THE IMPACT OF SHADOWING IN PHOTOVOLTAIC SYSTEMS AND HOW TO MINIMIZE IT

AN ANALYSIS WITH THE PVSYST SOFTWARE

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Abstract
Photovoltaic panels have always been considered one of the main ways to produce electricity from the solar energy, but only recently this technology have seen its importance enlarged. In some places of the world it is already cheaper to produce photovoltaic (PV) energy, compared to using fossil fuel. Much of this is largely a result of the faster deployment of solar PV in China and around the world as well as the policy support from many countries. As a consequence, the installation and production of PV panels have boosted all over the world.

The bigger investment in PV technology brings also more research to help resolving the drawbacks that still exist in this sector, as the shadow problems. Shadowing of PV panels causes mismatch losses that can strongly compromise the power output of a photovoltaic power plant. To minimize this problem some technologies are already available, such as bypass diodes and maximum power point tracking (MPPT) devices as for instance DC-DC optimizers.

This thesis has the aim of showing how the PV sizing program PVsyst works, as well as performing some studies with it, in order to analyze the effect of shadow in PV systems and ways to minimize it. First was tried to understand if the program is having bypass diodes in consideration in the I-V curve calculation. Then was explained step by step how to construct a model to be simulated in PVsyst. The model constructed was for a small system installed in the city of Borlänge (mid Sweden) and had the aim of analyse and see the impact of a chimney and some trees in the yearly energy output of the system.
To finalize, a real situation was simulated for a system in Gävle (mid Sweden). The study was done with and without optimizers, and for different module strings connections (horizontal strings and box strings). The aim was to understand how the optimizers and different connections between the modules reduce the effect of the shadow in the output.

The results show that the program is working properly in the calculation of the I-V curves, apparently having bypass diodes in consideration.

Regarding the study done for the small system it was shown that the reduction in the yearly power output by some shadow objects (chimney and three trees on Northern side or PV panels) was only around 1.2 %, meaning that, for this specific case the shadow impact was not significant.

The results of the case study done on the real system showed that the optimizers play a fundamental role in decreasing the electrical losses due to shadow. However, depending on the system surroundings, the arrangement of the module strings can also help to improve the system output, and sometimes saving money in optimizers.

Keywords: shading, PVsyst, bypass diode, photovoltaic energy, energy output, optimizers, shadowing;
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A friendly word to Diogo Cabral which always gave me his opinion and supported me during this work.
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<th>Description</th>
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<tr>
<td>$I_{sc}$</td>
<td>Short-circuit current</td>
<td>Ampere [A]</td>
</tr>
<tr>
<td>$V_{oc}$</td>
<td>Open circuit voltage</td>
<td>Volt [V]</td>
</tr>
<tr>
<td>$I_{pv}$</td>
<td>Light generated current</td>
<td>Ampere [A]</td>
</tr>
<tr>
<td>$I_{mp}$</td>
<td>Maximum power current</td>
<td>Ampere [A]</td>
</tr>
<tr>
<td>$P_{in}$</td>
<td>Incident power</td>
<td>Watt [W]</td>
</tr>
<tr>
<td>$P_{mpp}$</td>
<td>Maximum power point</td>
<td>Watt [W]</td>
</tr>
<tr>
<td>$V_{mp}$</td>
<td>Maximum power voltage</td>
<td>Volt [V]</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Letters</th>
<th>Description</th>
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<tr>
<td>RES_S</td>
<td>Renewable energy sources</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>FF</td>
<td>Fill factor</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum power point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum power point tracking</td>
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1. Introduction

1.1. Background
Since the oil crises in the 70’s many countries all over the world started to be concerned about their energy sources and the necessity to have a more reliable and secure energy system in order to have a less dependency from the exterior. Moreover, in the last decades, the threat of climate change accentuated even more this preoccupation allowing the construction of important actions shared by the majority of the countries to avoid the continued rise in temperature that the planet faces.
Currently, the majority of the reliable and resilient energy systems are still running with fossil fuels emitting greenhouse gases into the atmosphere which continue the create environmental and health problems. Despite this, renewable energy sources (RESs) have played an important role in order to mitigate the use of fossil fuels. Some of these technologies are now becoming economically sustainable, allowing their proliferation and fortification. It is expected that in 2030 the renewable energies will overtake coal becoming the largest energy source and reach 34 % of the total energy generation in 2040 [1].

1.2. Literature review
Within the RESs, the solar energy has seen its importance increased in the last years. PV technology has the potential of its available source, good visibility and flexible use for small and large scales. By the end of 2016, around 303 GW of photovoltaic panels were installed around the world [2]. The price of PV systems has decreased more than 50% in five years [3] giving strength to some market analysis which predicted that PV installations can reach 25% of the total energy generation by 2050 [4].
Photovoltaic technology still has some drawbacks that prevent the systems to give the maximum output possible. Partial shading is the major source of power reduction in photovoltaic systems where two problems can rise. Firstly, the presence of shadow in module can create multiple power peaks in which only one peak is the global one. This create problems to the conventional maximum power point trackers (MPPT) which can be trapped by their algorithms in the wrong power peak [5].
Another problem that reduce the power output is the power mismatch between series connected PV models. Mismatch losses in array can happen when the specifications of the modules are different or when the series connected modules are receiving different levels of irradiance [6].

Studies done in [7], using Ltspie, have shown that the I-V and P-V curves change depending on the shadow conditions applied in the PV module. The next figure show the modification in the I-V and P-V curve for different shadow percentages in one cell in each bypass circuits of the module. The orange curve corresponds the situation where one cell in the first bypass diode is shaded in 70%, 58% in a cell in the second bypass diode and no shadow in the third bypass diode. Following the same order, the blue curve corresponds to 90% in the first diode, 78% in the second and no shadow in the third. And finally, for the green curve, the respective shading percentages are 80 %, 68% and 0%.

![Figure 1- P-V and I-V curves for different shadow condition in a module [7]](image-url)
1.3. Aims

This thesis has three main aims. In first place, the program PVsyst will be evaluated in relation to its I-V curves calculations, to see if it is performing this curves rightly. After, a pedagogical view of the program will be shown. To do so, the construction of a model will be explained step by step through the program. Finally, will be studied how can the effect of the shadow can be minimized due to the use of optimizers and different connections between the modules.

1.4. Approach

The Approach used in this work was a quantitative one. All this thesis and the various studies were simulated using the PV sizing program PVsyst V6.66. The different situations studied were withdrawn from the program as all the system specifications introduced in the same. All the results as tables, graphs and diagrams, were also withdrawn from the program.
2. Theory

2.1. Solar energy

The earth is bathed by solar radiation, which is responsible by the existing of life in the planet. The solar energy received by the earth is much higher than any other renewable energy source. In fact, the other renewable energy sources as wind energy hydropower and waves came from the planet’s dynamic created by the sun’s energy reaching the planet. Approximately 1 kW (or more precisely 0.865 kW) of solar power reaches each square meter of the earth surface when the sun is directly overhead, assuming that clouds or atmospheric pollutants are not in the path of the solar rays. Although, the value in the top of the atmosphere is 1360 W/m² also known as solar constant [8].

2.1.1. Radiation balance of the Earth

Only about 50% of the incident solar radiation reaches the earth surface where approximately half of it in form of beam radiation and the other half in form of diffuse radiation. Within the other 50% that does not reach the surface, about 25% is absorbed by ozone, water vapor, aerosol particles, clouds etc. and the rest is backscattered into space [9].

![Radiation reduction through atmospheric extinction processes](image)

**Figure 2** – Radiation reduction through atmospheric extinction processes [9]
2.2. Photovoltaic basics

Solar cells, also called Photovoltaics or PVs, offer a way to directly transform solar energy into electricity. Solar cells are based in the photoelectric effect in which light incident in a material creates an electric current. Regarding the construction of a solar cell, the semiconductors materials and p-n junction have a high importance as will be explained in this chapter.

2.2.1. Semiconductors

Solar cells are made of semiconductor materials. These materials behave as conductors when energy is focusing on them and as isolators in other situations. Their conduction properties can be improved by the introduction of impurities into the crystalline structure. This phenomenon is called doping. The basis of the solar cell operation is the existence of two different doped regions in the same crystal which creates a semiconductor junction, the p-n junction.
The most mature technology currently in solar cells production is silicon-based where is included the multicrystalline or polycrystalline silicon and amorphous silicon. Figure 4 represents the different progresses in efficiency for several PV cells technologies. In the last years all the PV cells technologies have seen its performance improved reaching higher efficiencies [10].

Despite the efficiency of a solar cell is of the most importance, the technology must be reliable and cost effective in order to compete with conventional sources. Researches done in wafer, thin film and organic solar cells have help these technologies to become more reliable and cost-effective [11].

Between all the technologies, crystalline silicon is the more successful representing 90% of the global market [12]. Wafer technology can archive higher efficiency values while thin film has less material usage in the manufacture. However, both aspects are important to produce electricity at a low price and increase the market penetration of this technologies.
2.2.2. Generic solar cell operation

A solar cell consists basically in a slab of semiconductor with one or more p-n junctions that can be electrically connected to the outside world through metal contacts on the p and n faces. A p-n junction represents an interface between two types of semiconductors. The p side (positive) represents the semiconductor that contains an excess of “holes” (positive charges) and the n type an excess of electrons (negative charges). This configuration creates an electric field. When light shines in the cells, due to the built-in electric field, the free electrons will flow to the n-side of the junction while the holes go to the p-side generating current and voltage through the metal contacts. This process continues while incident radiation still reaches the cell and as long as a complete circuit is present, i.e., the cell is connected with other cells in series and eventually across a load.

![Typical solar cell](image)

**Figure 5 -** Typical solar cell [8]

2.3. Photovoltaic cell modelling

The term *photovoltaic (PV) performance model* represents a mathematical model that calculates the electrical response of a PV system under operating conditions namely, incident irradiance and cell temperature. There are many models with the aim of simulating the performance of solar cells.
In practice, two types of PV circuit designs are taken into consideration, the single diode PV model and the double diode PV model. These equivalents models define the I-V curve of a cell, module or array as a continuous function for a given combination of operating conditions.

2.3.1. Single diode model

The single diode model is the most widely used model in PV studies [13] and gives generally accurate and reasonable results. Moreover, this model can be applied not only to PV cells but also to modules, strings and arrays operating in uniform conditions. In Figure 6 is represented the single-diode model of a solar cell.

![Real single-diode model of a solar cell](image)

**Figure 6 - Real single-diode model of a solar cell [12]**

This model consists in a current source, $I_{ph}$, a diode saturation current $I_s$, a modified diode ideality factor $n$, a series resistance $R_s$ and a shunt resistance $R_{sh}$. The shunt and series resistance have an important impact in the efficiency of the solar cells [14].

The current equation of the model can be deduced using the Kirchhoff law and is given by equations (1) and (2).

$$I = I_{ph} - I_D - I_{sh}$$

(1)

$$I = I_{ph} - I_s \left( e^{\frac{q(V+IR_s)}{nK_BT}} - 1 \right) - \frac{V + IR_s}{R_{sh}}$$

(2)

$K_b$ represents the Boltzmann constant ($1.38062E - 23 \text{ m}^2\text{Kgs}^2\text{k}^{-1}$), $q$ is electrical charge of an electron ($1.602E - 19 \text{ C}$), $T$ is the absolute temperature of the P-N junction and $V$ is the output voltage.
2.4. I-V curve of a PV cell

The I-V curve of a PV cell, string our array is an important characteristic of this systems. It appears in most of the PV modules datasheets and represents all the possible combinations of current and voltage that a PV module can be operated or loaded according to the existing conditions of irradiance and temperature. Moreover, associated with this curve is often the P-V curve, which gives important data about the performance of the PV module as for instance, the power output.

![I-V curve](image)

**Figure 7 - I-V and P-V curve of a photovoltaic device [14]**

In Figure 7 is represented a typical I-V and P-V curve of a PV device as well as the main parameters which characterizes it.

$I_{sc}$ represents the short-circuit current. Its value corresponds to the current through the solar cell when the voltage across it is zero. Moreover, it increases with the intensity of the light because higher intensity gives more photons and electrons. The short-circuit current can be obtained from equation (2) when V=0.

$$I_{sc} = I_{ph} - I_s \left( e^{\frac{q(I_{sc}R_s)}{n_k R_s T}} - 1 \right) - \frac{I_{Rs}}{R_{sh}}$$  (3)

For an ideal cell, the short-circuit current $I_{sc}$ and the light generated current $I_{pv}$ is similar since there is no resistance affecting its performance.
Based on equation (2), it is also possible to calculate the open-circuit voltage, $V_{oc}$, which represents the maximum voltage available from the solar cell and occurs when the current is zero.

$$V_{oc} = \frac{nK_b T}{q} * \text{Ln} \left( \frac{I_{pv}}{I_s} + 1 \right)$$

(4)

At the “knee” of a normal I-V curve can be found the maximum power point, which corresponds to the point at which the array generates the maximum electrical power. Since the power can be calculated multiplying the current by the voltage, this point represents the higher value of this operation.

In ideal conditions the I-V curve of any PV device would be a rectangle having the higher efficiency possible. However, due to limiting effects such as shunt and series resistance, the efficiency will decrease. The fill factor (FF) is essentially a measure of quality of solar cells. It represents a comparison between the maximum power obtained by the ideal cell and the real one.

![Image showing fill factor](image)

**Figure 8** - The fill factor, defined as the gray area divided by the cross-hatched area [14]

The fill factor is calculated as next.

$$FF = \frac{I_{MP} * V_{MP}}{I_{SC} * V_{oc}}$$

(5)

Notice that, PV modules of the same model under the same conditions should have a similar fill factor. Therefore, the value of the fill factor depends strongly on the module technology.
and design. Usually, amorphous silicon modules have lower fill factors than crystalline silicon modules [15].

The I-V curve itself helps identifying the factors that reduce the maximum output power. Some of those effects are represented in Figure 9 such as shunt and series losses and mismatch losses where is included the shading. The mismatch losses are caused by the interconnection of solar cells or modules which do not have identical properties, due to manufacture imperfections, or which experience different conditions from one another. This is one of the most important problems in solar panels since that sometimes the output of one cell can compromise the output of the whole array.

Currently, the acquisition of PV modules from a reliable manufacturer with high quality control present low mismatch losses [16]. However, shadow is also included in the mismatch effects and cannot be controlled by the producers.

![Figure 9 - Several categories of losses that can reduce the PV output power](image)

A PV module can be considered as a construction of small PV building blocks (solar cells), and an array of PV modules is a construction of various PV modules. The I-V curve of a PV array is a scale-up of the I-V curve of a single cell, as is illustrated in Figure 10. For these cases, the calculation of I-V curve follow a proportional rule of
increasing the voltage in series connected cells (keeping constant the current) and increasing the current for parallel connected cells (keeping constant the voltage).

The efficiency of a PV module is given by equation (6) and represent the division of the module output power by the power of the incident light.

\[
\eta = \frac{FFI_{sc} V_{oc}}{P_{in}} = \frac{I_{mp} V_{mp}}{P_{in}}
\]  

(6)

The power of the incident light is given by the product of the total irradiance measured (\(\frac{W}{m^2}\)) in the module area (\(m^2\)).

2.5. Influence of irradiation and temperature in PV cells

Irradiation and temperature have a strong influence in the PV modules operation and output.

Typically, the efficiency of PV panels is about 10-15% meaning that they convert only 10-15% of the incident power to electricity while the remaining heat is rejected as heat. Besides that, the modules generated their own heat while they are generating power. This

**Figure 10** - Scaling the I-V curve from a PV cell to a PV array [14]
can increase the modules temperature up to 65 °C having as consequence the decrease of the output power [17].

The level of irradiation reaching the PV module is also of most importance in the energy production. Experiments done in a SY-90M monocrystalline module shown that, for every 100 W/m² increase in irradiation, solar cell output power increases by 2.94 W [18] . Moreover, the study also concluded that the efficiency of the solar cell decreases when cell temperature increases. Figure 11 resumes, for the previous study, the effect of temperature and irradiation in the PV system. Since most of the modules are constructed using the same technology this study can be generalized for the rest of the PV modules present in the market.

![Figure 11 – Output module versus module temperature at various irradiation levels [17]](image)

In order to mitigate the effects of modules thermal effects in photovoltaics, water cooling has been considered an attractive solution. In this field, studies carried out in a 5 kW PV power plant showed that, with an optimized water flow cycles, it is possible to increase the PV annual production by 12% reaching 17% of efficiency [19].
2.6. Mismatch losses

One of the drawbacks of photovoltaic systems are the mismatch losses that can occur. Mismatch losses can occur when different PV cells or modules have different electrical characteristics. Shadowing is the more often reason in power losses in PV systems. However, other causes can increase the mismatch losses, as differences in PV modules operation conditions, module damages and differences in manufacture [20].

In the last ten years, the I-V mismatch occurring in PV arrays has dropped. The manufactures of PV modules have decreased the power tolerance from 10% to 3% due to a more refined product manufacture [21]. In other words, photovoltaic technology has become more mature, permitting a more similar and accurate module manufacture, which decreased the mismatch problem that could come from manufactures differences in the modules. However, shadow is more difficult to control since that, sometimes, the PV power plant have to be installed in places with shadowing objects around as trees, chimneys, hills or buildings.

Clouds also have in important impact in the operation of the PV power plants since that, irradiance transitions caused by the edges of the clouds can lead to fluctuations in the output power of the PV systems.

2.6.1. The effect of shading

As said before, the power output of a PV module or array is strongly influenced by partial shading conditions. Clouds passing through the sky, snow, tree shading or buildings can cast shadow on the module and have consequences in the power output of the total array. Studies carried out in Germany showed that shading can compromise the output of a PV system in 20% [22]. Even if only one cell is shaded, the power output of all the string is compromise. This is due to the fact that when a solar cell is shaded, while the others are not, this one will operate as a diode in reverse direction dissipating large power in the shaded cell which results into local overheating (“hotspots”) [23].

The presence of shading in the modules also has an effect in the I-V characteristics of the PV string, creating multiple local maximum power points which increases the probability that the system is not working in the global maximum power point (MPP) [22].
In order to deal with these problems, currently most of the modules have bypass diodes installed. However, in order to have the maximum power output, MPPT (Maximum power point tracking) techniques emerged as a potential solution such as DC-DC optimizers and micro-inverters. The use of these devices can help the system recovering between 10% and 30% of the total output loss during one year [24].

2.6.2. Bypass diodes
In order to mitigate the effects of shading, bypass diodes (BPD) are currently the most often technology installed in the PV modules. Usually BPD is connected in parallel to strings of 15-24 cells preventing the shaded cells from reaching junction breakdown [25]. BDPs are connect in parallel but with opposite polarity as can be observed in Figure 13. In case the module is operating without shadow the BPD will not conduct current (reserve biased) and the whole cells are operating in forward biased. However, when a cell is reversed biased due to mismatch in short-circuit current between several series connected cells, the bypass diode will conduct allowing the current from the unshaded cells to flow in the external circuit [7]. When this happen, the I-V curve of the module or system change, occurring a reduction of the current produced. This current reduction and consequently

Figure 12 - I-V and P-V curve for an unshaded module (left) and for a module with 75% of one cell shaded (right) [6]
turning on of the bypass diode depends on the percentage of shaded area in a PV cell while is independent of the number of shaded cells [26].

Usually a PV module has 60/72 bypass diodes. In case one BPD is activated, one third of the cells and their power will be bypassed, meaning that they will not contribute for the final current of the system. This effect is shown in the next figure.

Figure 13 - PV module with one shaded cell which results in the bypass of one string of 20 cells [23]

Despite being an effective way to reduce the power loss due shading, bypass diodes can heat up significantly during its operation due to the high current of today’s cells, leading to a degradation of the diode and the module. However, a new generation of BPDs led to an increase of shading tolerance of convention solar modules [25].

2.6.3. Module inverters

An important step for the greater use of PV systems has been the inverters invented in the early 1980s. These devices convert the variable DC (Direct current) power from the PV modules or arrays in AC (alternating current) power, which is the one that flow in most electrical grids. These electronic devices have special functions adapted for use in photovoltaic arrays as maximum power point tracking.
There are two typologies of inverters, string and micro-inverters. Traditionally string inverters were used in PV systems. In this case, the modules are linked in series and an inverter is connected to the string as in Figure 14.

![Figure 14 – String inverter system](image)

The previous solution for the position of the inverter represents a good option in case there is no shadow in the modules. However, due to mismatch effect in series connection modules, in case of shading, the inverter condition the output of the array accordingly to the modules that are shadowed.

In this case, a good solution is the installation of micro-inverters connected to each one of the modules where the AC/DC conversion is done in each module. This solution reduces the mismatch losses between modules since the shadings only impacts individual modules. Besides, if one optimizers fail, only the correspondent module stops producing instead of all the system [28].

Figure 15 represents a scheme of six modules with three module inverters, each one connected with two modules.
2.6.4. DC-DC optimizers

DC-DC optimizers are electronic devices which allow each PV module to independently operate at its maximum power output providing a fine-grained control over the PV module voltages and currents [29].

When a PV system consist in modules connected in series, the current of all the string need to be the same. In case one or more module are shadowed, their corresponding DC-DC optimizer compensate the change in the current with the expense of changing the voltage. This way the current value of the string is not compromise [27].

DC-DC optimizers combine the benefits of module MPPT of micro inverters with the higher operating efficiencies of string inverters.
2.7. The PVsyst

PVsyst is a PV system sizing program recognized by its trustworthiness in the photovoltaic field.

It contains a variety of parameters and irradiation data related with many parts of the world as well as a vast gallery of photovoltaic components provided by the manufactures.
Moreover, the program has a wide range of digital aids for climate database, components database and data measured which helps facilitate the analysis of the system behavior.

It allows a system design in different levels [30]:

- **Pre-sized level** where is made a quick study about the dimensions of the system and its components as well. The program also gives an evaluation of the system production;
- **Design level** where is made a more detailed study. This option is more complete than the previous one since involves a choice of meteorological data, system design, shading studies, loss determination and economic evaluation;
- **Database level** where a more an accurate study is done accessing the program databases and change them if necessary.
3. Method and process

After having done the theory research needed in order to comprehend the background for this thesis is now time to discuss how the final results will be calculated and how all the thesis will be processed.

3.1. Validation of the program I-V curves for different shading conditions

In order to understand if the program is performed right the I-V curves, a small system was designed and simulated under different shadow conditions on the PV panels. A simple 3D draw of how the system is positioned is shown in the next figure.

![3D draw of the system studied. Source: PVsyst](image)

**Figure 18 –** 3D draw of the system studied. Source: PVsyst

The system is constituted by 12 photovoltaic modules connected in series, installed in a roof with a 25° tilt. The chosen inclination for the system did not followed a specific rule since this parameter is not important for the aim of this study. The simulation was performed for Borlänge, Sweden. Again, the localization of the system is not important for the results expected in this study, however, to make the simulation a localization has to be introduced.
The study was performed using one of the generic photovoltaic module present in the program databases, as well as the inverter. Next table present the most important characteristic of the selected module.

Table 1 – Module specifications in STC conditions (1000 W/m², 25 °C)

<table>
<thead>
<tr>
<th>Type of module</th>
<th>Monocrystalline silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal power [Wp]</td>
<td>250.0</td>
</tr>
<tr>
<td>Short-circuit current $I_{sc}$ [A]</td>
<td>8.630</td>
</tr>
<tr>
<td>Maximum power current $I_{mp}$ [A]</td>
<td>8.140</td>
</tr>
<tr>
<td>Open circuit voltage $V_{oc}$ [V]</td>
<td>37.40</td>
</tr>
<tr>
<td>Maximum power voltage $V_{mp}$ [V]</td>
<td>30.70</td>
</tr>
<tr>
<td>Number of cells</td>
<td>60</td>
</tr>
<tr>
<td>Module dimensions (LxWxH) [mm]</td>
<td>1640x992x50</td>
</tr>
<tr>
<td>Number of bypass diodes</td>
<td>3</td>
</tr>
</tbody>
</table>

The module I-V curve for different irradiation conditions is shown next.

Figure 19 – I-V curve for the module chosen for different irradiance conditions. Source: PVsyst
As said before, in order to see if the program is working correctly, different shadowing conditions were applied in the modules. The different shadows applied were chosen in order to understand if the program is having the presence of the by-pass diodes in consideration.

The different case studies performed in PVsyst are represented in the next pictures.

**Figure 20** - Case 1.1 (No shadow in the modules)

**Figure 21** - Case 1.2 (One row of modules shadowed)

**Figure 22** - Case 1.3 (One row of modules and 1 row of cells shadowed)
3.2. Effect of the shadow in the system output

After analyze if the program is calculating the I-V curves properly, is now important to see the effect of the shadow in the yearly power output of a PV system.

To see the effect of the shadow in the modules two simulations were performed, one with shading objects (chimney and some trees) and other without them. Is also important to mention that all the surrounding around the system were considered as flat terrain and without any houses close.
The system simulated was located in Borlänge, Sweden. The aim was to have the results for the city of Gävle. However, since no trustworthy meteorological data was included in the program database for Gävle, Borlänge was the nearest location possible with reliable data.

In order to give a more pedagogical explanation of how the program works, for this study will be shown step by step how the simulation is performed as well as how the program calculates the final results.

The first step in PVsyst is decide the type of project to be simulated. The program offers many options. The preliminary design calculates gross estimations for a PV system but is not suitable if the aim is to perform accurate study. To perform more accurate studies, the option should be “Project design” which does a full-feature study and analysis of a project.

This study was done as a grid-connect one.

**Figure 26 - Main panel of PVsyst**

The next figure show the project main window. Here, firstly, is possible to decide the name of the project, the location and input the metrological data from the program databases.
The next step is defining the orientation of the system. In this case, the system is headed south and had an inclination of 25º. Notice that the azimuth is related with the system orientation. In the north hemisphere, south correspond to 0º.
In the next picture can be seen the choices made for the system to be simulated. This step is mainly to choose the modules, optimizers and inverters for the system.

![Figure 29 - System overview to be performed. Source: PVsyst](image)

In this simulation were used ten modules with the same specifications as in the previous study (Table 1). Regarding the inverter, the one selected was the adequate for the system, this is, one that meets the electrical properties of the system and is not undersized or oversized.

The section “detailed losses” in Figure 27 was not changed since the program calculated automatically the detailed PV field losses.

The next step was the definition of the surroundings of the system. First, the far shadings were defined. This option allows the treating of the shadings when the objects are sufficiently far (more than ten times the PV field size). In this case, was considered the terrain as flat.
After the far shadings, the near shadings need to be defined. Next figure show the program window related with the near shading.

**Figure 30** - Far shading definition. Source: PVsyst

**Figure 31** - Near shading window. Source: PVsyst
In this step is necessary to decide how the shadings will be taken into account in the calculations.

The best option is the “detailed, according to module layout”, which computes the shadings having into account the detailed electrical losses of the system.

The next step is the construction of the three-dimensional global scene. This is done in a 3D editor included in the program.

Next picture show the 3D editor as well as the scene already designed for the study.

![Figure 32 - 3D editor of PVsyst. Source: PVsyst](image)

The general 3D overview of the system with and without shadow objects can be seen in Figure 33 and Figure 34.
The two different situations studied were the next:

- 2.1. Roof with 25º tilt with shadow;
- 2.2. Roof with 25º tilt without shadow;
So far, was explained the steps in the program until the construction of the 3D model. Next will be explained how is the program calculating the effect of the shadow in the system as well as all the steps it passes until reach the final output result.

In Figure 27 is possible to found an option called “module layout” which take the user to the next program window.

![Figure 27 - Definition of the module layout. Source: PVsyst](image)

Is in the previous program window the connection between the modules is chosen as well is possible to simulate the position of the shadow in the PV array for all the days of the year and all the hours. Moreover, for each shadow condition the I-V and P-V curve can also be extracted. In the discussion and results chapter, some I-V and P-V curves will be shown as well as the respective shadow condition in the PV array.

Since one of the most important issues of this thesis is the effect of shadow, now will be explained how PVsyst calculates the electrical losses due to shadow.

- The shading calculation is applied to each corner of each sub-module. The corner can be shaded or not;
- For each sub-module, the irradiance shading factor and the I-V characteristics is calculated.
• After, the IV characteristics of all the sub-modules (shaded and not shaded) are added in voltage (series connection). This is done for each string;
• The IV characteristic of all strings is added in current (parallel connection) and the I-V curve is then performed. Is important to remember that this operation can create multiple maximum power points;
• After, the inverter will search the maximum power point on the I-V curve;
• The shading losses is evaluated for this maximum power point with respect to the maximum power when the modules are not shaded. The total losses are then the sum of the irradiance deficit and the electrical mismatch losses that correspond to $P_{mpp}(\text{unshaded}) - P_{loss}(\text{irradiance}) - P_{mpp}(\text{shaded})$;

The final energy output of the system can be calculated with the help of a loss diagram, that provided a quick and insight view into the quality of a PV system by identifying the main source of losses. This diagram appears in the final report of the simulation and is represented in the next figure.

![Losses diagram in the final report of PVsyst](image)

**Figure 36** - Losses diagram in the final report of PVsyst. Source: PVsyst

Giving a quick view of the diagram is important to explain some important topics:
• The IAM factor on global corresponds to the decrease of irradiance really reaching the PV cells. It is due to the reflexions on the glass cover;
• The PV losses due to irradiance and temperature are also important. As explained in the theory chapter these parameters have an influence in the output of the system.
• The “mismatch losses, modules and strings” is related with the normal small differences between the modules, even if they are fabricated in the same way.
• The “array virtual energy at MPP” is the DC (Direct current) energy, i.e, before the inverter converts it to AC (alternate current).
• The last topics in the diagram are related with the inverter.

3.3. Minimization of shadow impact with optimizers and different module connections – case study

After explain all the program steps and how it calculates the final results as well as the impact of the shadow, a real situation was studied with PVsyst. The system is in the city of Gävle included in a complex of new buildings as is possible to see in the next figure.
The system is composed by 63 modules and is placed in a roof with 30° tilt and is headed south east, which corresponds to an azimuth of -45°. In order to see the impact of the surrounding buildings and how they could be minimized using optimizers and different module string connections, four simulation were performed to this system.

- 4.1. Horizontal strings of 21 modules with optimizers;
- 4.2. Horizontal strings of 21 modules without optimizers;
- 4.3. Boxes strings of 21 modules with optimizers;
- 4.4. Boxes strings of 21 modules without optimizers;

The different module connection can be seen in Figure 38 and Figure 39.

**Figure 38** - Horizontal strings of 21 modules

**Figure 39** - Box strings of 21 modules

Since it was not possible to know exactly which modules were installed, the simulation was performed using generic 250 Watt peak monocrystalline modules with 60 cells. The next picture show the composition of all the system.
Notice that in the simulations with optimizers, each module had one optimizer connected, having the system 21 optimizers in total.

The next figure show a 3D draw of the system and the surroundings.

**Figure 40** - System composition overview. Source: PVsyst

**Figure 41** - 3D view of the system surroundings
In the discussion and results chapter will be shown, for some hours of the day, pictures of the array *in loco* where the system is shaded. These will be compared with the program results in order to help understand if the program is calculating the position of the shadow in the array in the right way. Regarding this, is important to mention that the buildings measures as the height, length and width were not taken with an accurate procedure. This can create some changes between the program calculation and what happens in reality.

4. Results and discussion

4.1. Validation of I-V curves

As said in the methodology chapter, the first part of this thesis has the aim of evaluate if the program is calculating the I-V curves properly. Six different case studies were performed and next the results obtained will be shown. Firstly, all the I-V curve will be shown and afterword’s some important points will be discussed.

- Case 1.1 – Modules without shadow

![Figure 42 - I-V curve for case 1.1](image)

- Case 1.2. One row of modules shadowed;
- Case 1.3. One row of modules and one row of cells;

Figure 43 - I-V curve for case 1.2

Figure 44 - I-V curve for case 1.3
• Case 1.4. One row of cells in 6 modules;

Figure 45 - I-V curve for case 1.4

• Case 1.5. One row of cells in 12 modules;

Figure 46 - I-V curve for case 1.5
• Case 1.6. All the modules shaded;

![Figure 47 - I-V curve for case 1.6](image)

The behave of the I-V curve strongly depends in the module area that is shaded. In order to minimize that effects most of the PV panels have bypass diodes installed. Having this in consideration and knowing the behave of the module I-V curve from the factory specifications (Figure 19) and how the I-V curve is constructed (Figure 10), is possible to analyze the previous figures and understand if the program is calculating right the I-V curves.

Starting with case 1.1, as can be seen from Figure 42, the I-V curve of the system behaves as it should. Notice that the global irradiation reaching the panels is about 988 W/m$^2$ which is close to 1 kW/m$^2$. Since any shadow exists in the modules, and knowing that they are connected in series, the short circuit current must be the same as in Figure 19 which is around 8.7 A. Moreover, the $V_{oc}$ must be equal to the $V_{oc}$ of one module multiplied by the number of modules which will be around 420 Volt. Despite the behave of the current is the one expected, the same did not happen to the open circuit voltage which was lower than...
expected. This happened in all the cases meaning that some calculation made by the program might be wrong in the point.

Regarding case 1.6, the I-V curve given by the program is represented in Figure 47. In this case, since all the modules are shaded, the system output is close to be zero. The small current produced by the array is due to the diffuse radiation. Moreover, was not possible to set up the shadow touching the PV panels meaning that some distance had to be given in order to the program make the calculations. That distance allowed some diffuse irradiance to reach the system and create current.

Case 1.2 (Figure 43) and Case 1.4 (Figure 45) have the same I-V curve. This was expected since that, in both cases, at least one row of cells is shaded. The bypass diodes will then be activated and will conduct current.

When comparing Figure 46 (Case 1.5) and Figure 47 (Case 1.6), many similarities can be found. In fact, that means that the program is having the bypass diodes in consideration when performing the calculations. Notice that, in case 1.5 (Figure 46) the first row of cells is shaded in all the modules. In a system point of view, that means that all the bypass diodes are conducting current, as it happens when all the modules are shaded. Again, the current is not zero because the program is having the diffuse radiation in consideration.

4.2. Effect of shadow in the system output

Firstly, in the next table is possible to see all the results from the PVsyst regarding the power output for all the different situations studied (2.1 to 2.2).

<table>
<thead>
<tr>
<th>Case 2.1(with shadow)</th>
<th>Case 2.2 (without shadow)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy output (kWh)</td>
<td>Energy output (kWh)</td>
</tr>
<tr>
<td><strong>January</strong></td>
<td></td>
</tr>
<tr>
<td>50.6</td>
<td>50.7</td>
</tr>
<tr>
<td><strong>February</strong></td>
<td></td>
</tr>
<tr>
<td>126.7</td>
<td>126.9</td>
</tr>
<tr>
<td><strong>March</strong></td>
<td></td>
</tr>
<tr>
<td>232.7</td>
<td>234.6</td>
</tr>
<tr>
<td><strong>April</strong></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>304.2</td>
</tr>
<tr>
<td><strong>May</strong></td>
<td></td>
</tr>
<tr>
<td>365.5</td>
<td>370.9</td>
</tr>
</tbody>
</table>
This study had preferably the intention of explaining how the PVsyst is working and go through the different steps to construct the model. However, both simulations were performed and the results are in the previous table.

Regarding the two simulations done for this case, the impact of the shadow created by the chimney and the trees did not have a strong impact, being the difference between the power output of 1.2%.

Next is showed, for a specific time of the day, an example of the disposition of the shadow in the PV array as well as the corresponding I-V and P-V curves.

**Figure 48 -** Position of the shadow in the PV array for a specific time of the day
Figure 49 - System I-V curve with respect to the shadow condition in Figure 48

Figure 50 - System P-V curve with respect to the shadow condition in Figure 48

The impact of the shadow in the panels have a strong impact in the I-V curve of the system. Most of the modules are shadowed which strongly reduces the current output from the system as can be seen in the Figure 49. In the figure, the blue line represents the I-V curve when the system is not shadowed.
Since the power is given by the multiplication of the current by the voltage, the respective P-V curve (Figure 50) has multiple power peaks but only one is the real one. One of the inverters function is discover this power peak.

In appendix A are some more examples of I-V and P-V curves as well as the respectively shadow disposition in the array.

4.3. Minimization of shadow impact with optimizers and different module connections – case study

The simulation results for the real system are present next. In first place the program calculates the array nominal energy. This value is the same for all the simulations and in the next table.

**Table 3 - Fixed results to all the simulations**

<table>
<thead>
<tr>
<th></th>
<th>15.75 (0.250 kWp × 63 modules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System power (kWp)</td>
<td></td>
</tr>
<tr>
<td>Area of panels (m²)</td>
<td>102</td>
</tr>
<tr>
<td>Efficiency of one panel (%)</td>
<td>15.75</td>
</tr>
<tr>
<td>Global horizontal irradiation</td>
<td>932</td>
</tr>
<tr>
<td>(kWh/m².year)</td>
<td></td>
</tr>
<tr>
<td>Irradiation in the plane of the modules (kWh/m².year)</td>
<td>1083 (1.162 × 932)</td>
</tr>
<tr>
<td>Irradiation in the plane of the modules after shadow (kWh/m².year)</td>
<td>874 [1148 × (1 − 0.193)]</td>
</tr>
<tr>
<td>Effective irradiation after reflection losses (kWh/m².year)</td>
<td>848 [912 × (1 − 0.03)]</td>
</tr>
<tr>
<td>Array nominal energy (kWh/year)</td>
<td>13316 (886 × 102 × 0.154)</td>
</tr>
</tbody>
</table>

The final results, including the electrical losses due to shadow are next.

106692-
### Table 4 - Variable results for the simulations

<table>
<thead>
<tr>
<th>Simulations</th>
<th>Array nominal energy (MWh)</th>
<th>Electrical losses due to shading (%)</th>
<th>DC production (MWh)</th>
<th>To grid (MWh)</th>
<th>Specific production (kWh/kWp.year)</th>
<th>PR</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1. Horizontal strings With optimizers</td>
<td>13.32</td>
<td>1.9 %</td>
<td>12.22</td>
<td>11.82</td>
<td>751</td>
<td>751/1083 = 0.693</td>
</tr>
<tr>
<td>4.2 Horizontal strings Without optimizers</td>
<td>13.32</td>
<td>8.6 %</td>
<td>11.44</td>
<td>10.20</td>
<td>648</td>
<td>648/1083 = 0.598</td>
</tr>
<tr>
<td>4.3 Box strings With optimizers</td>
<td>13.32</td>
<td>2.5%</td>
<td>12.15</td>
<td>11.75</td>
<td>746</td>
<td>746/1083 = 0.689</td>
</tr>
<tr>
<td>4.4 Box strings Without optimizers</td>
<td>13.32</td>
<td>6.2 %</td>
<td>11.70</td>
<td>11.30</td>
<td>718</td>
<td>718/1083 = 0.663</td>
</tr>
<tr>
<td>4.5 With optimizers without shading buildings</td>
<td>16.42</td>
<td>0 %</td>
<td>15.46</td>
<td>14.98</td>
<td>951</td>
<td>951/1083 = 0.878</td>
</tr>
<tr>
<td>4.6 Without optimizers and without shading buildings</td>
<td>16.42</td>
<td>0 %</td>
<td>15.50</td>
<td>14.18</td>
<td>900</td>
<td>900/1083 = 0.831</td>
</tr>
</tbody>
</table>

2.88/
The results from Table 4 show that the array nominal energy is the same for all the simulations, 13.32 MWh. Notice that the array nominal energy comes from Table 3 and represents the irradiance that actually reaches the cells of the modules.

The electrical losses due to shadow were lower for the simulations with optimizers as was expected. The optimizers are devices that allow each module to work at its maximum power point, minimizing the shadow effect in the final output. The benefit with the use of optimizers can also be confirmed in simulation 4.1 and 4.3 where, both for horizontal strings or boxes strings, the energy output into the grid do not change much being 11.82 MWh for case 4.1 and 11.75 MWh for case 4.3.

The system production is higher in simulation 4.4 than in 4.2 which means that, if no optimizers are installed, in order to increase the system output, the best option is to connect the modules in box strings. This is related with how the shadow moves in the array. For this case, the mismatch losses for each string is higher when the modules are connected in horizontal strings.

Lastly, the program calculated the performance ratio (PR) which represents the global system efficiency with respect with the total installed power. As can be seen between the two cases without optimizers the best option is the one with box strings. In the other hand, if the system has optimizers the best option is horizontal strings. However, the difference between simulation 4.1 e 4.3 is not significant, 0.693 for horizontal strings and 0.689 for boxes strings.

Despite the optimizers most of the times improve the system performance, they may not be necessary, which allow money savings. Instead, a better string distribution can do the same effect. As an example, the performance ratio of simulation 4.1 and 4.4 are relatively close but the system with optimizers is costlier than the one without them.

To conclude, in order to evaluate if the program is calculating the position of the shadow in a right way, in appendix 2 is possible to see three pictures in loco of the array as well as
the respectively situations simulated by the program. Observing the figures, we realize that the reality and corresponding simulation do not match. This is probably due to the fact that the buildings measures (length, width and height) were estimated in an approximate way which creates displacements between the simulation and the reality.

For the cases without the shading buildings, both the option (with or without optimizers) have higher production values comparing with the other ones. However, again, the use of optimizers always is always better. The difference between this two cases with the other is that the system receives all the irradiation possible on the modules.
5. Conclusions

5.1. Study results

This thesis had the aim of analyze the impact of the shadow in photovoltaic systems as well as explain how PVsyst works. Moreover, the impact of the use of optimizers and different module connection were studied in order to see how it help minimizing the impact of shadow in PV systems.

After analyzing the I-V curve gave by the program, was possible to conclude that, despite some small differences, the program is performing rightly the calculations and having the bypass diodes in consideration.

Regarding the study done with the small system for the city of Gävle, was possible to conclude that the impact of the chimney in the system is almost negligible (around 1%).

To conclude, the study done for the real situation shown that the use of optimizers is of the most importance in decreasing the impact of the electrical losses due to shadow. Besides, the string connections between the modules can also strongly influence the power output of the system and, for some situations, help save money by not installing optimizers. For the situation studied, the best option was 4.1 (horizontal strings with optimizers) which had the higher performance ratio, 0.685.

5.2. Outlook

PVsyst is a powerful toll for sizing photovoltaic systems. In this thesis, only a small part of what the program can do was applied. For instance, the study simulated for the real system was done as the system was connected with grid connected. Could be interesting the study was the system would work for a stand-alone system with batteries. Other ways of including the inverters in the PV array could also be analyzed in order to make money saving. Moreover, the program can also make an economical evaluation for the system which was not done in this thesis.
Trusty wordy explications of how the optimizers affect the system performance were not studied, opening a space to study if the program simulated well the impact of optimizers. The results could be compared with other ones from a different simulation tool.

To conclude, PVsyst has a large range of options for the installation of photovoltaic systems and many studies can be performed related with technical and economic issues.

5.3. Perspectives

Due to the fast decrease of the prices in photovoltaic market and the maturity of the technology, photovoltaic energy has increase its presence and influence in the renewable energy sector. More countries have been investing in alternatives to fossil fuels in order to become more energetic and economically independent. Moreover, the climate change problem has strengthened this necessity.

Solar sector play an important role in this transition and have seen its technology integrated in small scale systems, as in our houses, in large scale as big power plants. Besides that, PV system can strongly help sub-developed countries to get access to energy which is of the most importance nowadays.

Because of the reasons mentioned before, is important to keep investing in improvements and research in the photovoltaic sector.
6. References


7. Appendices

7.1. Appendix A

**Figure 51** - Example 1 of the shadow in the PV array

**Figure 52** - Corresponding I-V and P-V curves for example 1 (Figure 51)
Figure 53 - Example 2 of the shadow in the PV array

Figure 54 - Corresponding I-V and P-V curves for example 2 (Figure 53)
Figure 55 - Example 3 of the shadow in the PV array

Figure 56 - Corresponding I-V and P-V curves for example 2 (Figure 55)
7.2. Appendix B

**Figure 57** – Position of the shadow (21 of May at 9h19 (normal hour))

**Figure 58** – Position of the shadow simulated by PVsyst (21 of May at 9h15 (normal hour))
Figure 59 - Position of the shadow (21 of May at 16h14(normal hour))

Figure 60 - Position of the shadow simulated by PVsyst (21 of May at 16h15(normal hour))
Figure 61 – Position of the shadow (21 of May at 13h43(normal hour))

Figure 62 - Position of the shadow simulated by PVsyst (21 of May at 13h45(normal hour))