592</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>156 925</td>
<td>9 812</td>
<td>30 830</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>245 159</td>
<td>323 964</td>
<td>504 804</td>
</tr>
<tr>
<td>Area system [m²]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>66 345</td>
<td>8 807</td>
<td>31 334</td>
</tr>
<tr>
<td>SC 50 %</td>
<td>51 965</td>
<td>5 756</td>
<td>21 757</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>30 691</td>
<td>3 090</td>
<td>11 609</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>16 958</td>
<td>1 055</td>
<td>3 328</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>19 505</td>
<td>6 481</td>
<td>14 657</td>
</tr>
<tr>
<td>Roof area available [m²]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net-zero</td>
<td>- 50 945</td>
<td>- 3 307</td>
<td>- 18 934</td>
</tr>
<tr>
<td>SC 70 %</td>
<td>- 16 291</td>
<td>2 410</td>
<td>791</td>
</tr>
<tr>
<td>SC 90 %</td>
<td>- 2 558</td>
<td>4 445</td>
<td>9 072</td>
</tr>
<tr>
<td>Transfer capacity</td>
<td>- 5 105</td>
<td>- 981</td>
<td>- 2 257</td>
</tr>
</tbody>
</table>