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Faculteit Industriële Ingenieurswetenschappen

master in de industriële wetenschappen: energie

Masterthesis

Optimization of photovoltaic generation for the buildings at the Montilivi campus of the University of Girona

PROMOTOR :

Prof. dr. ir. Wilmar MARTINEZ

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Pieter-Jan Hermans

Scriptie ingediend tot het behalen van de graad van master in de industriële wetenschappen: energie

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Preface

During my four years of education within the joint study of engineering technology at UHasselt & KU Leuven, I learned a lot about the challenges and difficulties within the energy sector. Before starting this program, I was already interested in science and technology. But during the program, my interest in renewable energy only increased. Because of this, I wanted to do my master thesis on something related to renewable energy. The University of Girona allowed me to design a PV installation and make a complete analysis of all the possibilities of the PV installation.

This master thesis was undoubtedly the biggest challenge of my school career. The thesis has taught me a lot, not only on the theoretical aspect but also the communication with supervisors and solving unforeseen problems were important competencies that I have gained in making this master thesis. This master's thesis would not have been possible without the support of several people whom I would like to thank.

Firstly, I have to thank Professor Lino Montoro for his supervision and support in the creation of my master's thesis. I also want to thank Prof. Dr. Lino Montoro because he was always there for me, and I could go to him with all my problems. I also thank Prof. Dr. Ir. Wilmar Martinez for the support of the master thesis and the knowledge and inspiration I have gained during the lessons "Power Electronics". Moreover, I want to thank Prof. Dr. Jeroen Lievens for the supporting material for the report.

I also have to thank my parents, brother, friends, and family for the support and advice I received from them during the entire course. In particular, I thank my mother Nathalie for her constant support throughout my school career.

Finally, I would like to thank you, the reader, for your interest in viewing my work.

Pieter-Jan Hermans,

07/06/2022

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Abstract

The Montilivi campus of the University of Girona is equipped with a 20-year-old photovoltaic installation consisting of 96 solar panels (BP4160). It has been found that the installation is operating with a low efficiency and that it generates a very limited supply of energy (17373 kWh/year) while the Montilivi campus consumes a total of 4565493 kWh/year. This master's thesis focuses on modeling the most economical and efficient solar panel installations for the twelve buildings on the campus.

Using the PVGIS software, additional data were collected on the panel output power during one year in Girona. This data allowed different simulations to optimize the PV installation for each building on the campus using the Sunny Design software. These simulations resulted in a reliable model for each building, based on reliable sources, datasheets, supplier prices, and calculations.

The calculations show that the new panels are most efficient when they are oriented towards the south with an inclination of 36°. In addition, data from PVGIS shows that inverters with a lower capacity (±13%) than the installed capacity are allowed for each configuration. Based on these simulations, installations that use the SPR-MAX3-400 panel achieve the best results environmentally. While installations that use the JKM390M-6RL3-B panel achieve the best results economically in the long term and installations that use the VERTEX PERC panel achieve the best results economically in the short term.

Abstract in Dutch

De Montilivi-campus van de universiteit van Girona is uitgerust met een 20 jaar oude fotovoltaïsche installatie bestaande uit 96 zonnepanelen (BP4160). Gebleken is dat de installatie met een laag rendement werkt en dat zij een zeer beperkte hoeveelheid energie opwekt (17373 kWh/jaar) terwijl de Montilivi-campus in totaal 4565493 kWh/jaar verbruikt. Deze masterproef richt zich op het modelleren van de meest economische en efficiënte zonnepaneelinstallaties voor de twaalf gebouwen op de campus.

Met behulp van de PVGIS-software werden extra gegevens verzameld over het geleverde vermogen van de panelen gedurende een jaar in Girona. Met deze gegevens konden verschillende simulaties uitgevoerd worden om een PV-installatie voor elk gebouw op de campus te optimaliseren met behulp van de Sunny Design software. Uit deze simulaties volgde een betrouwbaar model voor elk gebouw, dat zich fundeert op betrouwbare bronnen, datasheets, prijzen van leveranciers en berekeningen.

De berekeningen tonen aan dat de nieuwe panelen het efficiëntst zijn als ze naar het zuiden gericht worden met een hellingshoek van 36°. Daarnaast blijkt uit de data van PVGIS dat voor iedere configuratie geopteerd kan worden voor omvormers met een lager vermogen (±13%) dan het geïnstalleerd vermogen. Uit de simulaties volgt dat de installaties met het SPR-MAX3-400 paneel het milieuvriendelijkst zijn terwijl installaties met het JKM390M-6RL3-B paneel op lange en het VERTEX PERC paneel op korte termijn het meest economisch zijn.

1 Introduction

1.1 Context

This master's thesis is conducted in cooperation with the University of Girona within the "Superior Polytechnic School" faculty. The University of Girona is situated in the province of Catalonia in the north of Spain. The school is currently located on the Montilivi Campus and consists of 4 buildings. The university does a lot of research in various fields. In total, they have 12 research institutions [1] and university staff in 24 departments [2] and 107 research teams (49 in the humanities and social sciences and 58 in science, technology, and health fields) [3].

One of the many research groups within the university conducts research in renewable energy. The research that is been done can take out various forms. One of the most important things that are being researched in this research group is how the efficiency of a solar panel can be improved. This is done by carrying out various experimental tests on a solar panel set up in the lab. But also various measurements are regularly taken to see how efficient and economical a solar panel is after several years.

There are many elements to consider when building a PV installation. The most important parameters to consider are the technology of the solar cells to convert solar energy to electric power (in DC), the direction and inclination of the solar panel, the support structure for mounting the solar panels, the type of inverter, how it is technologically constructed and, finally, the type of cabling used. In addition to this, batteries can be connected to a PV system. This makes it possible to store energy and use it later. Moreover, the battery can connect to the solar panel in an AC or DC way (see Figure 1 and Figure 2) [4]. Depending on whether the battery is connected in AC or DC, the connection will differ. These parameters significantly influence the efficiency and how economic the PV installation will be during the following years. Figure 3 gives an overview of the elements used in a regular PV installation.

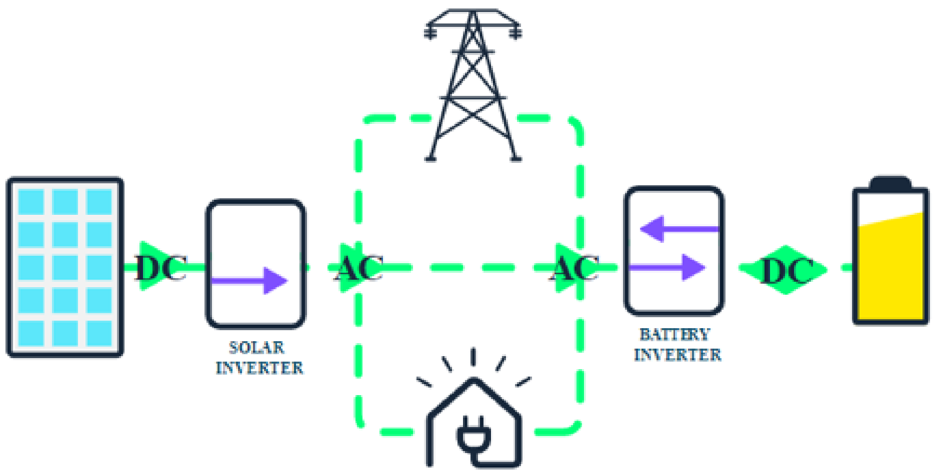


Figure 1: Example of an AC-coupled system [4]

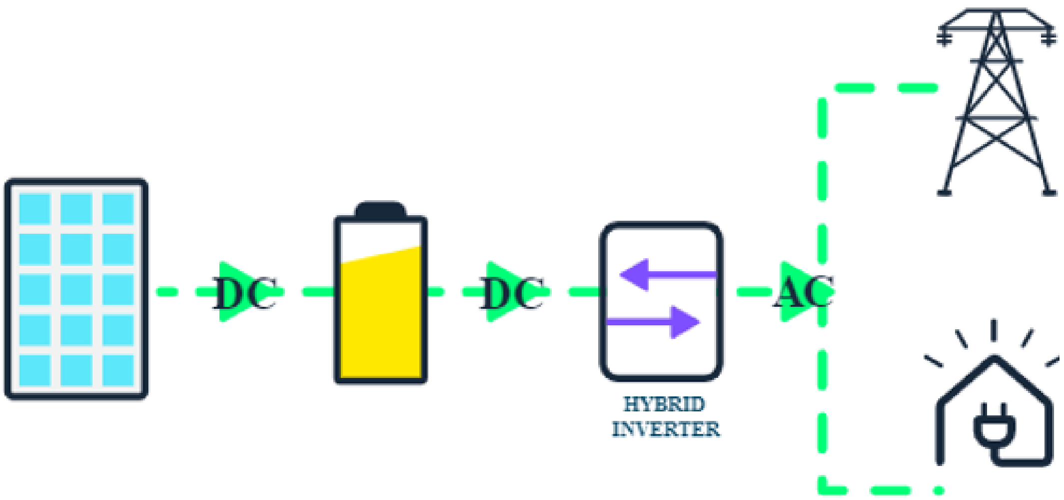


Figure 2: Example DC-coupled system [4]

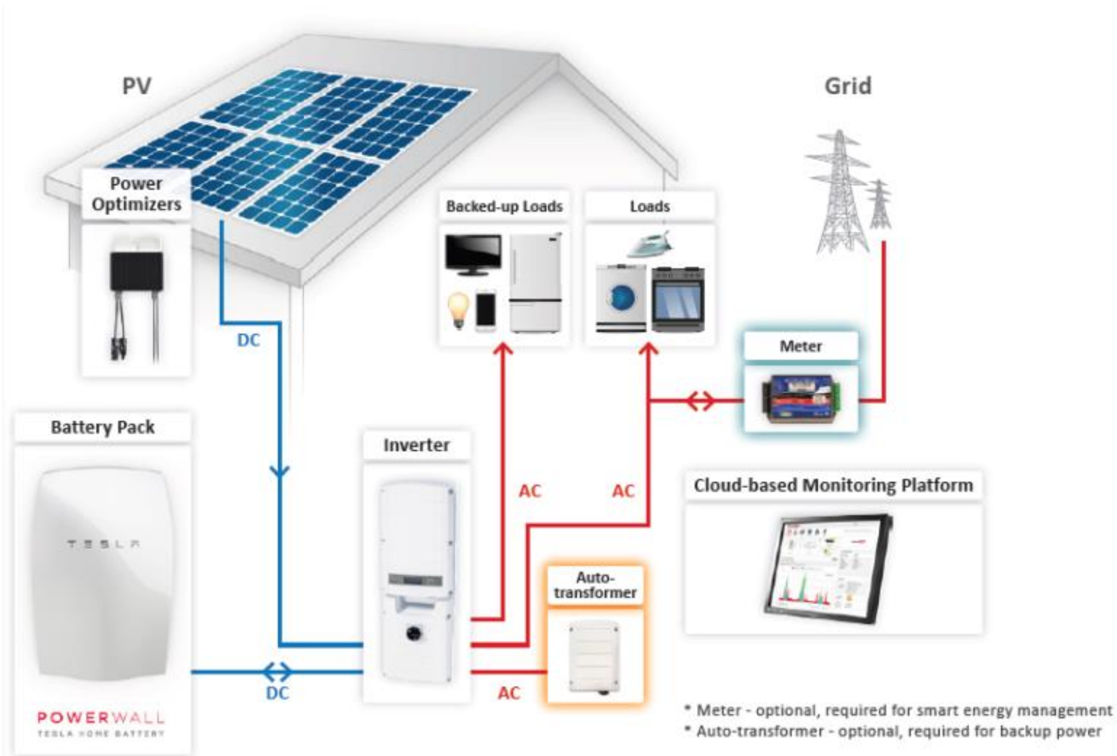


Figure 3: Overview of a regular PV installation [5]

Due to the high number of components in a PV installation, a roadmap will be developed in this thesis to create the most efficient PV installation. This roadmap is integrally applied at the Montilivi campus in Girona and is useful for larger companies. In addition, this thesis examines how solar panels can be applied in other ways on the Montilivi campus. This shows interested parties whether or not it is a good choice to use solar panels differently at this moment.

1.2 Problem statement / Research question

The Montilivi campus of the University of Girona has two problems with its photovoltaic generation. The first problem is that it has been established that based on 12 new solar panels, the 20-year-old installations consisting of 96 solar panels are operating with low efficiency (±30%). Due to this, the University must optimize its photovoltaic generation. The second problem is that there is a limited supply of photovoltaic generation on the campus. This results in an environmentally unfriendly campus and the economic benefit of the solar panels is not used.

The research question of this master's thesis is: "What is the most optimal PV plant design for the campus for the Montilivi campus of the University of Girona?". Today, the University of Girona mainly uses electricity generated from the grid. A large part of this grid electricity is generated from non-renewable energy sources. Moreover, it is known that the consumption of non-renewable energy sources is detrimental to the climate. This is because CO2 gases are released which cause the earth to warm up. Figure 4 shows a graph demonstrating global warming.

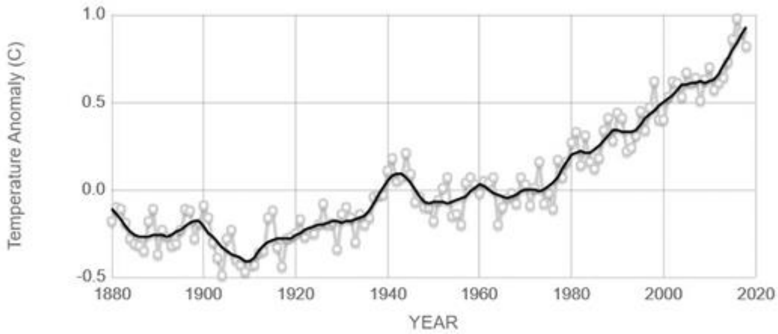


Figure 4: Temperature anomaly over the last decades [6]

The research question includes some sub-problems.

The first problem is the question of which brand of solar panel to choose for the 12 different buildings on the campus. Here, various considerations must be made in terms of economics, output power, and CO2 reduction.

The second problem is investigating which inverter configuration will give the highest output power for the different PV systems based on price.

The third problem is the DC wiring of the systems. The DC cabling of a PV system entails a lot of requirements in terms of safety, maximum short-circuit current, and maximum voltage, ...

In addition, an economic analysis of the various PV configurations is made. The problem of possible surplus electricity is examined. The electricity can be supplied to the grid or stored in batteries for later use. Which of these two possibilities is the most responsible choice needs further investigation.

Finally, opportunities that can increase the number of solar panels and the efficiency of a PV installation are discussed. A problem that occurs throughout the years is the decrease in the efficiency of solar panels. Two of the main causes for the lower efficiency of the solar module are a high operating temperature and the presence of dirt. Disregarding this problem, the solar module will never operate at full capacity during its production years.

1.3 Objectives

The main objective of the master thesis consists of designing a PV installation that will supply the Montilivi campus with electricity as efficiently and economically as possible. In addition to the main objective, the master's thesis also aims to move towards a more environmentally friendly campus.

Certain conditions must be met to bring this project to a successful conclusion. The first thing is to design the various PV installations in such a way that the solar panels operate as efficiently as possible. Different parameters are necessary, such as the orientation, the tilt angle, and the distance between the panels. Secondly, an inverter configuration is selected for each installation which converts the generated power as efficiently as possible. To achieve this, different types of inverters are compared, but also the strings are determined correctly. In addition, it is necessary to select the right cabling for the panels and inverters. Calculating the minimum cross-section and cable length allows the cabling to be selected. As a fourth point to realize the project, it is necessary to consider whether or not a battery system is appropriate. Furthermore, an economic analysis is made for each installation. Various economic parameters such as investment cost, electricity production costs for 20 years, IRR, payback period, and total savings after 20 years are studied to choose the most economical and efficient installation.

Finally, to reach the main objective of the thesis, some opportunities are discussed to increase the efficiency and photovoltaic generation on the campus. The thesis discusses one possibility that can improve efficiency, which is a cooling system. To achieve more photovoltaic generation, the effect of building-integrated PV and a solar charging station is studied.

1.4 Methods

This master thesis is conducted using various simulation/software tools. In the first phase of the project, a code is created using Python that predicts the positions of the sun during a whole year in Girona. With this code, it is possible to determine the correct placement of the solar panel.

The application of the PVGIS and Sunny Design software allows the development of a model for the optimal configuration of a PV installation on the Montilivi campus. The PVGIS software shows additional data providing information about the maximum power that each PV installation can generate. Based on this data, the appropriate inverter configuration is selected for each installation. Furthermore, Sunny Design allows determining the ideal configuration (solar panels, strings, inverters, and energy management) for each installation. Sunny Design also displays the output characteristics of the system and its profitability. In addition, Sunny Design provides a visual presentation of the different PV installations.

Besides using these simulation tools, a lot of research is also done. This research work is necessary to gain more insight into the properties of different solar panels, inverters, cables, support structures, and batteries. However, in some situations, the calculations are also based on known literature.

1.5 Contents

To solve the problem statement and objectives of this thesis, this master's thesis is divided into four major parts. First, there is the literature study in chapter 2. Here, cases are analyzed that can provide possible solutions to the problem statement of the thesis. Then chapter 3 describes step-by-step how to model the most economical and efficient PV installations for the Montilivi campus. In addition, Chapter 4 focuses on some additional possibilities in terms of PV installations for the Montilivi campus. Finally, in chapter 5 conclusions of this thesis are taken and what should be considered in future work.

2 Literature study

2.1 Introduction

To solve the research question, it is essential to have underlying information about the problem/research. This section summarizes the most relevant information needed to solve the problem in a verified way. First, different elements of a PV installation are reviewed in-depth to gain insight into how to install a PV installation most optimally. Then, the efficiency of a PV installation and how this can increase are discussed. Finally, the difference between the various solar panel specifications is discussed.

There are several things to consider when designing a PV installation. First, the choice of a good solar panel and inverter is essential for the optimal operation of the PV installation. Secondly, the number of components required to develop the PV installation must be considered. In addition, it is necessary to consider where the solar panels can be placed and how they should be connected. It is also relevant to consider how energy is produced most efficiently. Finally, it is worth considering how the cost of the installation can be determined [7].

2.2 Components

In this section, the main components of a PV installation are presented. These were briefly mentioned in section 1.1, but in this part, there will be a closer look at the usefulness and functioning of each component in more detail.

2.2.1 PV panels

Solar panels generate electricity under the influence of sunlight. The number of photovoltaic solar cells depends on the size of the panel. These are typically small plates with a small surface area and thickness. Most photovoltaic panels consist of a silicon cell layer, a glass shell, a metal frame, and various wires to conduct the current from the silicon cells. Once light begins to interact with a silicon cell, it sets electrons in motion, creating a current of electricity. This phenomenon is known as the "photovoltaic effect ", and it characterizes the overall functionality of PV panel technology [8]. Typically, the cells are connected in series so that the generated direct current can travel from cell to cell and panel to panel [9].

The electricity generation process can be classified into three steps [8]:

- the silicon photovoltaic cell absorbs solar light
- as sunlight reacts with the silicon cell, electrons start to move, generating an electric current
- wires collect this direct current and carry it to an inverter to be transformed into alternating current

Every photovoltaic module has different properties and a large part of the properties of a solar panel are indicated using the I-V curves. Several quantities of the solar panel are in the I-V curve. For example, it allows reading the short-circuit current I_{sc}. This is the current that flows through the panel at a voltage of 0V across the panel. A second quantity that can be derived out of the I-V curve is the open-circuit voltage V_{oc}. This voltage is the voltage across a panel the moment the current through the panel is 0A. Also, it allows the determination of the maximum power point (MPP) from the panel. The MPP is the point where the panel produces the most power at a given current I_{mpp} and voltage V_{mpp} [7]. Figure 5 illustrates an example of an I-V curve.

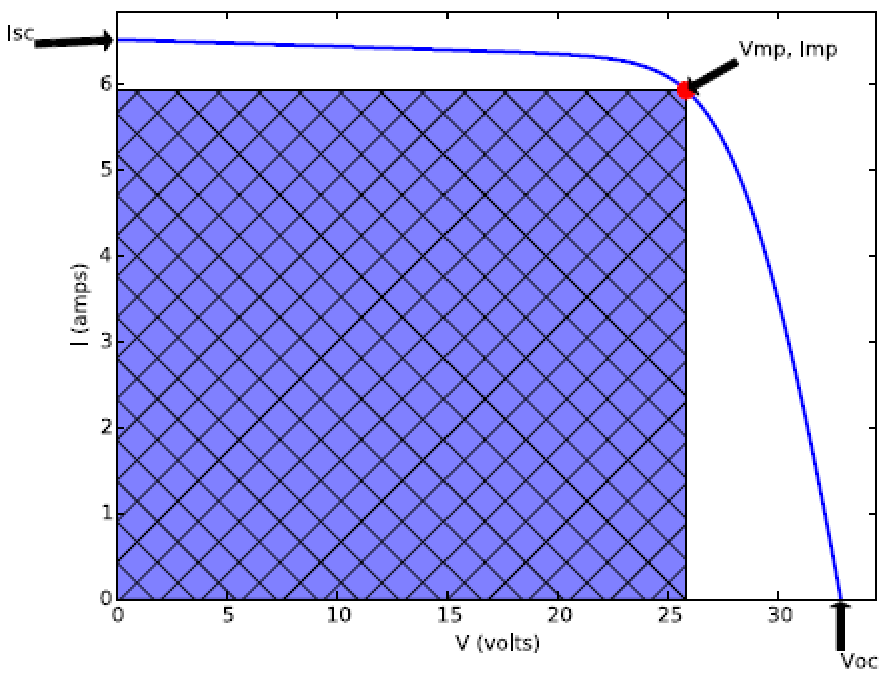


Figure 5: Example of an I-V curve of a PV panel [7, p. 5]

2.2.2 PV inverters

The inverters serve to transform the direct current produced from the PV panels into a usable AC current. This allows it to feed into either local or commercial electrical power grids. There are three categories of inverter setups, which differ significantly from one another.

Microinverters:

Each panel is individually equipped with an inverter in this type of inverter. The direct to alternating current conversion takes place at the microinverter itself, located behind the panel. The major advantage of the micro-inverter is that if one panel performs less (shadow), the other panels maintain their efficiency. A disadvantage, however, is that the installation of a separate inverter for every panel is often prohibitively expensive [7].

String inverters:

In this type of inverter configuration, a single inverter is used to transform the power of an array of panels. Each inverter has one or more maximum power point trackers (MPPT) and ensures that the panels can achieve their maximum output. This MPPT will adjust the current so that the maximum instantaneous power of the system can be produced, depending on the irradiation on each panel [7]. Another advantage of a string inverter is that this type of inverter is the cheapest compared to the other inverters. Financially, this inverter is the most interesting. The disadvantage of a string inverter, on the other hand, is that the yield can drop dramatically as a result of one panel catching shade. For this reason, the panels that receive the shadow at the same time can be placed on a separate circuit from the panels that get the full sun [9].

DC optimizers:

A DC optimizer configuration uses power electronics installed on every panel to maximize the power generated by any string by regulating the voltage across every panel individually. These power electronics mounted on every panel are less expensive in comparison to those found in micro-inverters while achieving approximately the same efficiency. Although they are more economical than a micro-inverter, DC optimizers are a still more expensive option than a string inverter [7].

2.2.3 Other components

Now that the power has been converted from DC to AC power, the AC power can be connected to various devices within the building. One of the components is the electricity meter. The electricity meter registers consumption. Depending on the energy yield and energy consumption, the value (kWh) of the meter will increase or decrease. Thus, the energy gain of the PV installation is directly integrated into the energy consumption [9]. It sometimes happens that the PV installation generates more energy than is consumed in the home. In this case, surplus power is supplied to the grid or can also be stored in a battery. As discussed in section 1.1, there are two possible ways to store the DC power generated by a solar panel in a battery.

2.3 Optimization for the entire PV installation

Since the main objective of the thesis is to design a PV installation, it is important to search in the literature on how a PV installation can be dimensioned as efficiently and well as possible. There is no single solution available to dimension a PV installation, but by taking into account some factors, the dimensioning can improve enormously. First, the effect of shade is examined and what influence this has on the PV installation. Then a comparison between monofacial and bifacial solar panels is made. After this, the installation design of solar modules for optimal energy generation is discussed. Finally, the parameters that have to be considered when selecting the inverter are briefly discussed.

2.3.1 The effect of shadow

Distance between the rows

Shade affects the efficiency of a solar panel. Solar panels in the shadow will not be able to work at full capacity. This implies that the efficiency of the PV installation will decrease. To prevent this, it is important to look at the effect of shadow. Figure 6 shows the quantities that are important to assess the effect of shade.

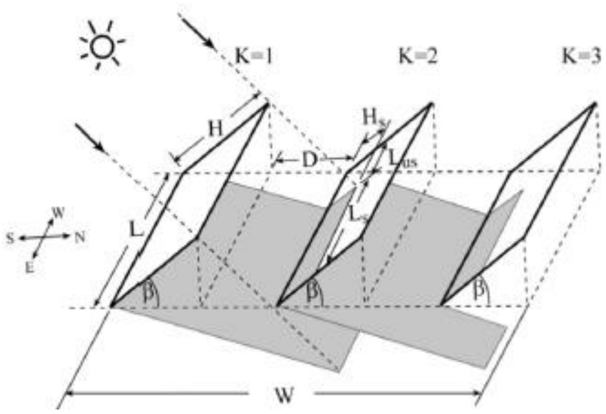


Figure 6: Dimensions related to the shading of a solar panel [10, p. 2]

Distance D is the distance between two solar panels. With constant height H and angle β, the influence of distance D on the incident radiation on the panel can be determined. Figure 7 shows in percent the change of the direct beam, global, and diffuse incident radiation in the second line compared to the first line of solar panels without shade. The difference between these three radiations is that diffuse radiation is referring to the radiation received from the sun after changing its direction by scattering from the atmosphere. Beam radiation is the solar radiation absorbed by the sun without being scattered by the atmosphere. Finally, global radiation is the complete shortwave radiation from the sky that falls on a horizontal surface of the earth. This covers both diffuse radiation and solar radiation due to scattered or reflected sunlight [11].

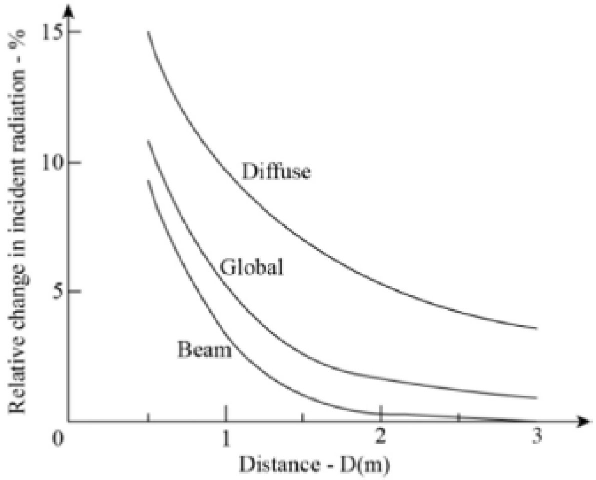


Figure 7: Relative change in incident radiation compared with the first unshaded row where D is a variable [10, p. 3]

From this figure, there can be concluded that when row 2 is placed closer to row 1, the radiation of row 2 decreases compared to row 1. Especially the diffuse radiation changes enormously when parameter D is changed [10].

With constant distance D and angle β, the effect of the height H on the incident radiation from the panel can be seen. Figure 8 shows this relationship.

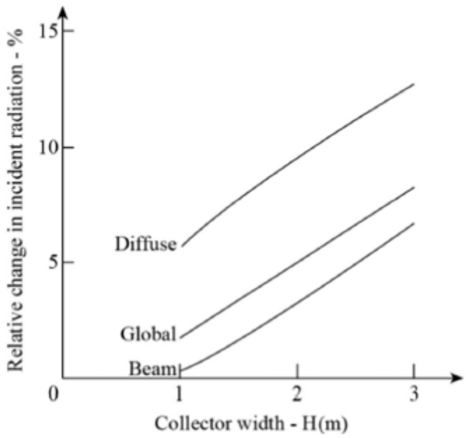


Figure 8: Relative change in incident radiation compared with the first unshaded row where H is a variable [10, p. 3]

From this figure, it can be concluded that when the height of the solar panel increases, the incident radiation on the second row of solar panels is reduced in comparison to the first row of solar panels. Here also diffuse irradiation has a more significant role [10].

The influence of the quantities D and H can also be linked to the maximum annual incident energy. Results indicate that the maximum energy is achieved if the distance D leans to the smallest possible values (which increases the number of rows K) while the height H of the solar panels is as high as possible. The benefit in incident energy of adding extra solar panels cancels the mutual shading losses caused by placing the rows closer together [10].

Also, for a certain amount of annual incident energy, the quantities D and H can be examined to see in which situation a minimum surface area for the PV installation can be obtained. The analysis shows that the minimal area is achieved when the distance D is as small as possible and the height H of the solar panels as large as possible [10].

The use of larger or smaller solar panels and the placing of panels closer or further apart have their advantages and disadvantages. Depending on the space available on and around the building and on the desired energy yield, the solar panels should be placed further or closer together. However, there must always be considered what is economically most interesting.

However, there is a limit to how close the rows of solar panels can be placed together. On a flat roof, it would be possible to place the panels so close together that there would be no space between them. This is not possible because the panels must also be able to be maintained. So there must always be a passageway between the rows [12].

Dust and shadow

Dirt on the solar module means that the solar module will not operate at full capacity (see Influence of dust). This dirt also causes shadow spots to appear on the solar module. As a result, some PV modules will stop working and the energy produced by PV modules not subject to shade will be blocked. This leads to the heating of the shadowy cell and the formation of a hot spot, which can eventually damage the circuit (see Figure 9).

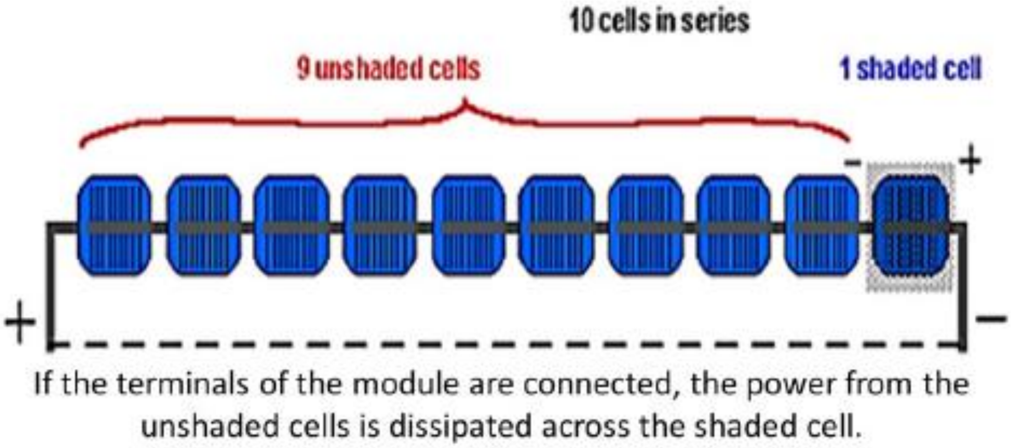


Figure 9: Flow of the current over the shaded cell [13, p. 2]

To avoid this problem, a possible solution is to use a bypass diode. A bypass diode will bypass the shaded cell. The current will flow around the shaded cell. Figure 10 shows this working principle.

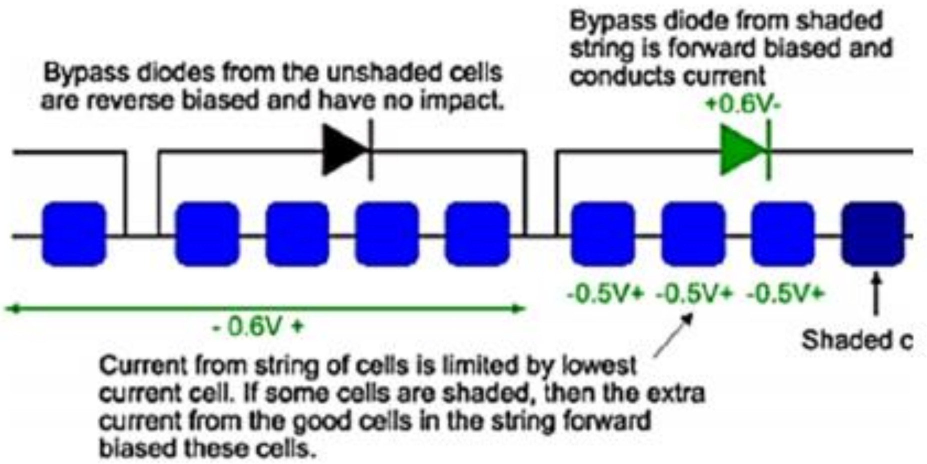


Figure 10: A bypass diode to avoid hot spots in PV modulus [13, p. 3]

2.3.2 Monofacial vs bifacial solar panel

Monofacial and bifacial solar panels are two different versions of how a solar panel can be made. A PV installation can be designed using either monofacial or bifacial solar panels and it is therefore interesting to find out which of these two types of panels is the most interesting to install. By comparing the advantages and disadvantages of both types of solar panels, it is important to know how these solar panels are constructed. Figure 11 shows the operating principle of both panels.

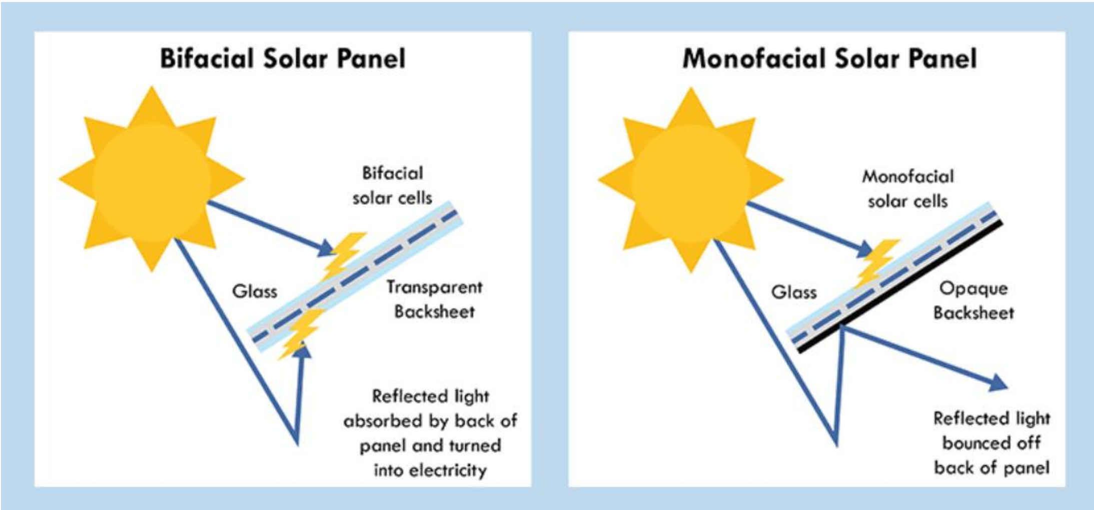


Figure 11: Difference between a bifacial and monofacial solar panel [14]

This figure shows that bifacial solar panels can capture light rays from both the front and the backside of the panel. By replacing the backside of a monofacial panel with a transparent back sheet, reflections allow the diffuse light to reach the backside of the module and produce energy. By optimizing the amount of power generated by the back of the module, the shadow created by obstacles such as the panel's racking system should be reduced.

How cost-effective monofacial and bifacial solar panels depend on several factors. These factors are the latitude, the albedo value (which is a value between 0 and 1 that indicates how much incident radiation is absorbed [15]), and how the systems are implemented. The first possible implementation is any module orientation (AMO). Here, any value can be assumed for the surface area and tilt of the solar panel. The second possible implementation is the vertical module orientation (VMO). This orientation is only used for bifacial solar panels where the tilt is 90° and the surface area can be chosen arbitrarily.

The main conclusions of the paper [16] are:

- monofacil AMO designs are generally less cost-effective than bifacial AMO designs for latitudes above 40°. For altitudes below 40°, monofacial AMO designs are more economical. However, if albedo values are kept to a minimum between 0,12 and 0,30, bifacial AMO designs can be more cost-effective
- monofacial AMO designs are less cost-effective than bifacial VMO designs at latitudes greater than 65°. However, at altitudes below 65°, the LCOE of bifacial VMO designs can be lower than monofacial AMO designs if the albedo value is kept between 0,29 and 0,57
- in terms of AMO designs, monofacial systems produce up to 12% less energy than bifacial systems for latitudes below 65°. For altitudes higher than 65°, AMO monofacial systems produce up to 71% less power than AMO bifacial systems. VMO bifacial systems generate less power than AMO monofacial systems (up to -23%) for latitudes below 65°. At higher altitudes, VMO bifacial systems generate more energy than monofacial systems (up to 71%)

As follows from the conclusions of the paper [16], bifacial systems have some advantages over monofacial systems. However, there are also some disadvantages [14]:

- bifacial systems cannot be installed like a typical roof-mounted system that lies flat against the roof. Some space is required between the back of the panels and the surface below to allow the reflected light to reach them
- the row spacing between panels must be specifically configured to prevent shadows from blocking the light at the bottom of the panel
- bifacial systems are best placed on surfaces with a high albedo value, whereas this does not matter for monofacial systems
- it can sometimes be difficult to find a solar company that installs bifacial solar panels in the vicinity

2.3.3 Alignment of a PV installation

There are various ways in which a PV installation can be aligned. There are four possible alignment scenarios. Some systems are not aligned, vertical, horizontal, and fully aligned. Depending on the alignment scenario, the efficiency of the PV installation will differ. Figure 12 shows what this alignment looks like in reality.

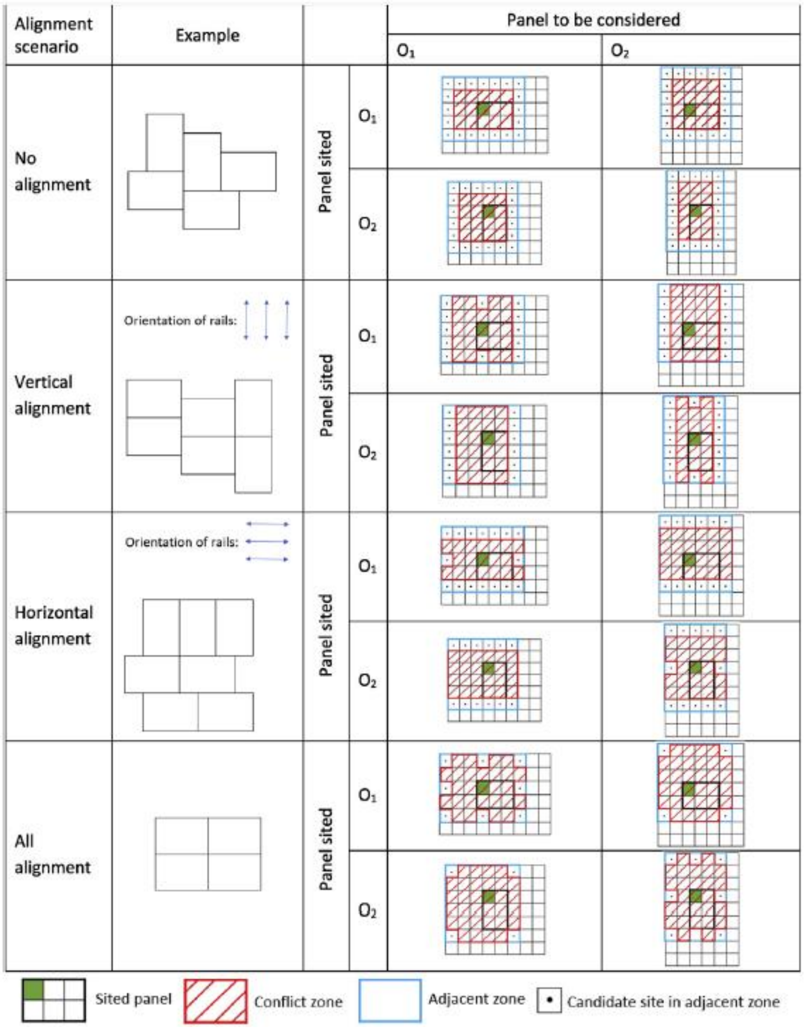


Figure 12: Alignment and conflict zones PV installation [12, p. 5]

This figure shows how the solar panels, when not aligned, have more flexibility to place the solar panels. When solar panels are not aligned, there are fewer conflict zones compared to the other installations. When all panels have the same orientation (all alignment configuration) there is less flexibility for placing the adjacent solar panels leading to a larger conflict zone [12].

Research shows that for the same given amount of panels, the highest coverage can be achieved when no alignment is needed. When the panels are fully aligned the least coverage is generated. This means that a rackless system without alignment can help to obtain the highest system efficiency. In the case of rail-mounted rack systems, horizontal alignment or vertical alignment are used to achieve relatively high system efficiency [12].

2.3.4 Cooling of the solar panels

In this section, the influence of temperature on the efficiency of a solar module will be discussed. In general, as the temperature rises, the solar panel's output power decreases (see Figure 13). On the other hand, this also has the consequence that when the temperature of a solar panel rises, its efficiency decreases linearly with the temperature. In Figure 14 this connection is shown. Here is visible that at higher temperatures the efficiency of, in this case, a Si-solar cell will be lower.

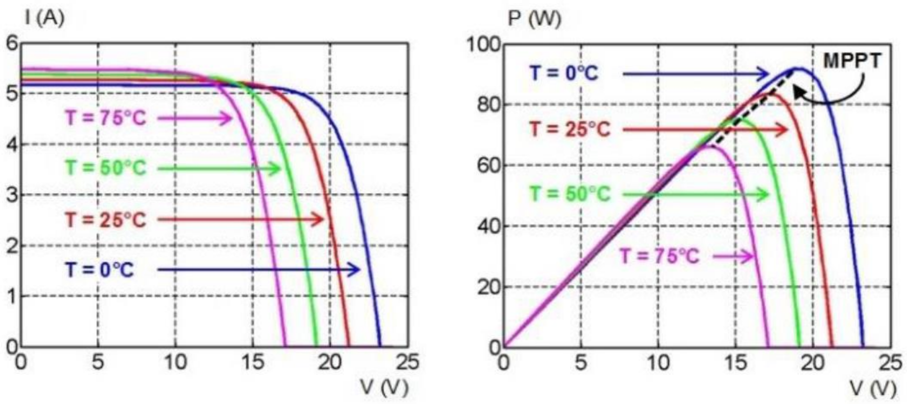


Figure 13: Relationship temperature and power [17, p. 1]

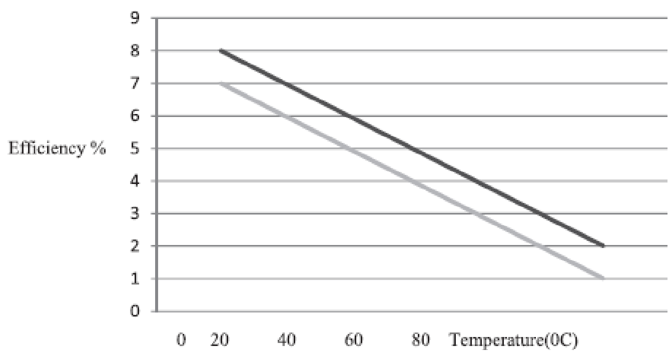


Figure 14: Relationship efficiency and temperature [18, p. 3]

There are various ways of cooling a solar panel. The first method of cooling a solar panel is the use of a cooling fan. This cooling fan can operate in such a way that it automatically switches on or off depending on the solar panel's temperature. However, it is inefficient to switch the cooling fan on when it is cloudy or when the inverter fails. For this reason, real-time monitoring is needed in some situations. By placing a temperature sensor on the solar panel, it is possible to control and operate the cooling fan in real-time [17].

A second way to cool the solar panels is to use a solar-powered photovoltaic water pump system (SPVWPS). This system can be implemented in three different ways. The first way is top cooling where the free flow of water takes place under the influence of gravity flows over the solar panels. The second method is a free flow of water under the influence of gravity over an aluminium channel. This aluminium channel is fixed to the underside of the PV module and open on all sides to allow air to pass through (without jute). The third system is very similar to the second system. Only here, in place of the free flow of water, a cloth is placed on top of the aluminium sheet and the water will pass over the cloth (with jute) [19]. Figure 15 shows how much the panel temperature drops using the various techniques.

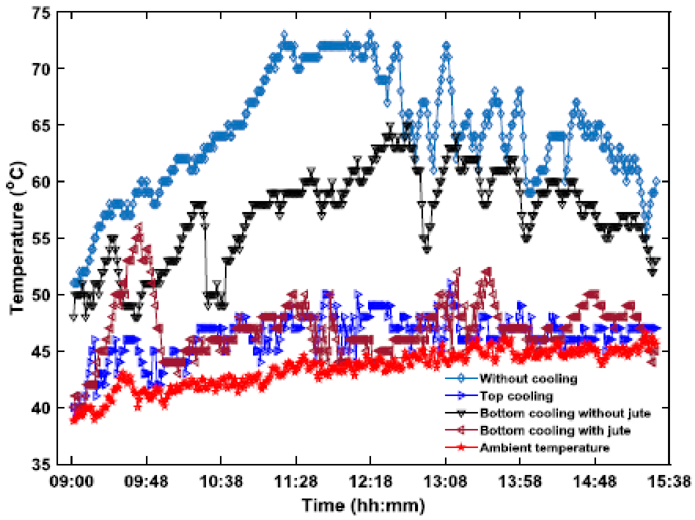


Figure 15: Comparison of panel temperature with and without cooling [19, p. 5]

From Figure 15, it can be observed that bottom cooling and top cooling with jute are the most efficient cooling techniques. When using these two techniques, the temperature of the module drops dramatically. It is also possible to look at the output power data of the PV installation. Figure 16 shows this.

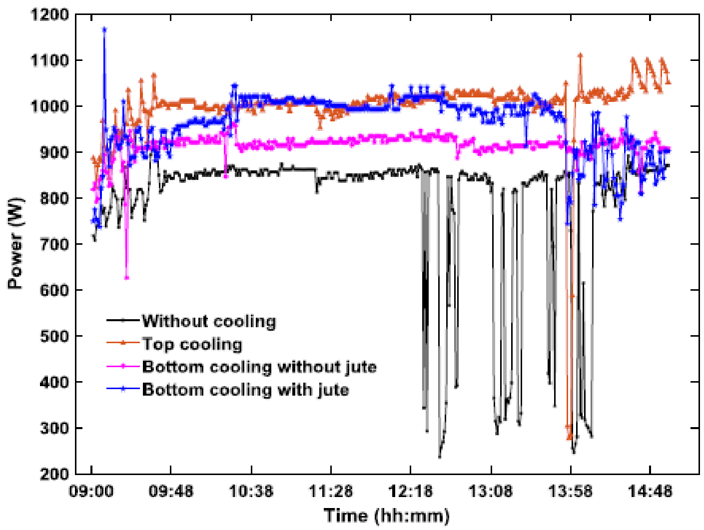


Figure 16: Comparison of PV array output power with and without cooling [19, p. 7]

Figure 16 shows that higher output power is achieved by cooling the panel. It is visible that the two better cooling techniques (bottom cooling and top cooling with jute) generate the highest output power [19].

The main conclusion due to the paper [19] is that bottom cooling using jute is the better cooling technique compared to all other cooling techniques. This cooling technique improves the overall efficiency of the SPVWPS without consuming a lot of water to cool the PV module. Bottom cooling with jute is only 2% more efficient than top cooling, but top cooling requires 50% more water to keep the PV module cool.

Besides these two main methods of cooling solar panels, there are many other cooling methods. The following list covers all possible cooling methods [20]:

- air-based cooling,
- spectrum filter cooling,
- heat pipe,
- microchannel heat exchanger,
- radiative sky cooling,
- nano-fluid based cooling,
- liquid-based cooling,
- thermoelectric cooling,
- evaporative cooling,
- phase change material (conductive),
- heat sink/fins/heat exchanger,
- hybrid/multi-concept cooling systems.

Cooling methods based on air and water are the most developed. Heatsinks have a great potential for cooling PV modules, but this needs further investigation. From paper [20] it is concluded that passive air cooling with cooling fins is the most valuable option from a technical and economic point of view. Active water-based cooling, on the other hand, can also be a good economic option, if optimized and intelligent control of the system is provided. In addition, water cooling has the advantage that the dirt on the panel can be removed.

2.3.5 Tracking system

Most PV installations are carried out with solar panels fixed to the roof. However, it is also possible to design solar panels so that they follow the direction of the sun. Such a system is also known as a solar tracking system. In general, solar tracking systems are usually based on a timer control (15° rotation per hour). As the solar time changes during the year, these systems have to be started and stopped manually [21].

A tracking system can be implemented in three different ways [8]:

- single-axis orientation tracking systems,
- single-axis tilt tracking systems,
- two-axis tracking systems.

In the single-axis orientation tracking systems, the path of the sun is followed by the rotation of the orientation angle, while the tilt angle is set to a fixed value. In single-axis tilt tracking systems, the path of the sun is followed by the tilt angle, while the oriental angle is set to an optimal value. In the two-axis tracking systems, the movement of both the tilt and orientation angle of the PV module follows the path of the sun to reach the peak irradiance value at any time [8].

Electricity output can increase by 27 to 32% when using a single-axis tracking system. In contrast, when using a double-axis tracking system, the electricity yield can increase by as much as 35 to 40%. However, it follows from the paper [12] that a double-axis tracking system has minimal performance improvement compared to a single-axis tracking system. There would be only 1-4% less energy production when using a single-axis tracking system compared to a double-axis tracking system [12].

Implementing a solar tracking system costs more than simply placing the solar panels fixed on the roof. But this extra cost is recouped through the extra energy production that the solar panels generate [21].

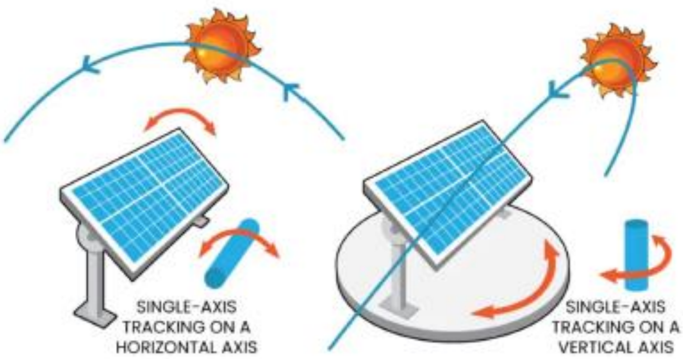


Figure 17: Example of a single-axis tracking installation [8, p. 14]

2.3.6 Influence of dust

Over the years, a PV module gets dirtier and dirtier. The build-up of debris on the PV module, water stains (salts), or bird droppings, can play a substantial role in the efficiency of a PV module. Therefore, the PV modules must be maintained and cleaned regularly.

It is possible to use two techniques to keep PV modules clean. The first technique is to clean the PV modules manually. This technique can be used in the same way as cleaning windows. However, it is essential that the panels are handled carefully and that scratches on the PV module are avoided. Another technique that can be used is mobile cleaning machines. The mobile cleaning machines are equipped with a spray water system that uses high-pressure water jets to remove the build-up of dirt and dust. This is particularly necessary in dry seasons and cases of heavy dust build-up. This is a straightforward and inexpensive solution [13].

2.4 Analysis of specifications of solar photovoltaic panels

2.4.1 Specifications

As discussed in 2.2.1, there are many specifications of solar panels to compare. To make a good choice of a solar panel for the PV installation at the Montilivi campus in Girona, it is essential to understand these specifications. In the paper [22], several solar panel technologies were compared, and the specifications were thoroughly examined. The research was carried out on a complete of 1300 panels from various manufacturers.

The different technologies compared are monocrystalline, polycrystalline, heterostructure, and thin film. Table 1 shows the result of the various specifications for these technologies. For every parameter, the result of the best and the median of a group of panels of each technology is given.

Table 1: The median and the best values of characteristics of the considered PVPs of Russian and foreign origins. [22, p. 27]

Parameter			Monocrystalline		Polycrystalline		Heterostructural		Thin-film	
			best	median	best	median	best	median	best	median
η	%	Foreign	21.50	18.86	18.47	17.01	21.70	20.45	18.00	16.40
		Russia	19.17	16.06	18.06	16.50	20.00	18.11	9.09	8.39
K_P	%/°C	Foreign	−0.290	−0.390	−0.355	−0.400	−0.260	−0.260	−0.240	−0.320
		Russia	−0.380	−0.440	−0.390	−0.427	−0.285	−0.311	−0.290	−0.290
K_V	%/°C	Foreign	−0.240	−0.290	−0.250	−0.304	−0.230	−0.240	−0.280	−0.280
		Russia	−0.290	−0.340	−0.318	−0.318	−0.244	−0.249	−0.330	−0.330
K_I	%/°C	Foreign	0.100	0.050	0.069	0.050	0.059	0.045	0.070	0.040
		Russia	0.100	0.050	0.060	0.042	0.055	0.040	0.070	0.070
K_{oc}	%	Foreign	86.9	82.2	85.1	81.5	86.0	84.10	84.3	81.7
		Russia	84.8	81.5	84.3	81.0	83.6	80.8	77.8	74.8
K_{sc}	%	Foreign	98.3	94.9	96.9	94.9	95.2	93.9	93.8	90.9
		Russia	97.3	94.3	96.6	95.1	94.7	93.2	87.2	82.1
FF	%	Foreign	82.4	78.1	80.7	77.4	80.9	79.2	79.0	74.3
		Russia	79.5	76.6	79.6	76.6	79.1	75.3	67.8	61.3
m_p	kg/kW	Foreign	47.3	60.8	51.7	66.9	51.3	56.8	77.4	85.0
		Russia	53.1	74.5	61.2	71.9	56.7	62.8	184.7	200.2
s_p	m^2/kW	Foreign	4.65	5.30	5.41	5.87	4.60	5.06	5.55	6.10
		Russia	4.90	6.33	5.53	6.37	5.00	5.53	11.01	11.93
NOCT	°C	Foreign	40.6	45.0	42.0	45.0	44.0	44.0	46.0	46.0
		Russia	45.0	46.8	45.0	46.8	38.8	38.8	47	47.0
GP	%	Foreign	100	97.5	100	97.5	98	98	98.0	98.0
		Russia	100	97.5	100	97.0	98	98	97.5	97.5
25-years GP	%	Foreign	92.0	81.4	90.0	80.7	92.0	90.8	86.0	86.0
		Russia	84.0	80.0	80.7	80.0	84.6	84.6	80.0	80.0
Lifetime	years	Foreign	30	25	30	25	25	25	30	30
		Russia	30	25	25	25	25	25	25	25

Looking at the median values, the most efficient panels are the heterostructural PVPs and the most inefficient are the thin-film PVPs. Paper [22] also concludes that heterostructural PVPs have a higher potential in the future than polycrystalline and monocrystalline PVPs in terms of efficiency. However, currently, there are mainly monocrystalline and polycrystalline panels on the market.

2.4.2 Solar photovoltaic generations

In addition to looking at the various technologies, a division can also be made based on solar photovoltaic generations. There are four different generations, namely first-, second-, third-, and fourth-generation solar cells. This division was made based on the materials used during the fabrication processes. Table 2 shows the difference between the various generations. It shows the type of material used, the efficiency, and the advantages and disadvantages of each generation of solar cells [23].

Table 2: Comparison table and its relevance for material properties [23, p. 4]

Generation	Type	Efficiency	Advantage	Disadvantage
1st generation	Single crystalline-Si	27%	Solar panel with the highest efficiency	Both material and energy-intensive
	Multi crystalline-Si	18%	Cost-effective	Efficiency less than sc-Si
2nd generation	GaAs	29%	High efficiency	Cost high
	CdTe	15%	Low cost	Toxic material
3rd generation	PSC	22%	Low cost than silicon	Quickly breaks due to exposure to heat
	DSSC	10%	Low cost	Physical damage easily
4th generation	Conducting polymer and inorganic nanostructures	22%	Low cost	Low efficiency

Today, first-generation PV photovoltaic cells dominate the market due to their high efficiency and low production cost. First-generation PV photovoltaic cells are also the most mature technology with a wide variety of manufacturers in the future. Although much has already been done to reduce the cost of first-generation PV solar cells, one of the goals in the future is to reduce this cost even further to make it more economically competitive [23].

In comparison to first-generation solar cells, second-generation PV cells are more immature and less common on the market. The thin-film PV cells compete also with low-cost c-Si modules and face challenges of availability, durability, and material toxicity (cadmium substrate) [23].

In contrast, third-generation technologies are still not on the market. CPVs are the most efficient, while other forms such as organic matter and DSSC have a low efficiency but lower costs. [23].

The fourth-generation technology promised to increase solar cell efficiency at a lower cost by using both organic and inorganic nanoparticles. The stability of inorganic nanostructures and the flexibility of conductive polymer films have been featured in 4G PV solar cells. The life of 4G PV solar cell devices changes nowadays PSC devices due to improvements in the optical characteristic and charge extraction [23].

2.5 Integrated PV

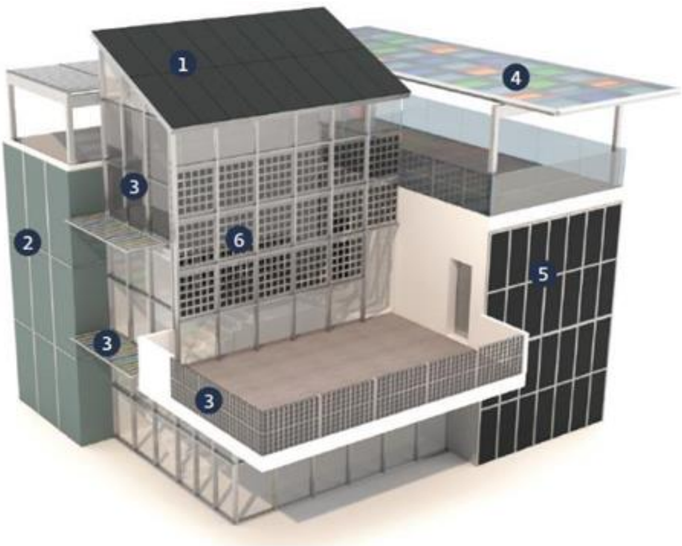
Currently, researchers and manufacturers are trying to find more and more solutions to generate green electricity. This also applies to solar panels, new applications have been devised to generate electricity using solar energy, namely:

- vehicle-integrated PV (VIPV),
- building-applied PV (BAPV),
- road-integrated PV (RIPV),
- building-integrated PV (BIPV),
- urban photovoltaics (UPV),
- floating PV (FPV),
- agrivoltaics (APV).

This section will discuss three applications of the above enumeration in more detail. First, BIPV and BAPV will be discussed. Then urban photovoltaics will be discussed.

2.5.1 Building-integrated photovoltaics

Building-integrated PV (BIPV) is an application where photovoltaic materials are used instead of building materials such as roofs, facades, and windows. The use of photovoltaic materials instead of building materials has the advantage that the costs that normally go towards building materials are now spent on photovoltaic materials [24]. This photovoltaic material, in turn, makes it possible to generate green electricity. Figure 18 shows how building-integrated PV can be applied.



(1) Opaque roof (PV tiles, in-roof mounting, full-roof solutions)
(2) Rainscreen (ventilated facade)
(3) External devices (venetian blinds, balustrades, etc.)
(4) Skylight / canopies
(5) Prefab systems
(6) Curtain wall (not ventilated)

Figure 18: Building-integrated PV [25]

Building-integrated PV provides opportunities but also has some challenges to consider [25].

Opportunities:

- energy-neutral buildings,
- low additional costs,
- aesthetics can be improved.

Challenges:

- complexity increases (assembly),
- planning effort increases due to many stakeholders.

Building-applied PV (BAPV) is an application where photovoltaic energy is retrofitted to the building after its construction is complete. Some builders and manufacturers make a distinction between the term BIPV and BAPV. A small comparison can also be made between BIPV and BAPV (see Table 3).

Table 3: Comparison of BIPV and BAPV [26]

Building integrated photovoltaics	**Building applied photovoltaics**
Integrated directly within the building structures like roof or facade	Indirect integration by using mounting hardware and roof perforations
Lightweight, and heavyweight	Heavyweight
Durable	Breakable
Highly resistance to winds	Lift or drag is possible
Aesthetically pleasing	Clunky looking

2.5.2 Urban photovoltaics

Urban photovoltaics is used in cities and towns for generating electricity using solar panels. Typical applications of urban photovoltaics are car parks, sports grounds, or squares, where photovoltaic systems are installed in combination with light sources, charging infrastructure, or sun blinds. In addition, photovoltaic systems can serve as billboards, for example. UPV installations must meet high expectations in terms of design and functionality and therefore usually require individual solutions. In addition, authorization processes and conditions for publicly accessible areas are difficult.

Urban photovoltaics has some advantages but also some challenges to consider.

Advantages:

- short connection distance to the grid,
- always double benefit, a photovoltaic system in combination with an application,
- visual beautification of areas,
- use of enclosed areas.

Challenges:

- combining design and functionality,
- clear specifications for the approval of UPV systems (safety, standards, etc),
- higher costs and greater planning effort.

Figure 19 shows examples of UPV systems.

Figure 19: Example of UPV systems

3 Design of the optimal photovoltaic system

In this part of the thesis, different parameters will be studied to come to an optimal design for a PV plant on the Montilivi campus. This is done by making simulations and then studying them thoroughly. To achieve a good choice, the following points will be studied in depth:

- the location of the campus,
- comparison of different solar panels,
- optimal solar panel position determination,
- consumption of the various buildings on the campus,
- inverter selection,
- support system,
- dimensioning and choice of the DC cabling,
- from the inverter,
- a battery or not,
- economic analysis,
- final selection of the optimal PV systems.

3.1 The Location of the campus

In the first step of the design of the PV installation, it is necessary to understand the geographical location of the Montilivi campus. The Montilivi campus is located in the north of Spain in the city of Girona, which is not far from Barcelona. The coordinates of the Montilivi campus are:

- latitude = 41,963233,
- longitude = 2,829836.

These coordinates will return in the further course of the report. With these coordinates, some calculations and simulations can be made.

Figure 20 shows the location of the campus.

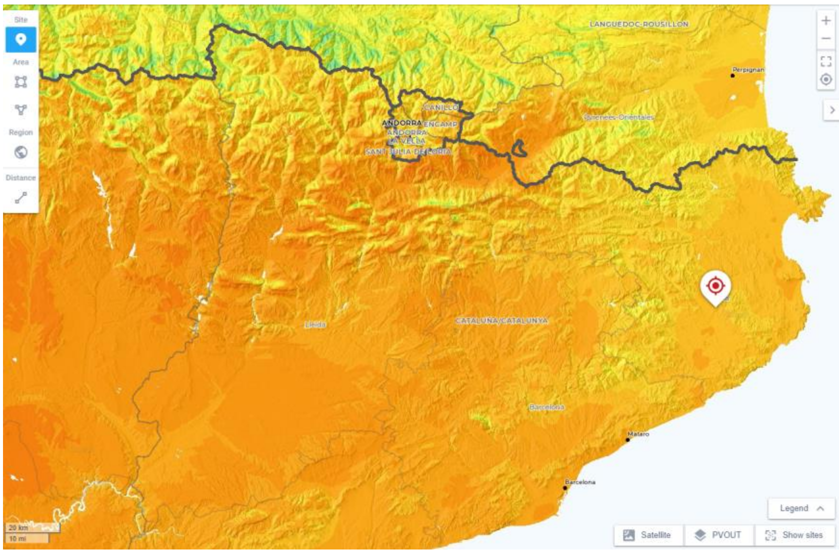


Figure 20: Location of the campus [27]

By zooming in on the location of the campus, there can be an idea of the available area for installing solar panels. Figure 21 shows the google maps location of the Montilivi campus.

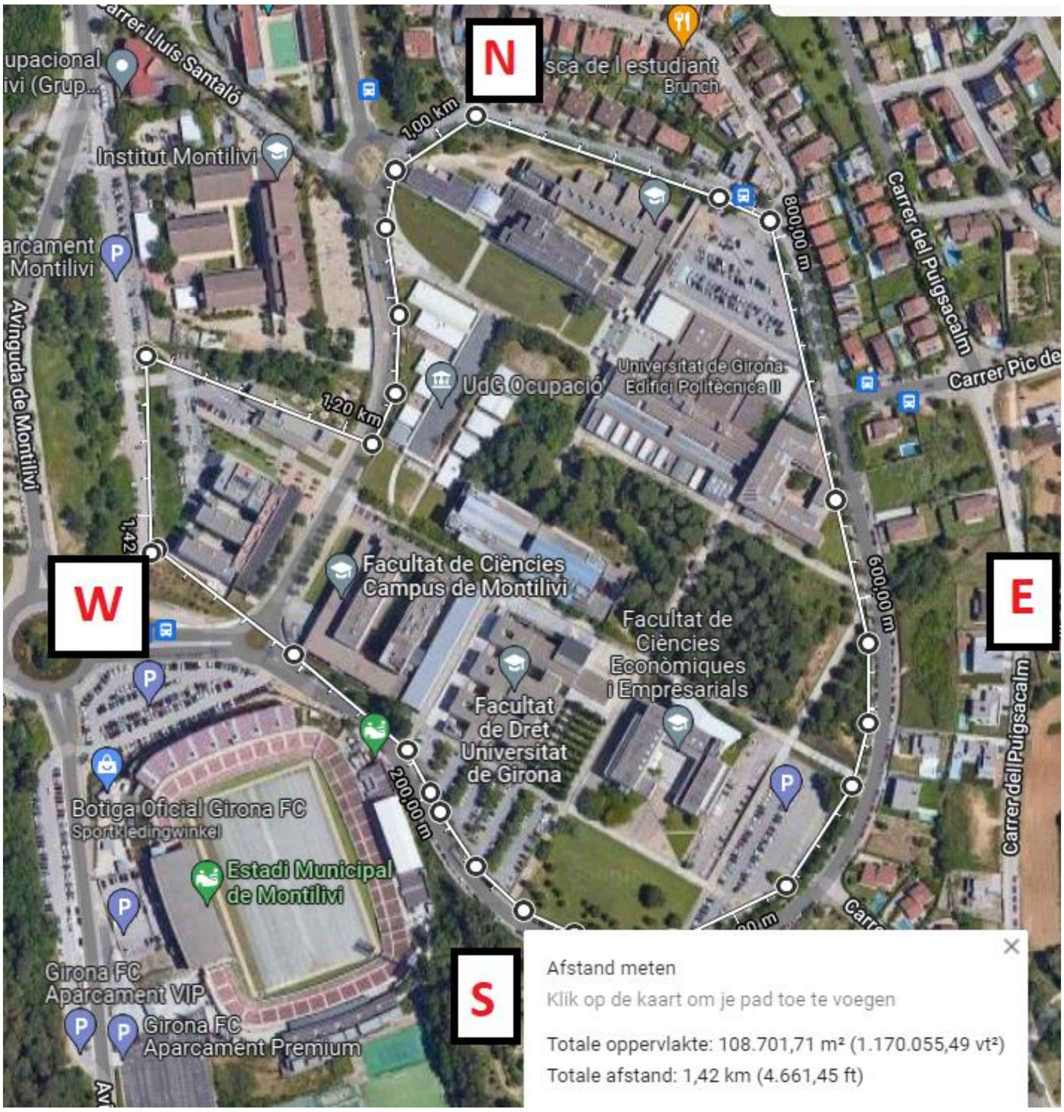


Figure 21: The google maps location of the Montilivi campus [28]

Figure 21 shows that the campus is located north of the official football stadium of Girona FC. It is also clear from Figure 21 that the Montilivi campus covers a large area. The total perimeter of the campus is ± 1.42 kilometers and the total surface area of the campus is ± 108.701m². In total, the campus has 14 different buildings. Of the 14 buildings, two are (number 13 and 14) left out of consideration for this thesis because they are located a little further from the campus. Figure 22 gives an overview of the different buildings on the campus.

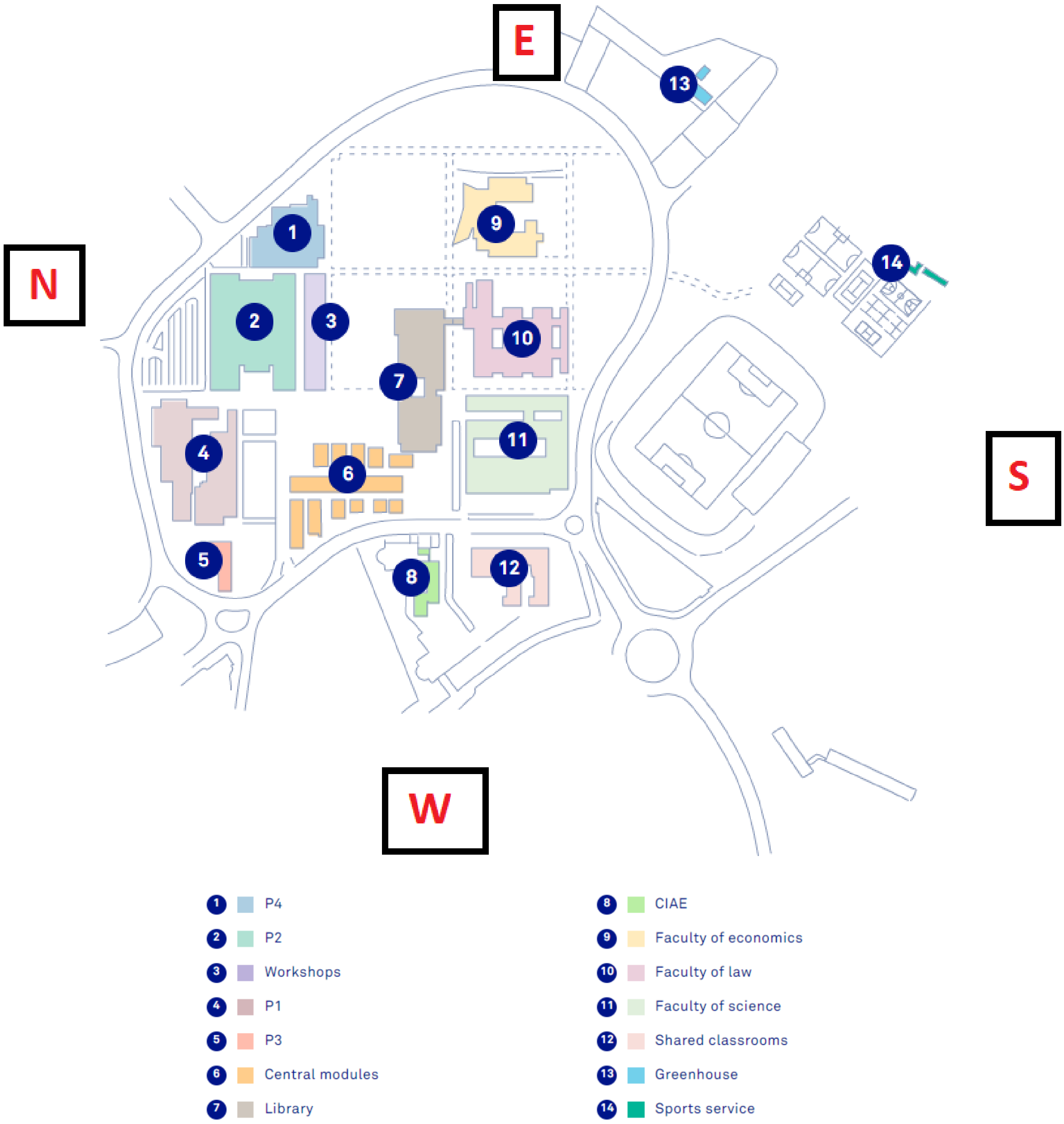


Figure 22: Map of the different buildings on the Montilivi campus [29]

Based on the location and more specifically on the latitude and longitude, location-dependent parameters can be determined. First of all, solar irradiation per year and per day can be looked up. The higher the value of solar irradiation, the more favourable it is to install solar panels. Table 3 and Table 4 show the solar irradiation per year and day for the Montilivi campus.

Table 4: Irradiation table (per year) [27]

Map data		Per year	
Direct normal irradiation	DNI	1697.1	kWh/m²
Global horizontal irradiation	GHI	1567.3	kWh/m²
Diffuse horizontal irradiation	DIF	606.6	kWh/m²
Global tilted irradiation at optimum angle	GTI opta	1870.9	kWh/m²

Table 5: Irradiation table (per day) [27]

Map data		Per day	
Direct normal irradiation	DNI	4.650	kWh/m² per day
Global horizontal irradiation	GHI	4.294	kWh/m² per day
Diffuse horizontal irradiation	DIF	1.662	kWh/m² per day
Global tilted irradiation at optimum angle	GTI opta	5.126	kWh/m² per day

It is also possible to get an idea of the sun's position in Girona by using latitude and longitude. With the help of Python software, it is possible to plot figures indicating the sun's position. Figure 23 and Figure 24 show the solar position of 2021 in Girona.

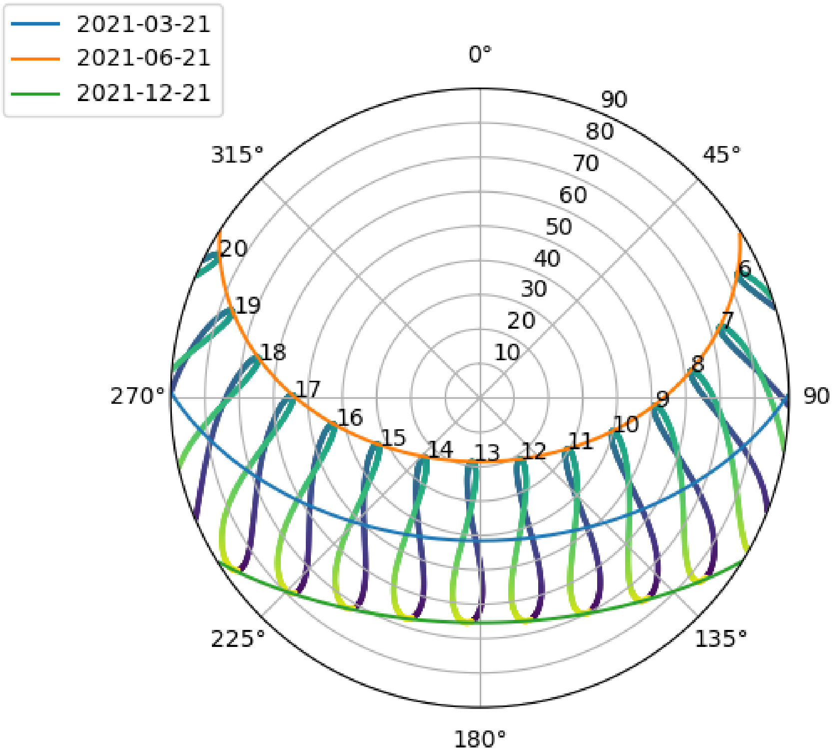


Figure 23: Solar position in Girona for March, June, and December (plot 1)

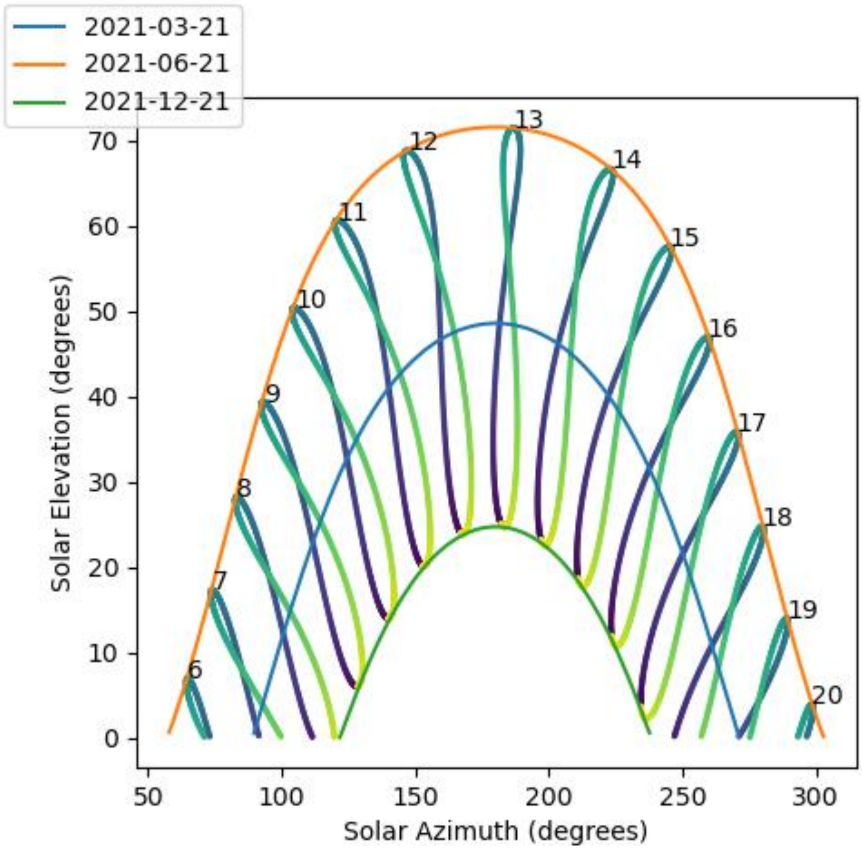


Figure 24: Solar position in Girona for March, June, and December (plot 2)

Both figures show the same thing but in a different way. Because both figures want to say the same thing, only Figure 24 will be discussed in more detail. The azimuth of the sun is on the x-axis and the elevation of the sun is on the y-axis. Both quantities are important to make a good choice for the tilt and orientation of the solar panels in a further phase of the design. Figure 24 clearly shows that in summer (the orange line) the sun shines longer, and it will go higher than in March (blue line) and December (green line).

3.2 Comparison of different solar panels

There are a lot of PV modules available in the market. By comparing the specifications of different PV modules with each other, a good choice for a suitable PV module can be made. In total, 10 panels with more or less the same rated power were compared. By checking the datasheets, making some calculations, and drawing up a decision matrix, the best solar panels can be selected. In Appendix A the specifications of the 10 different solar panels can be found. At the bottom of the two tables in Appendix A, some simple calculations are made to better compare the solar panels with each other. In totality, three calculations were made namely weight/rated power, Price/Wp, and Price/eff. Based on these tables a decision matrix is made to compare the most important parameters.

The different parameters that were compared with each other are:

- the rated power,
- the efficiency,
- the weight per power,
- the price of the panel,
- price per Watt peak,
- price per efficiency,
- the power output after 25 years.

By giving each of these parameters a factor based on importance (weight), it is possible to make a proper assessment of the various panels. The weight factor is chosen based on insight and knowledge.

From the decision matrix, it can be decided which solar panels have the best specifications. In Appendix B, the total score of each panel can be found at the bottom of Table 19 and Table 20

The score of the best three solar panels is marked in green. In addition, Figure 25 shows the scores of the different solar panels in a convenient way to quickly deduce which panels have the best and worst characteristics. Analysis shows that the best three solar panels are the SPR-MAX3-400, the VERTEX PERC, and the JKM390M-6RL3-B. These three modules use monocrystalline cells.

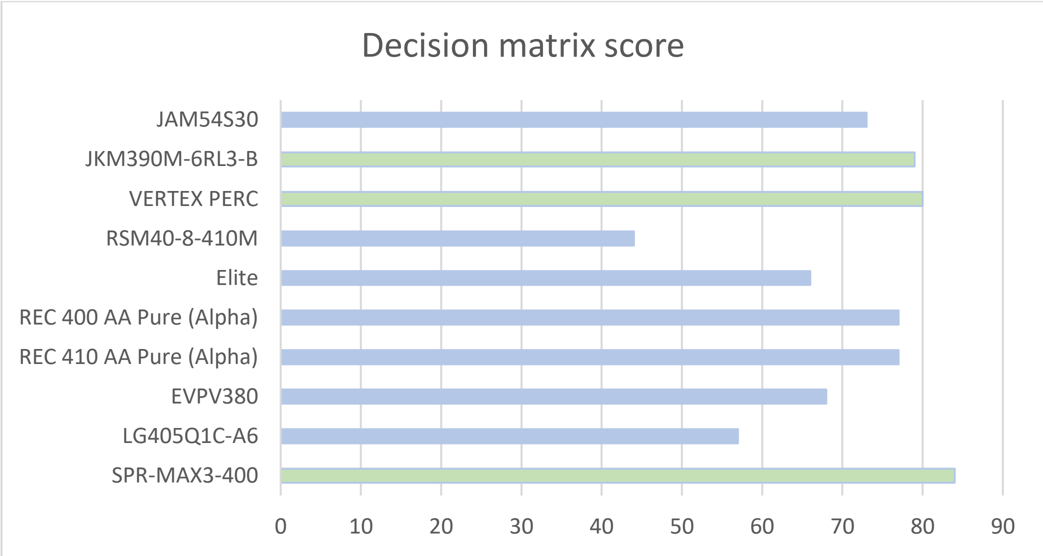


Figure 25: Results decision matrix

- SPR-MAX3-400:
    - this solar panel has the highest efficiency of all solar panels compared
    - this module is designed to provide 55% more energy in 25 years in the same space under realistic conditions such as partial shade and high temperatures than conventional panels
    - the panels are capable of providing panel power at 92% of rated power after 25 years
    - it is not an overly large PV module, therefore many panels can be installed if needed
    - the only drawback is that these solar panels are pricey, but this is compensated for by more energy output in the longer term
- VERTEX PERC:
    - the VERTEX PERC panel has the highest rated power of all the panels that were compared to each other;
    - the panel is cheap. The price per Watt peak is the lowest of all the panels;
    - a disadvantage is that after 25 years, the panel can only provide 84.4% of its total power.
- JKM390M-6RL3-B:
    - the panel is cheap. The price per efficiency is the lowest of all panels;
    - a disadvantage is that after 25 years, the panel can still provide only 83.1% of its total power.

As discussed, the properties of the SPR-MAX3-400, the VERTEX PERC, and the JKM390M-6RL3-B differ. Therefore, it is interesting to see which of these three solar panels is the most economically interesting for the PV installation for the Montilivi campus.

3.3 Optimal solar panel position determination

A solar panel's position has a considerable influence on the performance of the PV installation. In this section, some factors are discussed to determine the ideal position of the solar panels. The factors discussed are:

- optimal tilt angle,
- optimal orientation angle,
- the geometry of the buildings at the Montilivi campus,
- the distance between solar panel arrays to avoid self-shading,
- a portrait or landscape format?

3.3.1 Optimal tilt angle

The inclination angle is the angle that the PV module makes relative to the surface on which it is mounted. What the ideal tilt angle is can be found in the literature, but there are also formulas to help establish what the inclination angle of the solar panel is.

To maximize the output power of solar panels, the panel surface has to be perpendicular to the solar radiation. Because of this, the angle of the panel should ideally be equal to 90°-solar elevation. To determine the optimal angle of inclination, several factors must be taken into account. Those factors are location, time, and season. It is well known that the geographical location point is determined by two variables: longitude and latitude. In this instance, the latitude is extremely relevant because it defines the slope of the surface, something to consider when designing a photovoltaic system.

When consulting website [27] and paper [30], the optimal tilt angle would be 37° degrees. However, in paper [30] the optimal tilt angle was determined for Barcelona instead of Girona. But Barcelona is so close to Girona that this optimal tilt angle can be correct. In paper [8] a formula was derived to calculate the optimal tilt angle. However, this formula is only valid for latitudes between 25° and 50°. Formula 1 shows this formula.

$$\beta = 0{,}76\,.\,\theta + 3{,}1 \qquad (1)$$

For Girona, the latitude of the campus as discussed earlier in section 3.1 is 41.963233. By filling in this value in formula (1), angle β results in 35°. According to this formula, the optimal tilt angle in Girona would be 35°. This differs 2° from what was determined in sources [27] and [30]. It can therefore be concluded that for the Montilivi campus in Girona the optimum tilt for a solar panel lies between 35° and 37° degrees.

As discussed in section 2.3.5, the tilt of the panel can also be adjusted depending on the height of the sun. This makes it possible for the sun to shine perpendicularly on the panel at any time. However, this also has two major disadvantages. Firstly, the investment cost will be higher than if the solar panels were fixed on the roof. Secondly, in the winter, the panel will be at a great angle, which means that the panels will have to be placed further apart (because of shadow). As a result, a lot fewer panels can be installed. Therefore, a fixed tilt angle of 36 degrees is examined in this thesis (lies between 35 and 37 degrees).

3.3.2 Optimal orientation angle

The orientation angle for a PV module corresponds to the direction in which the PV module is oriented (north, south, east, and west). A solar azimuth of 0° corresponds to an orientation to the north and an angle of 180° corresponds to an orientation to the south. In contrast, a solar azimuth of 90° corresponds to an orientation towards the east and a solar azimuth of 270° to an orientation towards the west. Figure 24 showed earlier the trajectory of the sun during a winter month, a summer month, and a spring month. Based on this course, the ideal orientation angle of any solar panel installed in Girona can be determined. Figure 26 shows an extension of Figure 24. Here it is demonstrated what the ideal angle of orientation of a solar panel in Girona is.

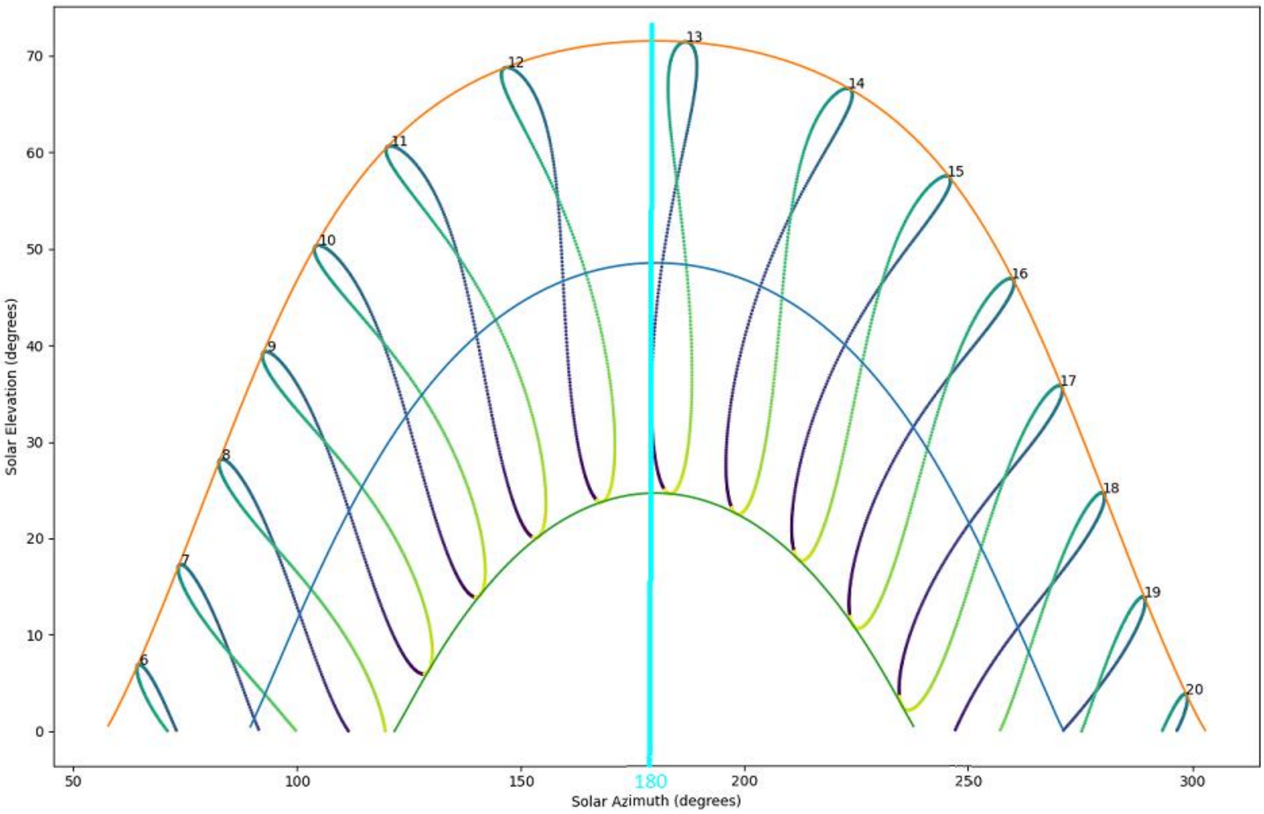


Figure 26: Ideal orientation angle for a Solar panel in Girona

It can be seen in Figure 26 that the ideal orientation angle for a solar panel in Girona is towards the south (solar azimuth of 180°). The peak value of solar radiation is obtained at this angle. However, this applies when the solar panel is fixed to the roof. To reach the optimal orientation angle at all times of the day, the sun's orbit should be followed. For maximum solar irradiation in summer (orange line in Figure 26) the panel should be able to turn from a solar azimuth of 57° to a solar azimuth of 302°. However, for a winter month (green line in Figure 26) this is only from a solar azimuth of 120° to a solar azimuth of 240°.

In the remainder of the thesis, a solar panel installation is discussed in which the solar panels face south for two reasons:

- a tracking system must be designed that can turn at least 240°. This fact does not make it easy to design a tracking system on the buildings of the Montilivi campus (wiring, shadow, ...). Also, the investment costs for tracking systems are higher than for a solar panel system that is fixed on the roof
- it is possible to design a solar panel system in an East-West configuration. This leads to greater power generation for a given surface area. However, this has the disadvantage that it involves a higher investment cost (more panels can be placed) and that the solar panels will work less efficiently than when they are facing south. Because there is a lot of space available on the Montilivi campus for placing solar panels, it is not necessary to apply an East-West configuration

3.3.3 The geometry of the buildings at the Montilivi campus

Almost all the roofs of the buildings on the Montilivi campus are flat. This makes it possible to place the solar panels on each building perfectly to the south. However, three things must be taken into account:

- there are some objects present on top of the buildings. On some buildings, ventilation cabins have been placed on top of the building, causing a shadow. Also, some buildings have two floors. This causes the second floor to cast a shadow on the roof of the first floor, so it is not always possible to install PV panels on the roof of the first floor
- the geometry of the buildings is such that it faces southwest (see Figure 21). In section 3.3.2 it was determined that the solar panels are most efficient when they are perfectly oriented to the south. For these two reasons, the solar panels are not placed according to the direction of the building but are rotated towards the south
- The campus is located in a hilly area which means that, for example, the building of the faculty of science is lower than the building of the faculty of Law (24m difference in height). Because of this, it must be taken into account that these higher buildings do not cast shadows on the lower ones. Figure 27 shows the hilly area of the campus

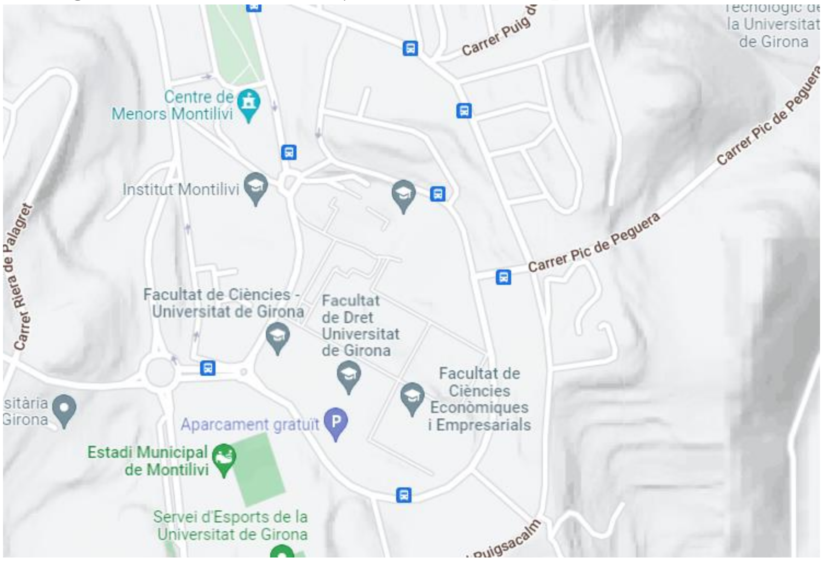


Figure 27: Hilly area around the campus [28]

3.3.4 The distance between solar panel arrays to avoid self-shading

The rows of solar panels must be placed at a distance from each other. This must be done to avoid the self-shadowing of solar panels, which results in reduced energy production of a PV installation. In this paragraph, the distance between the rows of solar panels is determined for the three best solar panels (SPR-MAX3-400, VERTEX PERC, and JKM390M-6RL3-B) determined in section 3.2.

The first step in calculating the distance between the solar panel's rows is to determine the difference in height between the back of the module and the surface on which it is placed. Here, it is important to know the optimum tilt angle. This lies between 35 and 37 degrees as determined in section 3.3.1. In addition, the SPR-MAX3-400, VERTEX PERC, and JKM390M-6RL3-B have different dimensions. Depending on the dimensions of the solar panel, the row distance will vary. Table 6 shows the dimensions of the different solar modules.

Table 6: Dimensions of solar panels

	SPR-MAX3-400	VERTEX PERC	JKM390M-6RL3-B
Length (mm)	1690	2384	1855
Width (mm)	1046	1096	1029
Thickness (mm)	40	35	50

With these values, the height difference can be calculated. However, it should be noted that a solar panel can be installed in both a horizontal and a vertical position. If the panels are installed in a portrait position, the row distance between the panels will increase but more panels can be installed next to each other. If, on the other hand, the panels are installed in a landscape position, the number of panels that can be installed next to each other will decrease and the distance between them will become smaller. Table 7 shows the height difference for both a landscape and a portrait panel and this for a tilt angle of 36 degrees. As discussed in section 3.3.1 a fixed tilt angle of 36 degrees is examined in this thesis (lies between 35 and 37 degrees).

Table 7: Height difference of solar panels

	SPR-MAX3-400	VERTEX PERC	JKM390M-6RL3-B
Tilt angle (°)	36	36	36
Portrait panel height difference (mm)	993	1401	1090
Landscape panel height difference (mm)	615	644	605

Now that the height difference has been determined, the next step is to look at the solar elevation. The solar elevation has a big influence on the row distance between solar panels and differs from place to place. Figure 28 shows the solar elevation for the different months in Girona.

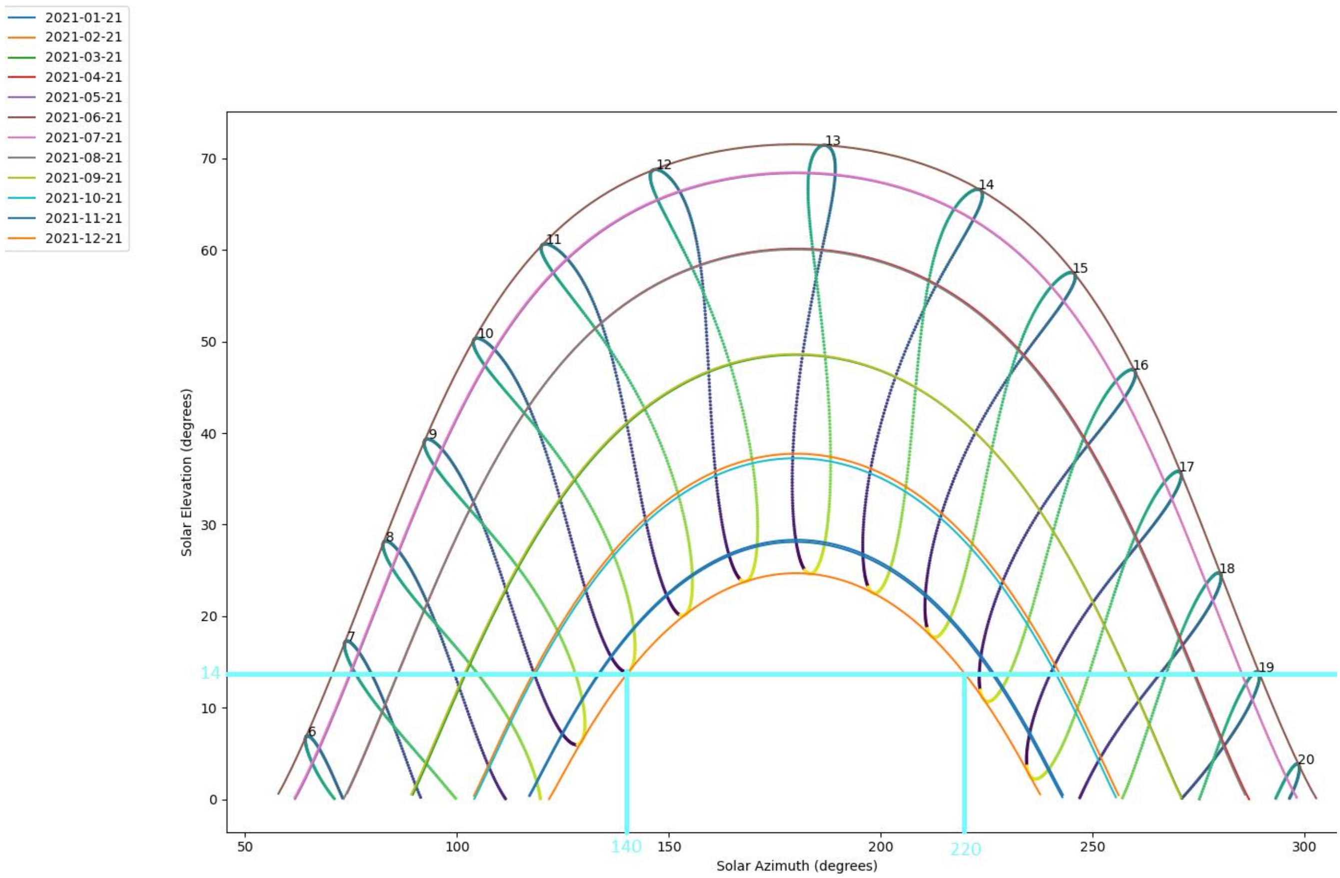


Figure 28: Solar elevation for each month in Girona

In Figure 28, three blue lines are drawn. The solar panels are exposed to a shadow below the horizontal line (solar elevation = 14°). However, this is only a small area and occurs during sunrise and sunset. The irradiation of the sun during sunrise and sunset is not as large as when the sun shines throughout the day.

Figure 28 shows that the solar elevation is determined at 14 degrees. With this angle, the row distance between the solar panels can be determined. Figure 29 visually shows the situation and formula 2 shows the calculation for the row distance.

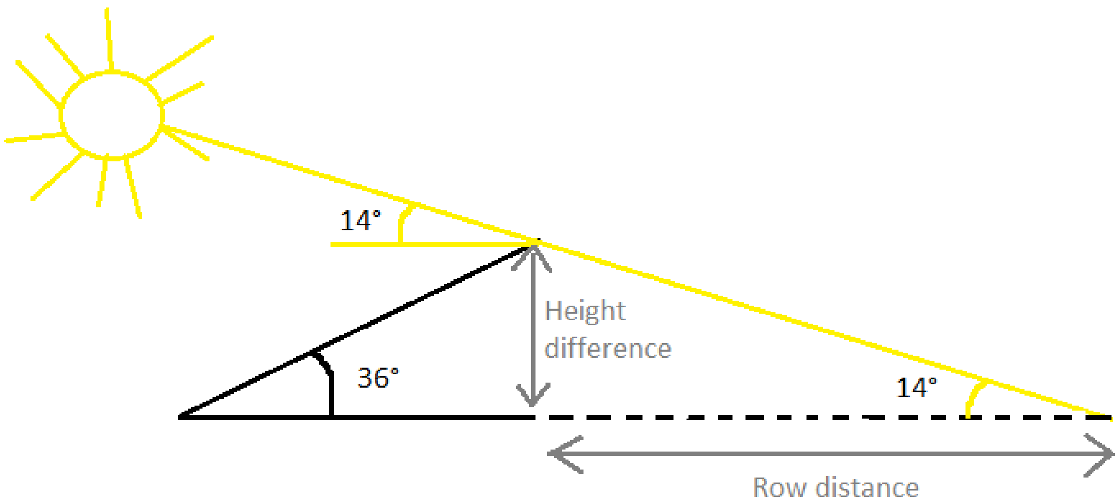


Figure 29: Visually overview to calculate the row distance

$$Row\ distance = Height\ difference / Tan(14°) \quad (2)$$

By entering the height difference calculated in Table 7 into formula 2, the row distance of the different solar panels under three different tilt angles can be determined. Table 9 shows the result of this calculation.

Table 8: Row distance between the solar panels

	SPR-MAX3-400	VERTEX PERC	JKM390M-6RL3-B
Tilt angle (°)	36	36	36
Portrait panel row distance (mm)	3984	5620	4373
Landscape panel row distance (mm)	2466	2584	2426

The calculation is made under the assumption that the sun is shining at an azimuth of 180°. This is not the case, the sun is shining at an azimuth of 140° or 220° when the sun has a solar elevation of 14° (see the two vertical blue lines in Figure 28). For this reason, a correction has to be made to the row distance. Figure 30 visually shows the situation and formula 3 shows the calculation for the minimum row distance.

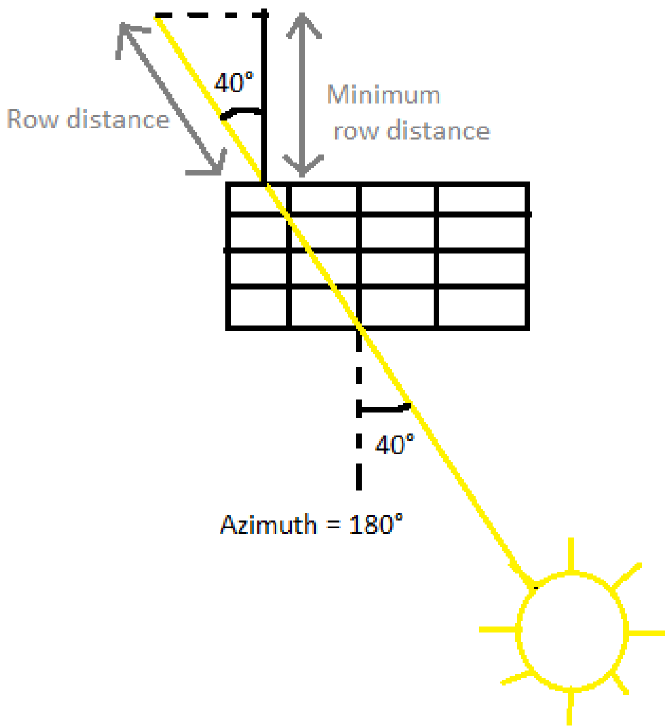


Figure 30: Visually overview to calculate the minimum row distance

$$Minimum\ row\ distance = row\ distance * \cos(220° - 180°) \quad (3)$$

By entering the row distance in this formula, the minimum row distance can be determined for the various solar panels. Table 10 below shows the minimum row distance.

Table 9: Minimum row distance between the solar panels

	SPR-MAX3-400	VERTEX PERC	JKM390M-6RL3-B
Tilt angle (°)	36	36	36
Portrait panel minimum row distance (mm)	3052	4305	3350
Landscape panel minimum row distance (mm)	1889	1979	1858

Using the minimum row distance, the simulations can be carried out and the number of solar modules can be determined.

3.3.5 A portrait or landscape format?

In this section, a comparison is made as to whether there is a difference between laying the panels in a portrait or landscape format. For each solar panel (SPR-MAX3-400, the VERTEX PERC, and the JKM390M-6RL3-B), two simulations are carried out to determine whether more panels can be installed in a portrait or landscape format. The simulations are carried out on an imaginary roof that corresponds to the orientation of the campus. On this roof, some obstacles are present to ensure that the simulation is as close to reality as possible. Figure 31 and Figure 32 below show an example of the roof arrangement where the solar panels are placed in a portrait and landscape format.

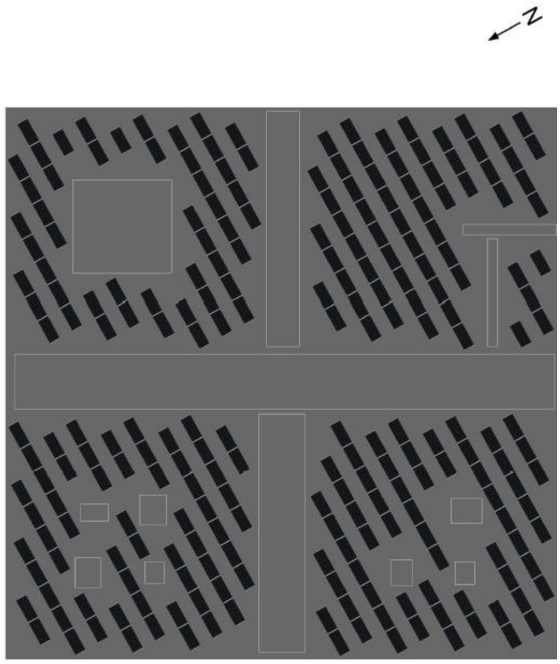


Figure 31: Example of a landscape format of the panels

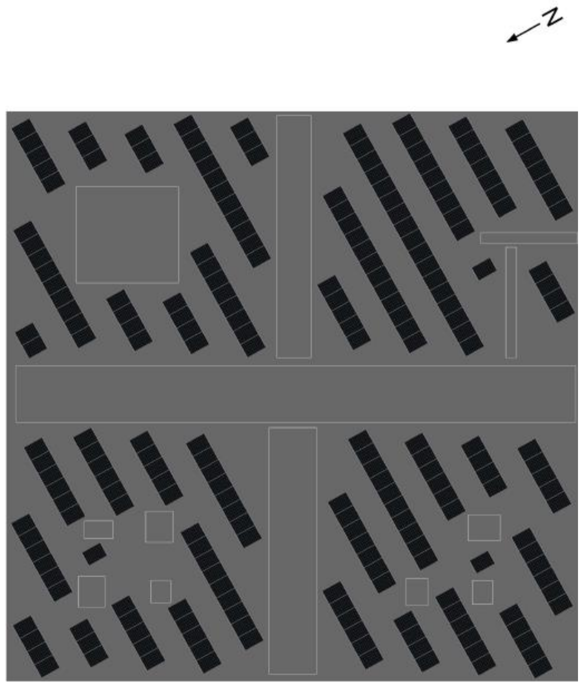


Figure 32: Example of a portrait format of the panels

To reach a correct decision for each panel, some parameters were compared. All simulations were carried out with the same inverter so that only the effect of the solar panel arrangement is compared. In Appendix C, Table 26, Table 27, and Table 28 gives an overview of the comparison between a portrait and landscape format for each panel (SPR-MAX3-400, the VERTEX PERC, and the JKM390M-6RL3-B).

Note: The IRR value and the Payback time are not completely correct in these tables. The calculation of these values is discussed in section 3.10. However, the values do indicate the most efficient setup to achieve the highest profit.

For the SPR-MAX3-400 module, however, there is a minimal difference between placing the solar panels horizontally or vertically. The preference leans slightly more towards the portrait format than the landscape format. Therefore, in future simulations, a portrait arrangement will be used for the SPR-MAX3-400 PV module.

The VERTEX PERC module allows more panels when it is placed vertically. It should be noted that the IRR and payback period are slightly in favour of a landscape installation. It is difficult to say which setup is the best. But because with a portrait format more panels can be placed, a portrait format will be used in further simulations.

With the JKM390M-6RL3-B module, slightly more panels can be placed horizontally than vertically. However, it is visible that every other parameter is in favour of a portrait format despite having 3 panels less than the landscape format. This difference could be due to a not optimal generation when these panels are placed horizontally. Another possible cause is that the PV modules with a landscape format cannot be optimally connected to the inverter. Although fewer panels can be placed vertically, a portrait format of these PV modules will be used in further simulations.

In general, it can be concluded that there is not a major difference between a portrait and landscape installation of solar modules. The above analysis shows that a portrait arrangement is slightly preferred for each solar panel. Further simulations are carried out with a portrait arrangement of the panels.

3.4 Consumption of the various buildings on the campus

The Montilivi campus covers a large area, making it possible to install many solar panels. However, to obtain an idea of how many solar panels need to be installed, it is necessary to look at the electricity consumption of the different buildings. The electricity consumption for every month of the different buildings for 2019 is shown in Figure 33. The year 2019 was chosen because it is the year before the corona era, and it gives a more accurate view of the effective consumption of the building in a normal academic year.

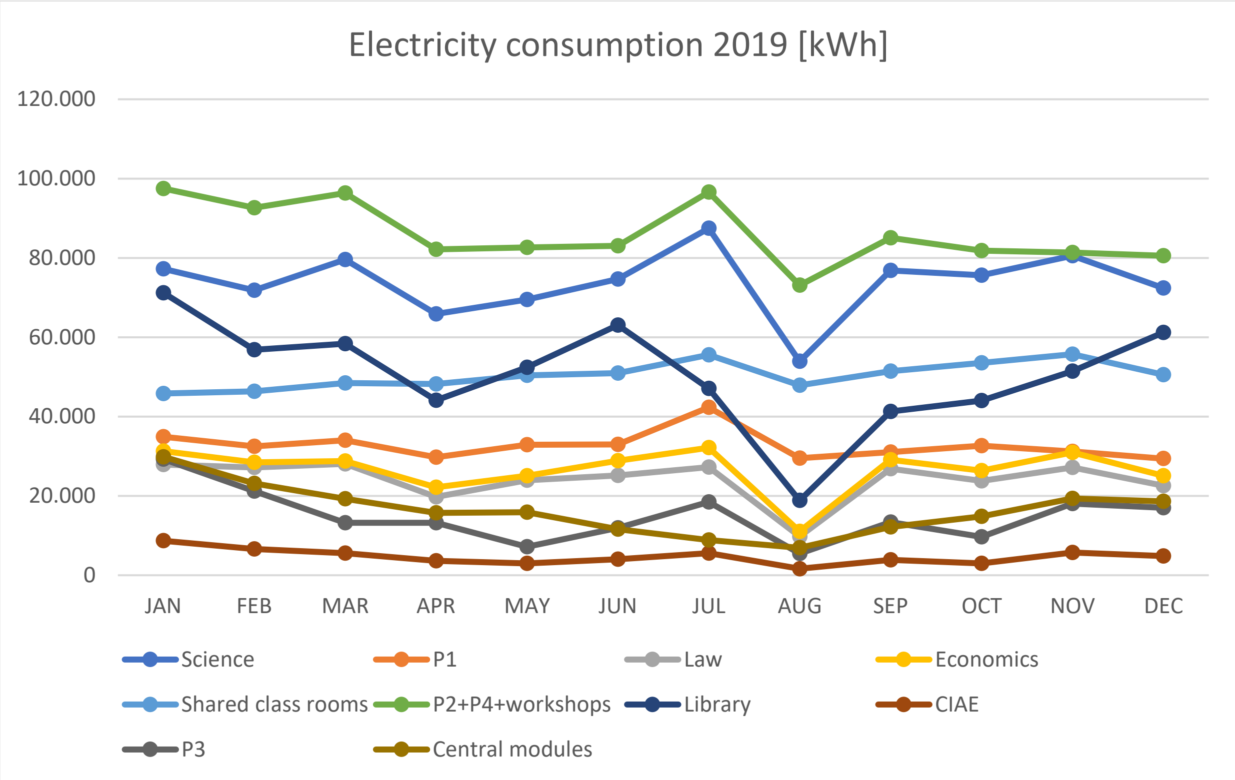


Figure 33: Electricity consumption for each month in 2019 of the different buildings

The P2+P4+workshops buildings and the sciences building consume the most electricity. This makes sense since these are the largest buildings on the campus (see Figure 3). The decrease in August corresponds to the closure of the university. The electricity consumption in August corresponds to maintenance such as the locks, computer servers, lighting, etc. To give a clearer idea of the total consumption of each building for the year 2019, consider Figure 34. Using these total values, the economic analysis is elaborated in section 3.10.

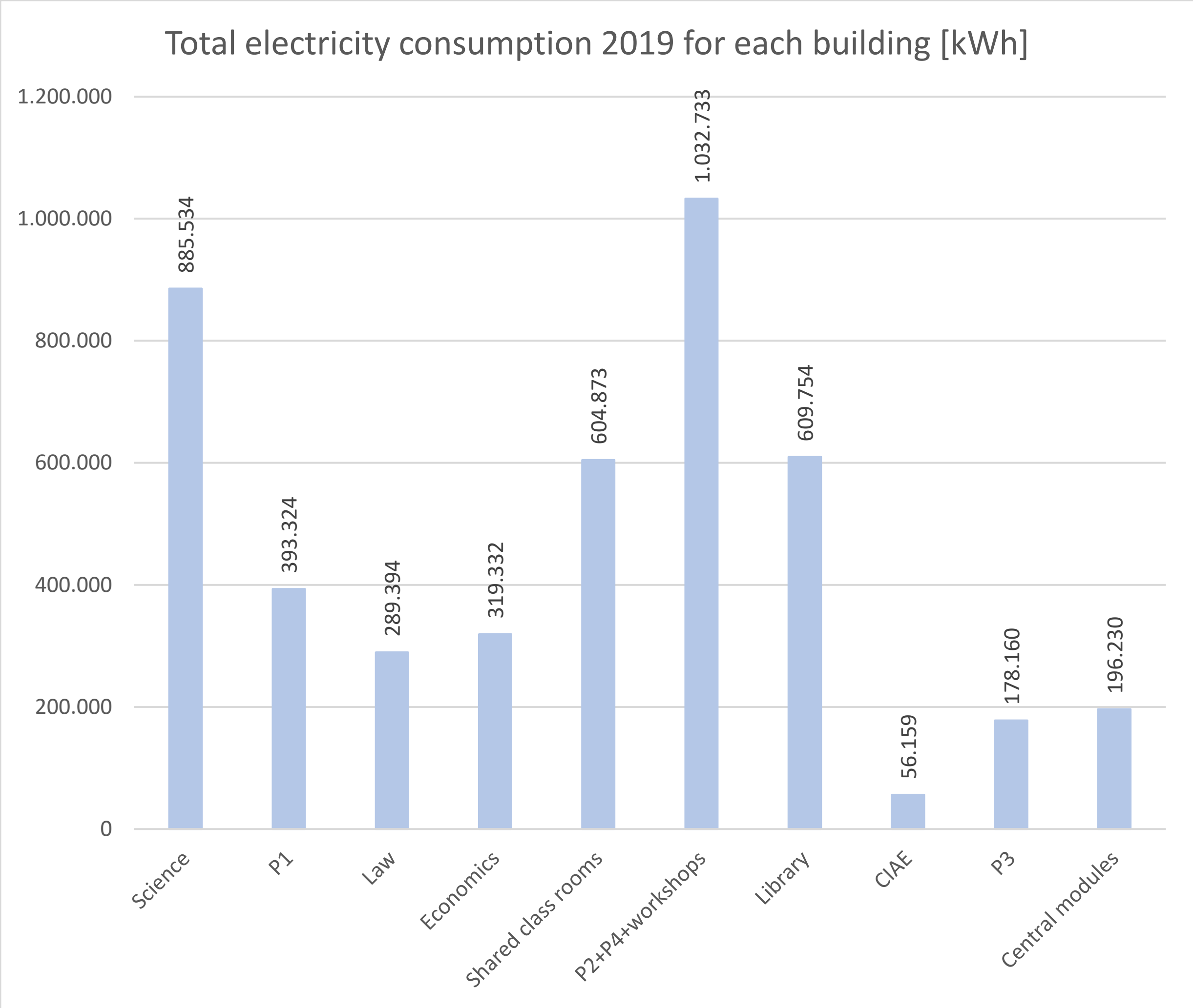


Figure 34: Total electricity consumption in 2019 for each building

3.5 Inverter selection

Every PV installation requires inverters to convert the DC voltage of the PV modules into an AC voltage. The literature study (section 2.2.2) has shown that a string inverter is financially the most interesting. Therefore, a string inverter will be used for the buildings at the Montilivi campus. However, a string inverter has two disadvantages. The first disadvantage is that shadows can be formed on the PV module. To compensate for this disadvantage, the solar panels were designed/calculated in such a way that they would experience as little shadow as possible. The radiation of the sun on the solar panels must also be taken into account. For example, if one panel faces east and the other south, the solar radiation will be different. This difference in irradiation is disadvantageous for a string inverter. This is why in the simulations all panels were placed perfectly with an inclination angle of 36° to the south. This would also give the highest efficiency of the PV installation.

To choose the correct inverter configuration for each building, there are several stages to go through:

- determining the maximum generated output power of each installation,
- comparing different types of inverters,
- determining the strings.

3.5.1 Maximum generated output power of each installation

To choose the right inverter configuration for each building on the Montilivi campus, it is important to determine as a first step the total capacity (in kWp) that the solar panels can supply. The number of kWp that a PV system can deliver varies from building to building and from solar panel to solar panel (SPR-MAX3-400, the VERTEX PERC, and the JKM390M-6RL3-B).

The Sunny Design software is used to determine the total installed capacity of each building. With the help of this software, the number of solar modules on a roof can be determined. In Appendix D, the configuration of the solar panels for each building can be found. These figures show how the panels can be placed on the roof.

After the installed capacity of each building has been determined, the maximum generated output power of each installation can be determined using PVGIS. PVGIS is another simulation tool that can be used to retrieve data from a PV installation on an hourly basis. By analysing this data per hour, the maximum generated output power of each installation can be determined. The inverter must be able to withstand this maximum power to prevent power losses and to prevent the inverter will be overloaded. Table 10 shows the installed kWp for each solar panel per building. Next to the column of installed kWp, the effective maximum generated power (kW) can be found.

Table 10: Installed kWp and maximum generated power

	SPR-MAX3-400		VERTEX PERC		JKM390M-6RL3-B	
	Installed kWp	Max output power generated (kW)	Installed kWp	Max output power generated (kW)	Installed kWp	Max output power generated (kW)
Faculty of Science	231,6	201,4	197,1	171,4	207,5	180,5
Faculty of Law	212	184,3	174,4	151,7	181	157,4
Faculty of economics	163,2	141,9	137,7	119,8	143,5	124,8
CIAE	44,4	38,8	37,8	33,05	40,2	35,1
Central modules	205,6	178,8	173,4	150,8	183,3	159,4
Library	146,8	127,6	119,3	103,8	129,5	112,6
P1	192,4	167,3	159,3	138,5	170	147,8
P2+P4+workshops	266,8	232	210,6	183,1	234,8	204,2
P3	39,2	34,3	32,9	28,8	34,3	30,1
Shared classroom	71,2	61,9	61,02	53,05	62,4	54,3

The conclusion from Table 10 is that for every installation, the inverter can be chosen smaller than the number of kWp of installed solar panels. This is because there are losses (quality of the solar cell, the temperature of the solar cell, the brand of the solar cell, etc.). It is also clearly visible that with the SPR-MAX3-400 module the most kWp can be installed. The reason for this is that this PV module has the highest efficiency. Although the JKM390M-6RL3-B has the lowest efficiency of these three PV modules, more kWp can be installed than with the VERTEX PERC. The reason for this is the size of the VERTEX PERC module. This panel is wider than the JKM390M-6RL3-B, so it is sometimes difficult to place it in more difficult places.

3.5.2 Comparing different types of inverters

In this section, several inverters will be compared. Eventually, one branch of an inverter (from the same manufacturer) will be placed on the campus because in this way possible failures can be solved more easily. If two different types of inverters are placed on the campus, troubleshooting will be more difficult. It also has the disadvantage that two various technologies have to work together, which can lead to more complex situations.

The inverters from Fronius, SMA, and SolarEdge will be compared. Fronius and SMA are located near Barcelona, not too far from Girona. Solaredge, on the other hand, is not located in Spain but is a well-known manufacturer that produces inverters. To come to a well-founded choice, datasheets of inverters of different capacities are studied and compared in detail In Appendix E, Table 24 shows this comparison.

The following conclusions can be made from Table 24:

- the inverters of SolarEdge are the cheapest. Especially for the larger inverters, it is visible that the inverters from SolarEdge are cheaper than those from SMA and Fronius. However, since the inverters come from abroad, the prices in the table also include additional costs such as transport costs. The disadvantage of the SolarEdge inverters is that they cannot support such a high Wp compared to the SMA and Fronius inverters
- the inverters from SMA have the highest efficiency. Another big advantage of this inverter is that there is a wide range of SMA inverters available on the market. There are inverters where the rated power can go to values of 11000W. The biggest inverters of SolarEdge and Fronius have a rated power of only 27500W and 20000W. In addition, the minimum input voltage of the SMA inverters is the lowest, which means that fewer solar panels need to be installed in a string to activate the inverter. Finally, the SMA inverters have the highest maximum input voltage, which means that more panels can be connected per string than is possible with the Fronius and SolarEdge inverters
- the inverters of Fronius are the least good and most expensive inverters. These inverters are the most expensive and have the lowest efficiency. Besides that, the biggest inverter of Fronius as discussed in the previous point achieves a rated power of only 20000W

After studying various inverters from different manufacturers, further simulations in the thesis will be carried out with the inverters from SMA. The reason for this is that these inverters have the best characteristics and a very good price-performance ratio. Also, the PV installations on the Montilivi campus are large (mostly above 100kWP). Because of this, it is appropriate to use larger (SMA) inverters. Another reason why the choice fell on this manufacturer is that SMA has inverters available with a rated power of up to 110000W. For achieving a nominal power of 110000W, 4 SolarEdge SE27.6K inverters or 6 Fronius Symo 20.0-3M inverters must be installed. This costs more than 1 SMA Sunny Tripower CORE2 inverter.

For the datasheets of these inverters, see Appendix F. This contains useful information, namely:

- how the AC connection should be made,
- what the input and output characteristics are,
- what protections there are in the inverter,
- some general information (noise, dimensions, operating temperature, ...),
- additional accessories and functions.

3.5.3 Determining the strings

In previous parts, the actual maximum generated output power of the PV installation was determined, and a choice of inverter manufacturer was made. Based on this, the strings for each PV installation can be calculated correctly. First, an example calculation is worked out to show how the strings of a PV installation should be determined. For this example calculation, the PV installation of the faculty of Science with SPR-MAX3-400 solar panels is used. Then, with the help of the Sunny Design software, the best possible string configuration is created for each installation and each type of solar panel.

The first step in the calculation is to consider the size of the solar installation. Depending on the maximum output power of the installation, the size of the inverters can be chosen. For the Faculty of Science, the installed power is 231.6 kWp. This is what the PV installation will be able to deliver in optimal conditions. However, using PVGIS, it was determined that this installation can deliver a maximum output power of 204.1kW. It is therefore not necessary to choose the inverters in such a way that they can deliver the peak power of 231.6 kWp. If the inverters together can deliver 204.1 kW, the maximum power produced by the modules of the PV installation on the Science building can be delivered.

As a second step, the characteristics of the solar panel must be considered to determine the optimal inverter. The table below lists important characteristics of the SPR-MAX3-400 that are relevant for the inverter.

Table 11: Important features SPR-MAX3-400

Vmpp (V)	Voc (V)	Pnom (W)
65,8	75,6	400

V_{OC} is the open-circuit voltage of a single solar module, V_{mpp} is the maximum voltage of a single solar module, and P_{nom} is the maximum power of a single solar module [8].

Now that these characteristics are known, the next step is to respect the voltage limits of the inverter, using Table 24 and Table 11. Both the minimum and maximum input voltage of the inverters must be taken into account. Because the PV installations on the Montilivi campus are large (100kWp and more), there will be opted for larger inverters. Therefore, only the input voltages of the Sunny Tripower 15000TL, 20000TL, and 25000TL and the Sunny Tripower CORE2 are considered. For the first three, the maximum input voltage is 1000V and the minimum input voltage is 150V. For the Sunny Tripower CORE2, the maximum input voltage is 1100V and the minimum input voltage is 200V.

With the help of the formulas below, it is possible to determine for the Sunny Tripower 15000TL, 20000TL, and 25000TL and the Sunny Tripower CORE2 how many modules must be connected to these inverters per string to comply with the minimum input voltage.

<u>Sunny Tripower 15000TL, 20000TL, and 25000TL:</u>

$$n = \frac{Minimum\ input\ voltage\ inverter}{V_{mpp} * k} = \frac{150}{65{,}8 * 0{,}85} = 2{,}68 \approx 3 \qquad (4)$$

k is a safety factor [31] taking into account the temperature coefficient and n is the minimum amount of panels to be installed in a string. For the Sunny Tripower 15000TL, 20000TL, and 25000TL inverters at least three SPR-MAX3-400 modules must be installed per string.

Sunny Tripower CORE2:

$$n = \frac{Minimum\ input\ voltage\ inverter}{V_{mpp}*k} = \frac{200}{65{,}8*0{,}85} = 3{,}58 \approx 4 \qquad (5)$$

For the Sunny Tripower CORE2 inverter, at least four SPR-MAX3-400 modules must be installed per string.

The next step is to calculate the maximum amount of solar panels that can be placed in a string of an inverter. The maximum number of solar panels can be determined by considering the maximum input voltage of the inverter. It should also be noted that the rule of thumb with this calculation is to take the open terminal voltage plus 15%. Thus, the maximum input voltage is never going to be exceeded [31].

Sunny Tripower 15000TL, 20000TL, and 25000TL:

$$n = \frac{Maximum\ input\ voltage}{V_{OC}*1{,}15} = \frac{1000}{75{,}6*1{,}15} = 11{,}50 \approx 11 \qquad (6)$$

For the Sunny Tripower 15000TL, 20000TL, and 25000TL, a maximum of eleven SPR-MAX3-400 solar modules may be installed in a string.

Sunny Tripower CORE2:

$$n = \frac{Maximum\ input\ voltage}{V_{OC}*1{,}15} = \frac{1100}{75{,}6*1{,}15} = 12{,}65 \approx 12 \qquad (7)$$

For the Sunny Tripower CORE2, a maximum of twelve SPR-MAX3-400 solar modules may be installed in a string.

The same calculation was also carried out for the VERTEX PERC and JKM390M-6RL3-B solar panels. The table below shows the minimum and maximum panels to be installed when using these two panels.

Table 12: Number of minimum and maximal panels for different SMA inverters

	Minimum number of Solar modules			Maximum number of Solar modules	
	VERTEX PERC	JKM390M-6RL3-B		VERTEX PERC	JKM390M-6RL3-B
Sunny Tripower 15000TL, 20000TL, and 25000TL	6	5		23	19
Sunny Tripower CORE2	8	7		25	21

Now that these data are known, a configuration can be made for each PV installation. With the help of Sunny Design, it is easy to compare different inverter configurations and choose the best one. Sunny Design also takes into account the size of the installation and the minimum and maximum voltage that the inverter can handle. This ensures that the inverters are always correctly connected. In Appendix G, the configurations of the different PV installations can be found.

3.6 Support system

Now that the solar panels and corresponding inverters have been selected, a choice can be made for a support system. The support system ensures that the solar panels can be fixed on the roof at their ideal tilt angle. It is also essential that the support system prevents the solar panels from starting to fall on the roof when weather conditions are poor.

There are various support systems on the market. While studying the market, it was noticed that one should pay attention to the following aspects when choosing the right support structure

- possible inclination angles
- dimensions
- number of panels per support structure
- whether it is used to place landscape or portrait format panels
- what force and wind speed it can withstand

After a thorough search of several sites, a support structure by Aliscolar was chosen. On Alibaba.com, this product is sold at a discount, mainly because the price per unit decreases when purchasing large quantities. Thus, for an installation of 1000-99999W the product costs €0.0649 per Watt, from 100000W to 999999W only €0.0556 per Watt, and above 1000000W only €0.0463 per Watt. It is also possible to set the inclination angle to 36° with this support structure. This is exceptional, because most support structures can only be set to a few fixed inclination angles, but not to the most optimal 36° as previously determined. The table and figure below give more information about the product details, and what the product looks like.

Table 13: Support structure product details

Place of Origin:	Jiangsu	Brand Name:	Alicosolar
Model Number:	AS-F0210-a4a0	Product name:	solar system mounting bracket
Material:	Stainless Steel, Aluminum	OEM Service:	Available
Application:	pv panel mounting bracket	Feature:	Corrosion resistance
Wind load:	<60m/s	Snow load:	1.4KN/m2
Angle:	5°~66°	Warranty:	25 years
Standard:	AS1170.2 TUV SGS		

Figure 35: Support structure

3.7 Dimensioning and choice of the DC cabling

Now that the PV panels, inverters, and the support structure have been chosen for each building, the next step is to connect the PV panels and inverters using cables. This section will dimension the cables for each building and each configuration. This makes it possible to calculate the price of the cabling for each configuration that can later be implemented in the economic comparison.

3.7.1 Collecting the data

To correctly dimension the DC cabling, some data must first be obtained. This data is needed to determine the minimum section required for the cabling. The variables listed below influence the calculation of the optimal cable section:

- Panel inclination angle,
- azimuth,
- location of the PV plant,
- number of arrays of an installation,
- the peak power,
- the number of strings/panels,
- the length of the cable,
- characteristics of the PV module.

Using these variables, a first simple calculation can be made for each array to determine the MPP voltage, the MPP current, and the short-circuit current. These three data are important for further calculation of the minimum cable section.

$$U_{MPP} = \frac{number\ of\ panels}{number\ of\ strings} * U_{MPPpanel} \qquad (8)$$

$$I_{MPP} = number\ of\ strings * I_{MPPpanel} \qquad (9)$$

$$I_{short\ circuit} = I_{open\ circuit} * number\ of\ strings \qquad (10)$$

3.7.2 Calculation of the minimum cable section [32]

In the second step of the calculation, the minimum cable section is determined. This is done using the maximum voltage drop and the maximum generator current that can occur.

<u>Based on the maximum generator current:</u>

Before the maximum generator current can be determined, the maximum short-circuit current must first be determined. The maximum short-circuit current is a temperature-dependent value. After that, the generator current can be determined by taking into account some correction factors (established by the standard). Based on the calculated maximum generator current, the appropriate section can then be determined using a table containing three different parameters (insulation, cable material, and the maximum generator current). The formulas below illustrate the calculation.

$$I_{max\ short-circuit\ current} = \left(1 + 0{,}0003 * \left(T_{maximal} - T_{standard}\right)\right) * I_{short-circuit\ current} \qquad (11)$$

$$I_{max\ generator} = 1{,}25 * \frac{I_{max\ short-circuit\ current}}{2*0{,}9} \qquad (12)$$

By using the table below, the minimum cable section can be read off. For example, a maximum generator current of less than 140A and greater than 110A will require a minimum cross-section of 25mm² (see highlighted values).

Table 14: Minimum cable section based on the maximum generator current

Required cross section													
	mm²	Maximum current after temperature correction (A)											
Cu	1,5	11	11,5	13	13,5	15	16	16,5	19	20	21	24	25
	2,5	15	16	17,5	18,5	21	22	23	26	26,5	29	33	34
	4	20	21	23	24	27	30	31	34	36	38	45	46
	6	25	27	30	32	36	37	40	44	46	48	57	59
	10	34	37	40	44	50	52	54	60	65	68	76	82
	16	45	49	54	59	66	70	73	81	87	91	105	110
	25	59	64	70	77	84	88	95	103	110	116	123	140
	35	72	77	86	96	104	110	119	127	137	144	154	174
	50	86	94	103	117	125	133	145	155	167	175	188	210
	70	109	118	130	149	160	171	185	199	214	224	244	269
	95	130	143	156	180	194	207	224	241	259	271	296	327
	120	150	164	188	208	225	240	260	280	301	314	348	380
	150	171	188	205	236	260	278	299	322	343	363	404	438
	185	194	213	233	268	297	317	341	368	391	415	464	500
	240	227	249	272	315	350	374	401	435	468	490	552	590
	300	259	285	311	360	396	423	481	525	565	630	674	713
Al	2.5	11.5	12	13.5	14	16	17	18	20	20	22	25	-
	4	15	16	18.5	19	22	24	24	26.5	27.5	29	35	-
	6	20	21	24	25	28	30	31	33	36	38	45	-
	10	27	28	32	34	38	42	42	46	50	53	61	-
	16	36	38	42	46	51	56	57	63	66	70	83	82
	25	46	5,050	54	61	64	71	72	78	84	88	94	105
	35	-	6,161	67	75	78	88	89	97	104	109	117	130
	50	-	73	80	90	96	106	108	118	127	133	145	160
	70	-	-	-	116	122	136	139	151	162	170	187	206
	95	-	-	-	140	148	167	169	183	197	207	230	251
	120	-	-	-	162	171	193	196.5	213	228	239	269	293
	150	-	-	-	187	197	223	227	246	264	277	312	338
	185	-	-	-	212	225	236	259	281	301	316	359	388
	240	-	-	-	248	265	300	306	332	355	372	429	461
	300	-	-	-	285	313	343	383	400	429	462	494	558

Based on the maximum voltage drop:

It follows from the standard that the maximum voltage drop between the generator and the point of connection should not exceed 1.5% at the MPP current. This voltage drop of 1.5% can then be further divided into a part that is responsible for the voltage drop over the main DC line (1%) and a part that is responsible for the rest of the cabling (0.5%).

Based on this percentage (1%), the theoretical maximum voltage drop can be calculated. Once the theoretical maximum voltage drop has been determined, the minimum cable section can be determined. The formulas below illustrate this calculation.

$$\Delta U_{MAX} = 0{,}01 * U_{MPP} \quad (13)$$

$$S = (L * I_{MPP})/(\Delta U_{MAX} * \gamma) \quad (14)$$

Where S is the minimum cross-section of the cable, L is the total length of the cable and γ is the resistivity.

Based on the previous two calculation methods (maximum generator current and maximum voltage drop) the minimum cable section for each array from each installation can be determined.

3.7.3 Results for the minimum cable section

This section explains what the minimum cable section must be for each PV installation. The minimum cross-section can be determined from the configurations created by Sunny Design. In some cases, an array is wired to the input of the inverter. A PV array is the parallel connection of several strings. If a PV array with more than one string is connected to the input of the inverter, the short-circuit current will increase which may cause the minimum cable cross-section to increase as well. There are mainly two things to consider when setting up a PV array:

- the panels in the array must have the same tilt angle and must face the sun in the same direction, if this is not the case there will be yield losses
- the shading must be taken into account, this problem is solved by placing a bypass diode

Table 15 below shows the short-circuit current values for the various PV modules (SPR-MAX3-400, JKM390M-6RL3-B, VERTEX PERC).

Table 15: Short circuit current

	SPR-MAX3-400	VERTEX PERC	JKM390M-6RL3-B
Short circuit current (lsc) (A)	6,58	18,14	11,32

Based on these values, Sunny Design has automatically calculated the maximum number of strings that may be placed in parallel to ensure that the inverter's maximum DC short-circuit current is not exceeded. For the Sunny Tripower CORE2, this is 40A per input and for the Sunny Tripower 15000TL, 20000TL, and 25000TL this is 43A per input. This means that with the SPR-MAX3-400 module a maximum of 5 strings can be placed in parallel, with the JKM390M-6RL3-B a maximum of 3 strings can be placed in parallel, and with the VERTEX PERC module not a single string can be placed in parallel on the input of these inverters. The latter is remarkable because 2*18,14A = 36,28A, which is less than 40 and 43A, but at higher temperatures, the short-circuit current will increase considerably. For this reason, one string is always connected to the input of the inverter for the VERTEX PERC module.

Using the formulas from section 3.7.2, the minimum cable section for each configuration can now be determined. The minimum cable section is **4mm²** in every PV installation unless 5 strings from the SPR-MAX3-400 module are connected in parallel or 3 strings from the JKM390M-6RL3-B module are installed in parallel to the inverter. In that case, the minimum cable section is **6mm²**.

3.7.4 Cable length

The last property to be determined for the DC cables is their length. The cables only need to be laid between the ends of each PV array and the corresponding inverter. The solar panels themselves are equipped with cables with connectors. Therefore, it is not necessary to take the length of a string into account when determining the cable length. Table 25 shows what the cable length should be for each configuration. Table 25 in Appendix H shows the cable length for each configuration.

From this table, it can be concluded that depending on the building, the length of the cables will differ. However, it is noticeable that the type of solar panel used does not have a great influence on the length of the cable.

3.7.5 Choice of the DC cable

Now that the minimum cable section has been determined, a choice can be made as to which DC cable will be used in the various PV installations on the Montilivi campus. In total, three agencies that sell PV cables were compared with each other, namely:

- Draka Tecsun,
- elektroproducten,
- elektramat.

On the Montilivi campus, only cables with a diameter of 4mm² and 6mm² are needed. By now comparing the price per meter of cable of each instance, the cheapest alternative can be chosen. Figure 36 shows this comparison.

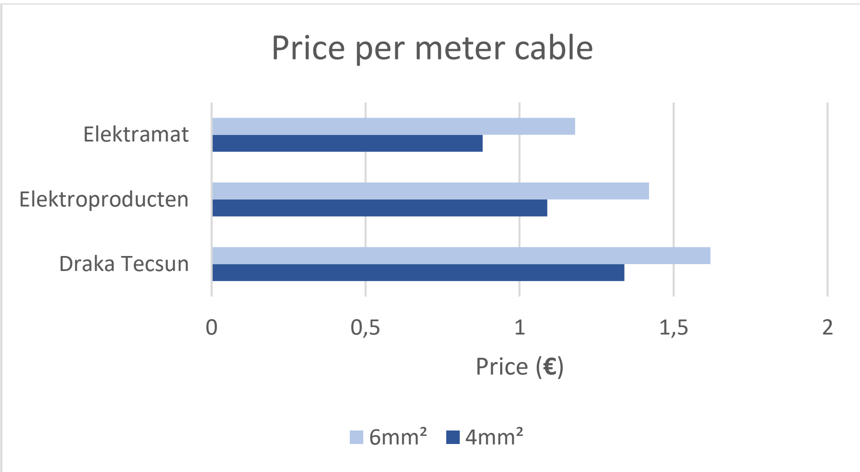


Figure 36: Price comparison for cable selection

It follows from this figure that Elektramat sells the cables at the cheapest price (€ 0,88 for 4mm² and € 1,18 for 6mm²). In addition, Elektramat gives discounts if large lengths of cable are purchased. This is not the case with Elektroproducten and Draka Tecsun.

3.7.6 MC4 connectors

Finally, to make the connections between the inverters and the PV arrays, MC4 connectors must be attached to the DC cables. On each side of the cable, one male and one female connector must be pressed with MC4 pliers. The MC4 connectors are purchased from Elektramat, just like the DC cables. The price for a male connector is €1.30 each and for a female connector €1.34 each. Table 26 in Appendix I shows the number of connectors for each configuration.

3.7.7 DC cable protection

As already discussed in section 3.7.3, the current between a PV array and the inverter should never exceed 40A and 43A (depending on the inverter). Therefore, fuses are used on the DC side of the cables. A fuse protects the PV array against excessive currents. If a short circuit or overload occurs (too high current), the wire of the fuse melts and the circuit is interrupted.

For the PV installations at the Montilivi campus, there are fuses chosen sold by Electromaterial. The fuses cost €1.50 each and cut off the current when it exceeds 40A. It is also advisable to install fuse holders. These cost €4.50 each. These two items can be found in Appendix J.

3.8 From the inverter

When the DC cables are connected to the inverter, there can now be taken a closer look at what is happening from the inverter. This section briefly discusses AC cabling and how the energy management of each installation can be done.

3.8.1 AC cabling

Once the DC cables have been connected to the inverter, the inverter can convert the direct current into alternating current. As previously discussed in section 3.5.2, the datasheet of the inverter indicates how the AC connection can be made and what the output characteristics of the inverter are. For the Sunny Tripower CORE2, it can be seen that the AC connection is three-phase and that an earthing cable must also be provided. For the Sunny Tripower 15000TL, 20000TL, and 25000TL and the Sunny Tripower CORE2 the connection must be 3-phase where no earthing cable is required. Depending on where the cables run, the length will vary. For this reason, it is difficult to say how much money exactly has to be spent on these cables.

3.8.2 Energy management

The energy management of the installation is important for most private individuals and companies to have an overview of the generation and consumption of their buildings. How the energy management of a PV installation is done depends on which inverters are used in the installation. For example, if there is no Sunny Tripower CORE2 inverter placed in the PV installation, the energy management will be done without the need of an SMA Data Manager M. If, however, a Sunny Tripower CORE2 inverter is installed in the PV installation, the SMA Data Manager M is required. This section discusses how the energy management of a PV installation works and how it will differ depending on the installation (with or without Sunny Tripower CORE2 inverter).

<u>With Sunny Tripower CORE2 inverter:</u>

If a Sunny Tripower CORE2 inverter is installed in the PV installation, the installation of an SMA Data Manager M is required. The SMA Data Manager M is a data logger which functions as an energy manager and system gatekeeper. Using an Ethernet interface, various PV system components can be integrated into the SMA structure along with power generators and energy consumers. Up to 25 appliances including inverters, battery inverters, energy meters, and up to three I/O systems can be linked to the SMA Data Manager M [33]. It can be purchased for €695.00.

As the Sunny Tripower CORE2 does not have a web connect interface, it is not possible to connect the inverter directly to the Sunny Portal app via the internet. However, Sunny power has two Ethernet interfaces. This allows the Sunny Tripower CORE2 inverter to be linked to the SMA Data Manager M via an Ethernet cable [33]. The three other inverters (Sunny Tripower 15000TL, 20000TL, and 25000TL) do not have an Ethernet interface but a Speedwire interface. Therefore, a Speedwire connection is established between these inverters and the SMA Data Manager M. A Speedwire is a cable, based on the Ethernet standard and the SMA Data2+ communication protocol [34]. Once the inverters have been connected to the SMA Data Manager M, a connection can be made with the Sunny Portal app via the web. This is an internet connection and allows the remote data from an SMA Data Manager M to be visually displayed. Figure 37 and Figure 38 show how the SMA Data Manager M can be connected with other systems.

Note: The systems in Figure 38 (outside the inverters) that are linked to the SMA Data Manager M are optional.

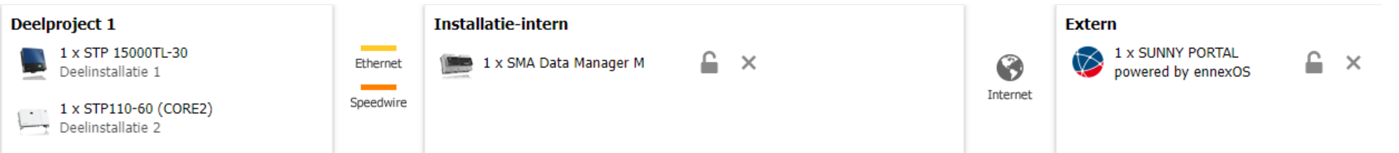


Figure 37: Example intern and extern connection with SMA Data Manager M

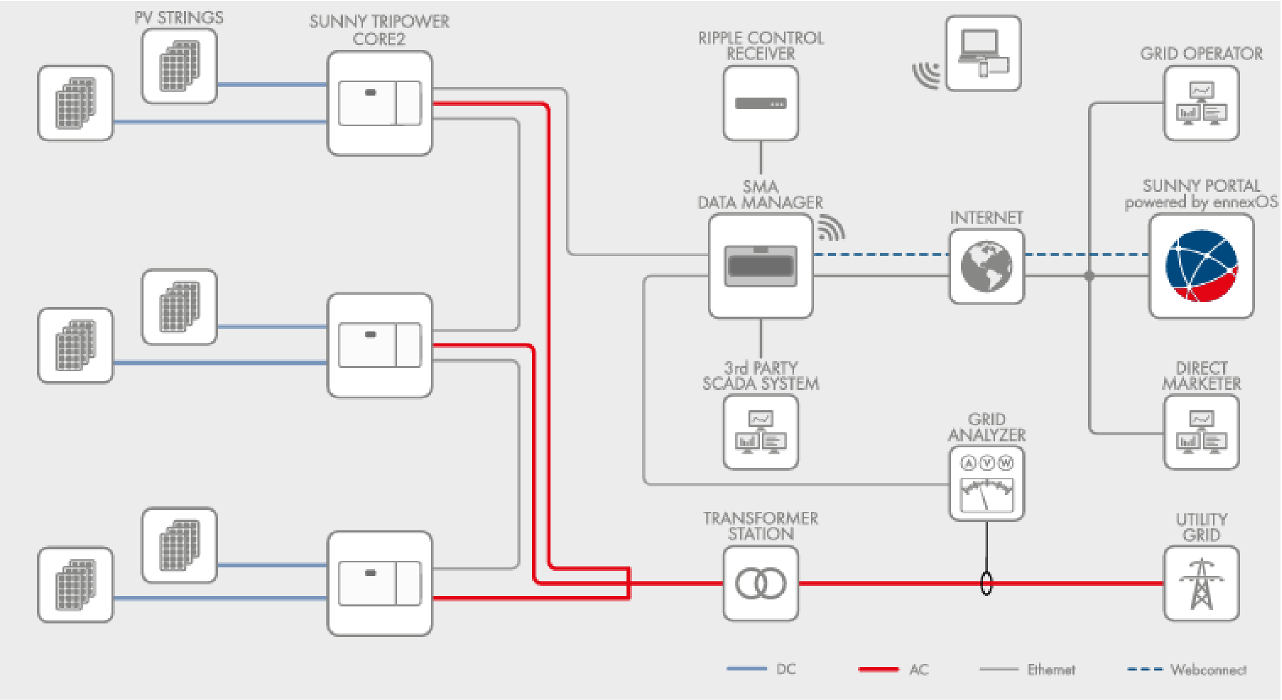


Figure 38: Possible connections SMA Data Manager M [35]

<u>Without Sunny Tripower CORE2 inverter:</u>

If no Sunny Tripower CORE2 inverter is used in the PV installation, the use of an SMA Data Manager M is not necessary. In an installation where only a Sunny Tripower 15000TL, 20000TL, or 25000TL is used, the connection can be made directly via the internet. This is because these inverters do have a web connect interface that allows them to connect via the internet with the Sunny Portal app. Figure 39 shows this connection.

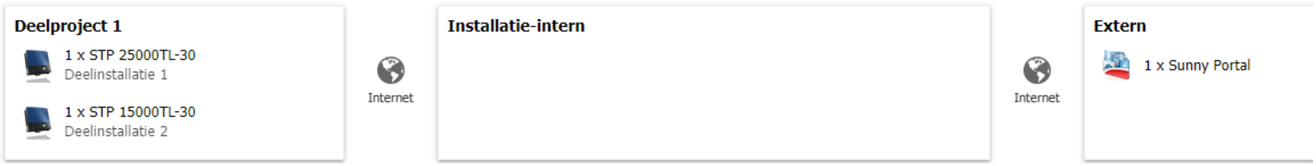


Figure 39: Example intern and extern connection without SMA Data Manager M

3.9 A battery or not?

This section discusses whether the use of a battery is a good choice for different PV installations. If the PV installation generates more power than it consumes, it is possible to store the surplus power in a battery. Doing so can further increase self-consumption. It is also possible to feed the surplus power into the grid. Which of these two solutions is the most profitable is briefly explained here.

A first point to consider is the amount of consumption in the buildings and the amount of production of electricity per building. Almost each PV installation of each building generates less electricity than it consumes during the year (see sections 3.4 and 3.5.1). Although more will be produced than consumed at some moments, in general, no, or little, overproduction of electricity will occur.

In addition, it can be seen how long a fully charged battery can store the surplus energy from the solar panels. A fully charged battery can store its energy for an average of one to five days [36]. This is not very long and will not make an additional contribution to the Montilivi campus. At the school, there is activity between 8 am and 6 pm. During this time the sun shines so that the total self-consumption can be compensated by the energy generated by the installed PV panels. During the evening and night, there is little or no activity on campus so the energy stored in the battery will not provide added value.

Finally, a battery for storing solar energy is not cheap. Depending on the size of the battery, the price per kWh that it can store will vary. The figure below shows how much an average solar battery system (including installation) costs per kWh that it can store.

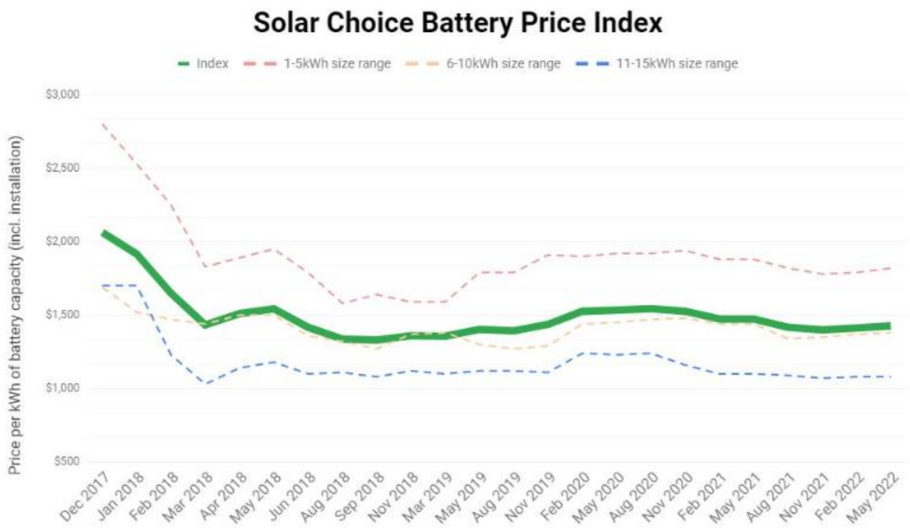


Figure 40: Price per kWh for different sizes of batteries [37]

It can be seen from Figure 40 that the price has not fallen in the past three years. There is a need for new technology to bring this price down further in the coming years. This will make the use of a battery more economically interesting.

Because of these three arguments, the use of batteries for the PV installations at the Montilivi campus is not a good choice. The investment in batteries is not going to bring any economic benefits.

3.10 Economic analysis

In this part, an economic analysis is made for the different PV installations. To make this analysis as thorough and detailed as possible, the following economic parameters are considered:

- investment cost per installation,
- electricity production costs for 20 years,
- annual profit (IRR),
- payback period,
- total savings after 20 years.

To correctly determine the economic parameters, it is important to look up some prices in advance. Professor Montoro shared information that the university currently has to pay 0.0839 € /kWh for electricity. This is a reduced rate because the university belongs to the government. In addition, Professor Montoro also indicated that the annual rate of increase in electricity prices is approximately 5%. Research work further revealed that the duration of the subsidy is 25 years. Finally, the price for selling electricity to the grid must be determined. This fluctuated hard the recent years. From January 1, 2022, to the present day, the average price is 0.215 €/kWh. For determining the economic parameters, this price was taken, but it should be taken into account that this price can still change significantly over the coming years. Figure 41 shows the fluctuation of electricity sales over recent years.

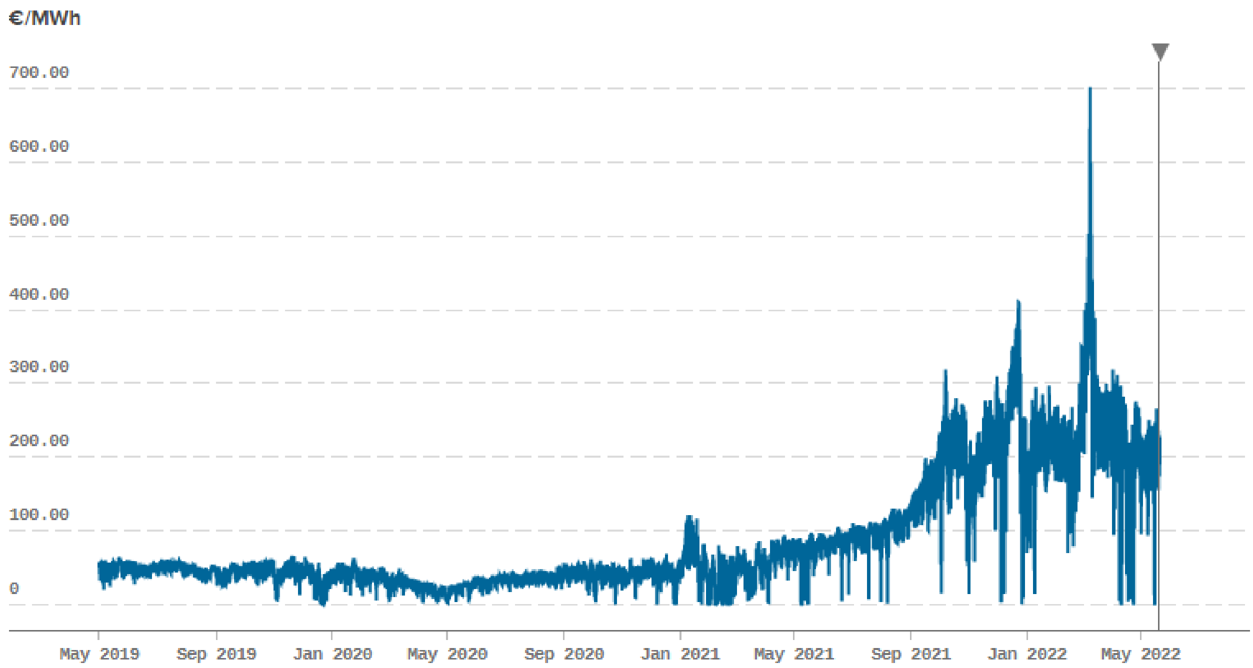


Figure 41: Price over the last years for selling electricity to the grid [38]

Based on these parameters and information an economic comparison can be made for the different PV installations (with SPR-MAX3-400, JKM390M-6RL3-B, or VERTEX PERC module) of each building of the Montilivi campus. In this way, the most economical PV installation for each building can be determined.

3.10.1 Investment cost per installation

Installing a PV system costs money. This section gives a visual indication of the total investment required for the installation of each system. To determine this investment as accurately as possible, the following costs are taken into account:

- price of the solar panels,
- price of the inverter ears,
- price of the support structure,
- price of the cables,
- price of the MC4 connectors,
- price of the DC cable protection,
- price of the energy management,
- taxes,
- installation cost.

The price of these costs was always mentioned in previous sections. Only the installation cost of each PV installation was not discussed in previous sections. This is estimated at ± 25% of the overall cost. Depending on the total price of the materials for the PV installation, the installation cost will increase or decrease. In addition, 21% tax must always be paid along with the total installation cost.

By taking the sum of the above costs, the total investment cost for each PV installation can be determined (see Figure 42).

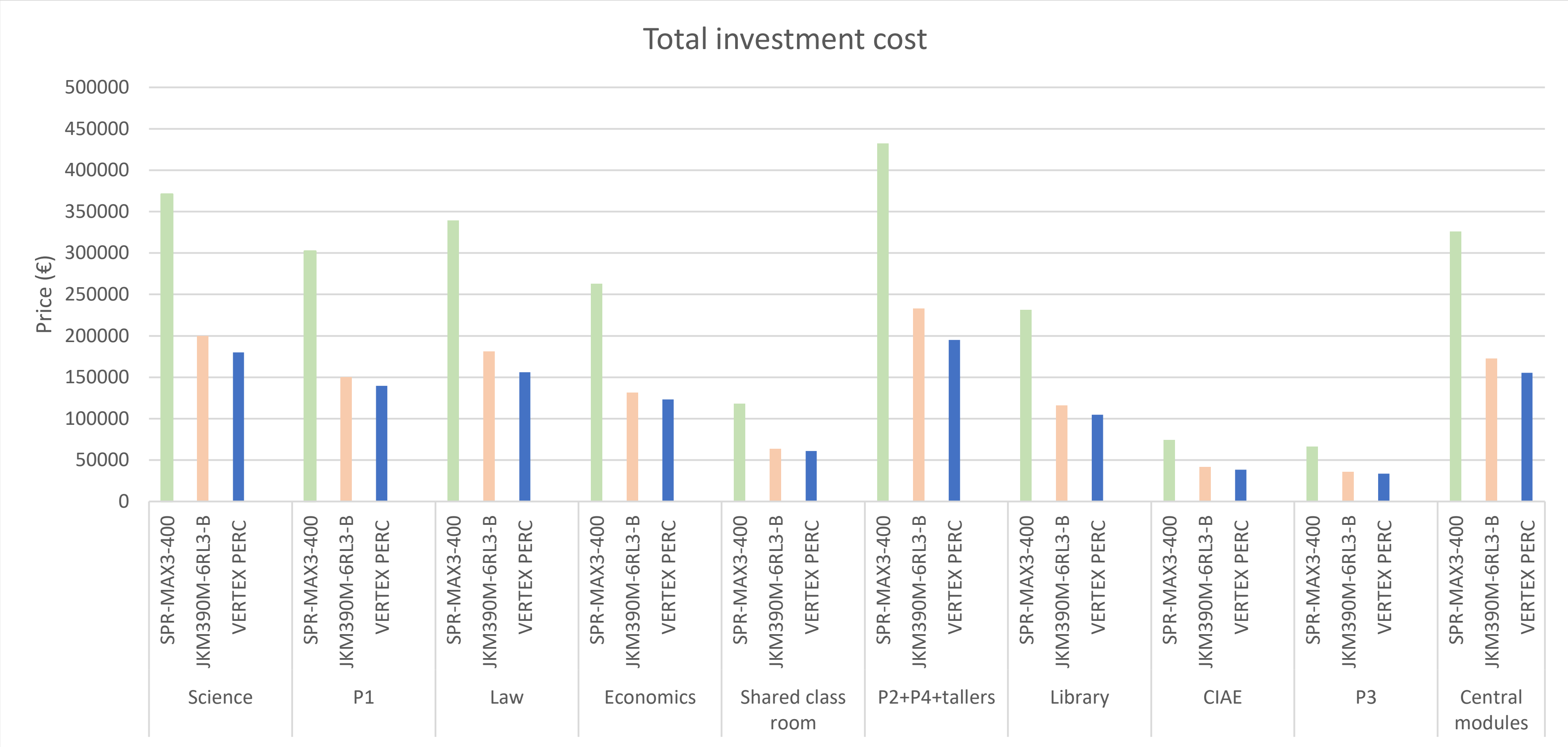


Figure 42: Investment cost for the different PV installations

In Figure 42 it is visible that the PV installations that use the SPR-MAX3-400 module have the highest investment cost. This is because the SPR-MAX3-400 module is rather expensive (€334) compared to the JKM390M-6RL3-B and VERTEX PERC (€168 and €224). In addition, it can be concluded that for a PV installation where a JKM390M-6RL3-B or VERTEX PERC module is used, the investment cost is slightly in favour of the VERTEX PERC module despite the difference in module prices. This is because the JKM390M-6RL3-B module is smaller than the VERTEX PERC module so more panels can be installed. **Based on this economic parameter, the VERTEX PERC module is the best choice.**

3.10.2 Electricity production costs for 20 years

The electricity production costs are calculated using the investment, financing, and operating costs ratio concerning the PV energy produced within the operating period. This includes the degradation of the solar panels in the generated energy and the inflation percentage in the operating costs. Figure 43 shows for each installation what the electricity production cost is seen over 20 years.

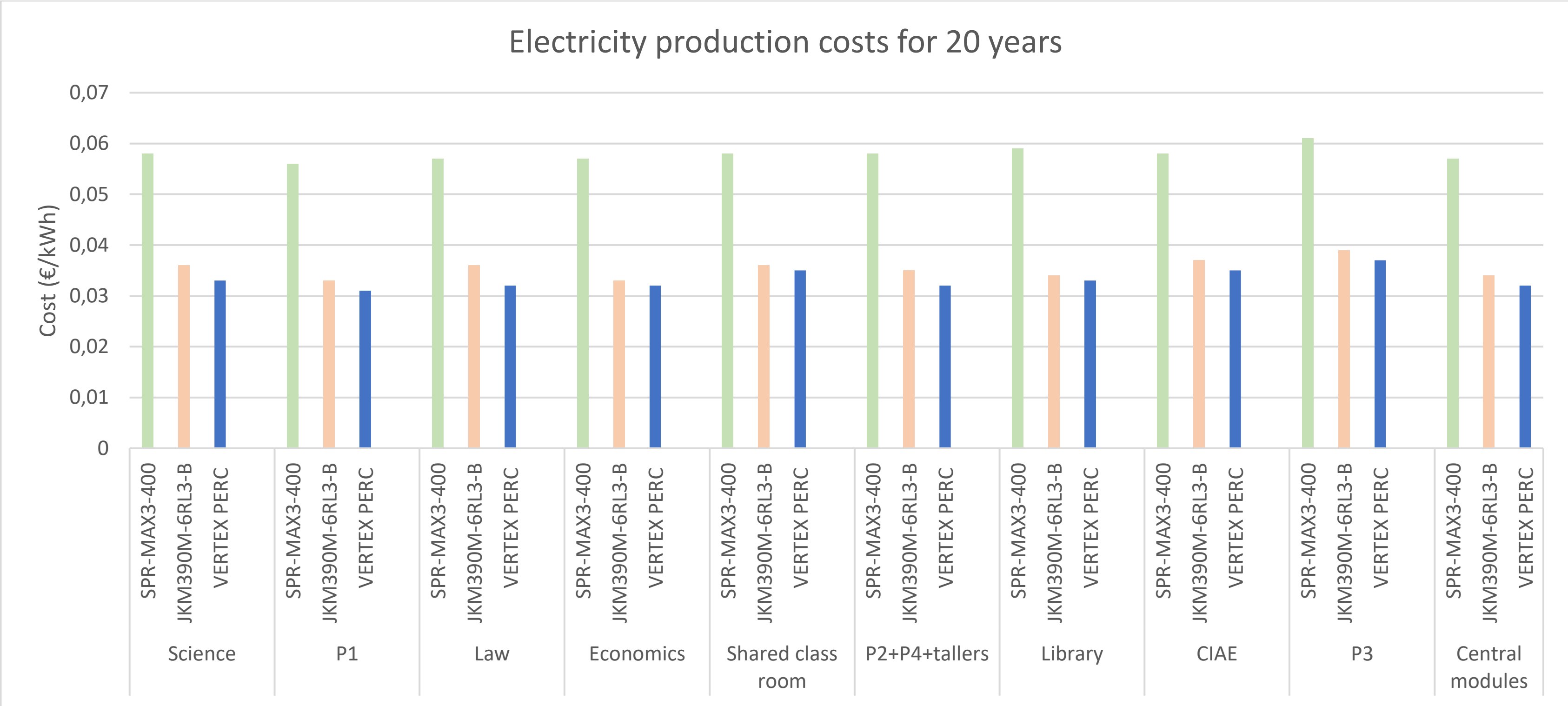


Figure 43: Electricity production cost for 20 years for the different PV installations

From this figure, it can be concluded that the installations using the SPR-MAX3-400 module will cost the kWh produced more (average 0.058 €/kWh) than installations using a JKM390M-6RL3-B (0.035 €/kWh) or VERTEX PERC (0.033 €/kWh) module. **Based on this economic parameter, the VERTEX PERC module is the best choice.**

3.10.3 Annual profit (IRR)

The IRR is the expected return on investment, taking into account the timing and level of cash flows for expenses and revenues concerning the investment. The return on the total investment is related to the total capital invested (investment cost) and places it on the profit (feed-in tariff + off-take cost savings + energy consumption tariff - self-consumption charge - operating costs). For the calculation long-term influences on the return due to inflation, module degradation, and power tax rates are taken into account. It should be noted, however, that the IRR only indicates if the investment in a project is worthwhile, but not which project is preferred. It may be that if two projects are compared that one project has a higher IRR value than the other, while the other project is going to have a higher total money growth. Figure 44 shows the IRR value for each installation.

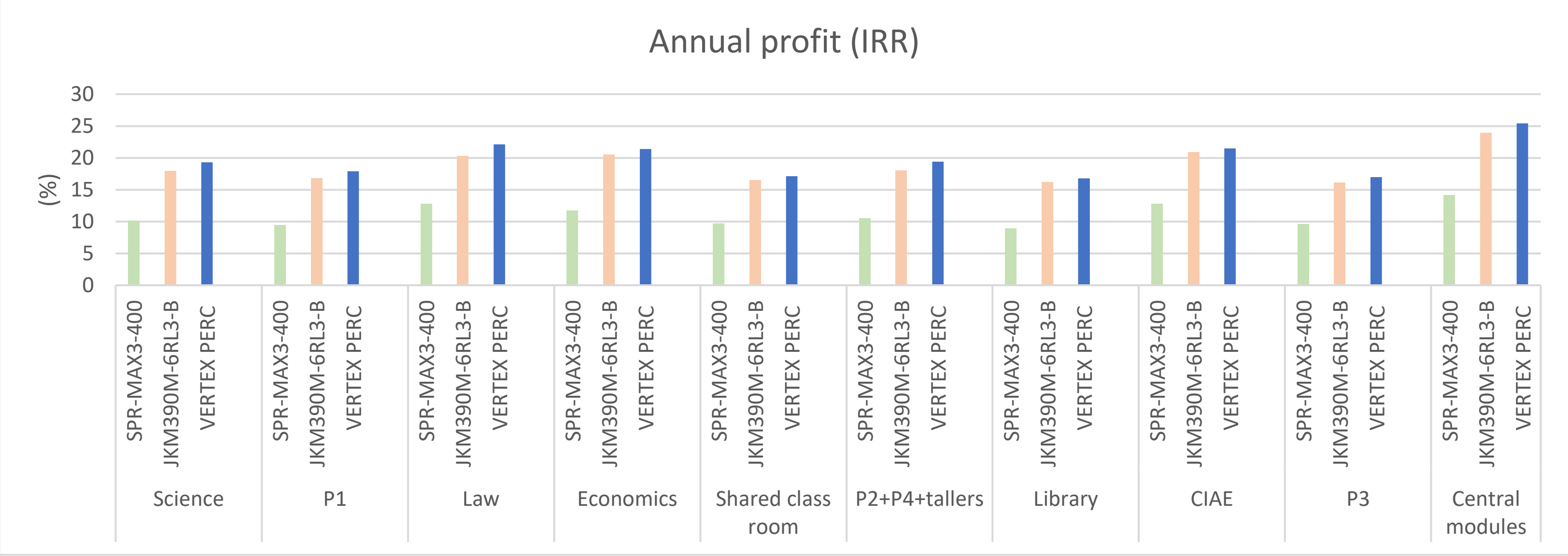


Figure 44: Annual profit (IRR) for the different PV installations

From this figure, it can be concluded that in the installations where the VERTEX PERC module is used the IRR is on average the highest (19,79%). This means that investing in this module is a good choice. But also the IRR values of the installations where the SPR-MAX3-400 and JKM390M-6RL3-B module is used are high. **From this calculation follows that investing in one of these modules is a good choice**

3.10.4 Payback period

The payback period indicates how long it takes before the invested amount is earned back. Once this amount is earned back, a profit is made on the earlier investment. Figure 45 shows the payback period for the different installations.

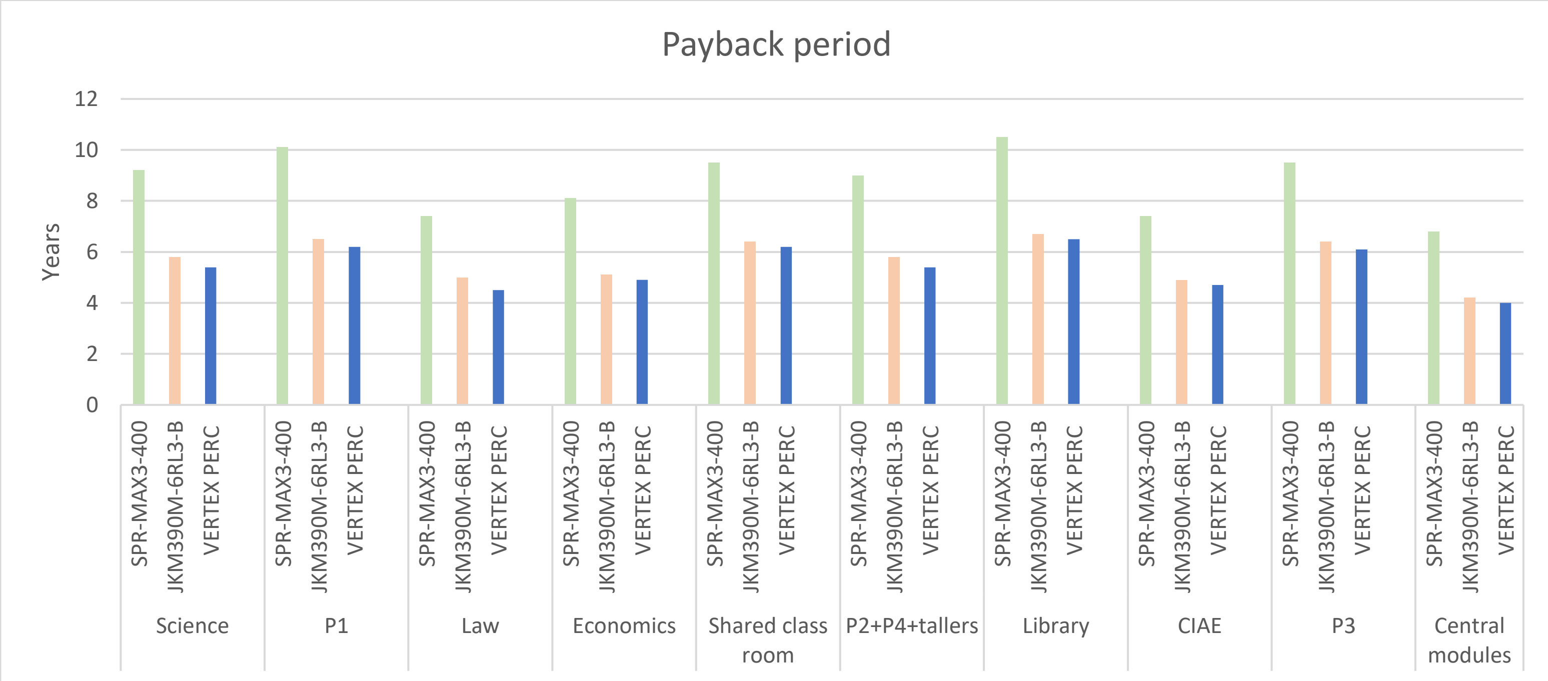


Figure 45: Payback period for the different PV installations

From the determination of the payback period it can be observed in the figure above that it takes longer to earn back the invested amount in installations that use the SPR-MAX3-400 module (8.75 years on average). This is because as discussed earlier the investment amount is a lot higher when using these modules (see figure 42). For the installations where the JKM390M-6RL3-B module is used, the payback period is on average 5,68 years. For installations where a VERTEX PERC module is used, the average payback period is 5,39 years. Based on this, it can be concluded that the payback period of the VERTEX PERC module is the lowest. **If the University of Girona wants to recover its investments as soon as possible, installations using the VERTEX PERC module are the best choice.**

3.10.5 Total savings after 20 years

The total savings after 20 years are calculated from the total electricity cost savings and the feed-in tariff. The investment costs, financing costs, and operating costs are deducted from this. This includes the inflation rate for operating costs and the rate of increase in electricity prices for electricity costs. In addition, the degradation of the solar panels is taken into consideration in the calculation of the feed-in tariff. Figure 46 shows the total savings after 20 years for each PV installation.

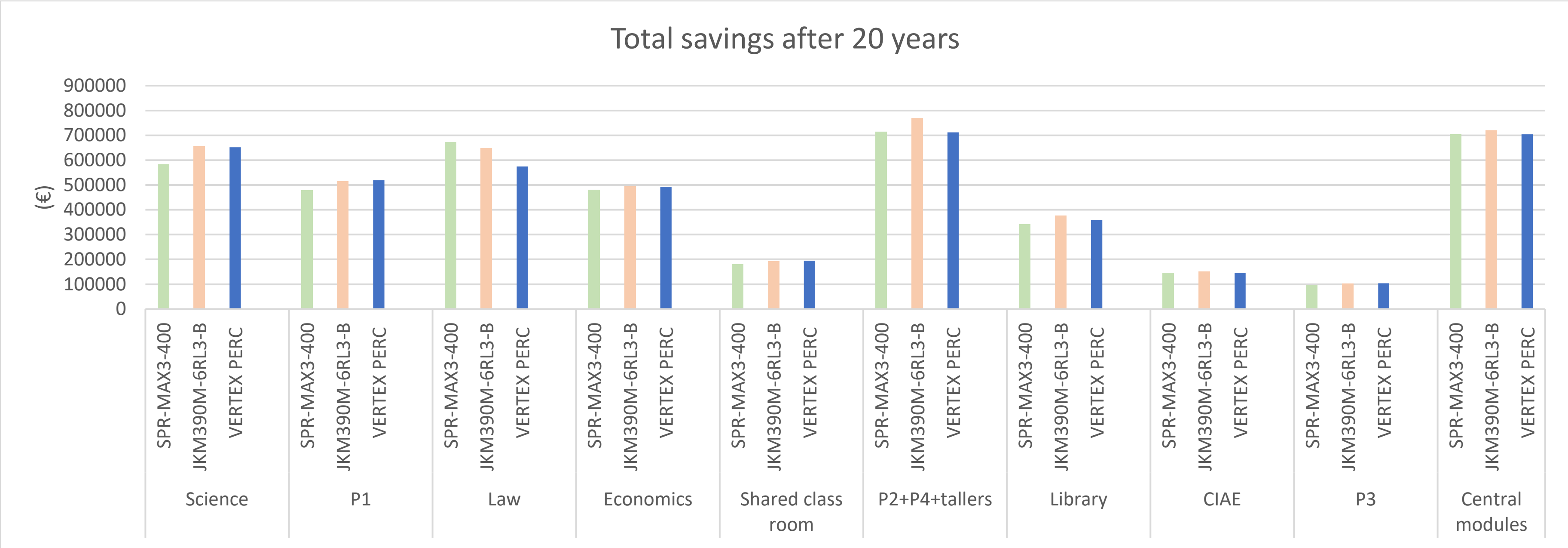


Figure 46: Total savings after 20 years for the different PV installations

From this figure, it can be concluded that installations that use the JKM390M-6RL3-B module will save the most money after 20 years. By taking the sum of the total savings of the different installations where the SPR-MAX3-400 module is used it can be concluded that in total €4402360 can be saved. In the case of installations where the JKM390M-6RL3-B module is used, a total of €4629290 can be saved. Finally, for installations using the VERTEX PERC module, total savings of €4456930 can be made. **Based on this economic parameter, it is best to choose installations using the JKM390M-6RL3-B module.**

3.10.6 Conclusion economic analysis

From the economic analysis, it can be concluded that for the installations where the SPR-MAX3-400 module is used, the investment cost and the electricity production costs will be the highest for this module. In addition, the annual profit (IRR) will be the lowest, which indicates that the return on the total investment is the lowest. It will also take longer to recover the investment cost for installations using this module. Finally, it was demonstrated that installations using the SPR-MAX3-400 module can save a total of €4402360 after 20 years. **From this, it can finally be concluded that based on economics the SPR-MAX3-400 module is not the best choice.**

The installations using the JKM390M-6RL3-B module have more or less the same investment cost and electricity production cost for 20 years as the installations using the VERTEX PERC modules. In addition, the payback period for the installations of this module is 5.39 years on average. In addition, €4629290 can be saved after 20 years. These installations return 226930 and 172360 euros more after 20 years than installations using the SPR-MAX3-400 module and VERTEX PERC module, respectively. **Based on this, it can be concluded that in the long run, installations using the JKM-390M-6RL3-B module will be the most economical.**

The installations using the VERTEX PERC module have the lowest investment cost and electricity production cost over 20 years. In addition, the IRR for these panels is on average the highest and the payback period the lowest. These installations have a 3.36 and 0.29 year faster payback than using the SPR-MAX3-400 module and JKM390M-6RL3-B module, respectively. In conclusion, installations using this type of panel are going to save €4456930 over 20 years. **Based on this, it can be decided that this panel is the most economically interesting in the short term.**

3.11 Final selection of the optimal PV systems

In this section, a choice is going to be made for the final PV systems on the Montilivi campus. To do this, two things are going to be considered namely:

- the yearly production,
- CO2 reduction

By taking into account both these factors and the economic analysis performed in section 3.10 a final PV system can be chosen.

3.11.1 The yearly production

Depending on the panel chosen, the total annual production will vary. Of the total annual production of the solar panels, a part is going to be used to compensate for the consumption in the building and another part is going to be given to the grid. There are three situations where power is given off to the grid:

- the university is open between 8 am and 6 pm. Outside these hours, there is sometimes going to be generated from the solar panels, while consumption is very low. In this case, power will be provided to the grid
- during the weekends, schools are closed. Therefore, a large part of the generated power will be provided to the grid
- as discussed in section 3.4, during the summer month of August, consumption is very low. During this month, on the other hand, production is going to be high, so a lot of power is going to be provided to the grid

Figure 47 shows how much power is used per year as self-consumption and feed-in.

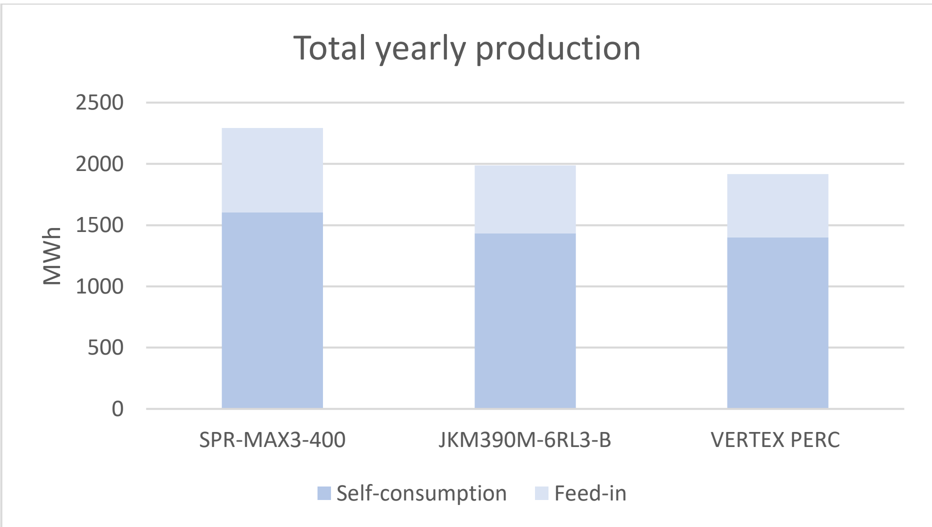


Figure 47: Total yearly production

If the Montilivi campus would opt for an SPR-MAX3-400 module, it is going to have the highest production every year (±2294MWh). This is because, on the one hand, these panels are the most efficient, and, on the other hand, as these panels age, the efficiency does not rapidly decrease. It can also be deduced from Figure 47 that about 30% of the total annual production is used as feed-in to the grid. And that the yearly production of the installations using the JKM390M-6RL3-B module is ±1987MWh per year and for the installations using the VERTEX PERC module ±1917MWh.

Note: as already discussed in section 3.10, currently the selling price of electricity to the grid is 0,215 €/kWh in Spain while the price the university has to pay for electricity is 0,0839 €/kWh. Because of this reason, the university would best sell their entire generation to the grid at this time (more economical). But since this may change in the future, it was assumed that a large part of the generation is best used to compensate for self-consumption anyway.

3.11.2 CO2 reduction

A PV installation is also going to ensure that CO2 emissions are going to be reduced. The figure below shows how much less CO2 will be emitted within the Montilivi campus when using a PV installation on each building.

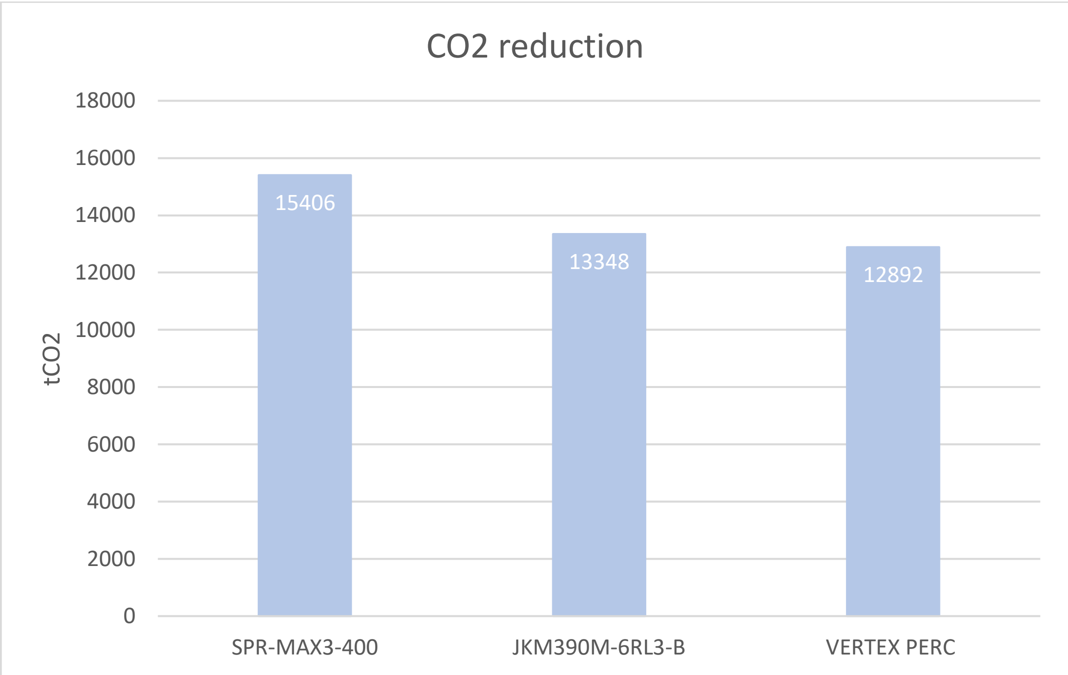


Figure 48: CO2 reduction

Because the installations where the SPR-MAX3-400 module was chosen will deliver the most power, this will also automatically ensure that the most CO2 will be reduced.

3.11.3 Conclusion final selection of the optimal PV systems

Based on generation and CO2 reduction, the SPR-MAX3-400 module is the best choice for the Montilivi campus (2514tCO2 and 2058tCO2 more reduction than the JKM390M-6RL3-B and VERTEX PERC module, respectively). The choice of installations using this module is going to be the most ecological way to create a green environment in Spain.

Depending on what is most important to the University of Girona, a more economic or a more ecological choice can be made. The most ecological choice is to opt for the installations using the SPR-MAX3-400 module. The most economical choice, in the long run, is installations using the JKM390M-6RL3-B module. The most economical choice in the short term is installations using the VERTEX PERC module.

Based on my knowledge, installations with the JKM390M-6RL3-B panel would be the best choice for the Montilivi campus. These are going to be the most economical in the long run. But in addition, these installations did not score the worst score in any of the parameters compared which make this panel the suitable choice for the Montilivi campus.

4 Additional opportunities for PV installations on the Montilivi campus

In section 3, a full investigation has been made of what the best possible PV configuration is for the different buildings on the Montilivi campus. In this section, additional possibilities will be discussed. First, there will be discussed how the efficiency of the panels can be improved by using cooling systems. After that, two possibilities for placing extra solar panels will be discussed. A first possibility is the application of building-integrated PV. A second possibility is the installation of a solar charging station.

4.1 Cooling systems

When solar panels heat up, their efficiency decreases. In section 2.3.4, the influence of heat on solar panels was discussed earlier, and which cooling techniques can be used to reduce the temperature of a panel. This study showed that water-based active cooling of the panel is a widely used technique that is economical. Also, a water-based cooling system ensures that the dirt on the panels can be removed. Because of these two reasons, it is appropriate to use a water-based active cooling system to increase the efficiency of the panels. This section discusses whether or not it is appropriate to install a water-based cooling system on the Montilivi campus.

4.1.1 The climate in Girona

Girona has a Mediterranean climate. This implies that the winters are mild and wet, and the summers are dry and hot [39]. The figure below shows the average climate data per month based on data from the last 30 years [40].

	Jan	Feb	Mrt	Apr	Mei	Jun	Jul	Aug	Sep	Okt	Nov	Dec
Temperatuur (°C)	12	12	15	17	20	25	28	28	24	21	16	13
Neerslag (mm)	24	21	41	37	33	30	20	23	32	49	44	13

Figure 49: Average climate data per month [40]

Based on these data, it can be deduced that precipitation falls all year round in Girona. Rain is not necessarily bad for solar panels. Rain ensures that the panels are cleaned of dirt that lies on them. It can also be observed that in the summer months there is significantly less precipitation than in the other months (spring, autumn, and winter months) and that the temperature is significantly higher in the summer months. For this reason, a cooling system may be appropriate to keep the temperature of the panels low during these months to increase their efficiency.

4.1.2 The system

In this section, different active water-cooling techniques that can be used for cooling solar panels are discussed. In total, three different active water-cooling systems are possible, namely:

- liquid immersion cooling,
- forced water circulation,
- water spraying.

The implementation of the systems differs fundamentally from each other. Forced water circulation requires the installation of heat pipes at the back of each panel, where a liquid is consumed as a cooling medium for cooling the cells. In the liquid immersion cooling technique, each PV module is immersed in water. Finally, with the water spraying system, water is sprayed by nozzles onto the PV module. These nozzles are connected via pipes and a pump ensures that the water can be sprayed (see Figure 50) [20].

Each of these techniques also has advantages and disadvantages. Table 16 lists the advantages and disadvantages of each technique and by how many degrees they can reduce the temperature of a PV module.

Table 16: Merits and demerits of different active water-cooling techniques [20]

Technique	Merits	Demerits	Temperature reduction
Water spraying	Very efficient Simple process	Partial cooling Wastage of water	Max 20 °C
Forced water circulation	Very efficient Reuse of water	High investment Equipment Degradation	20-30 °C
Liquid immersion	Highly efficient Eco-friendly	Low performance in cloudy days Ionised water impact	40 °C

Because forced water circulation involves a high investment cost, this is not the appropriate way to cool the PV modules on the Montilivi campus. In addition, liquid immersion is a technique that is difficult to apply to the PV modules on the Montilivi campus. With this technique, a lot of water is required to submerge all the PV modules and the installation is not easy either. For these reasons, water spraying is the most appropriate way to cool the PV modules. Although this technique has the disadvantage of wastage of water, it is a simple and efficient process. Besides that, it is a cost-effective solution.

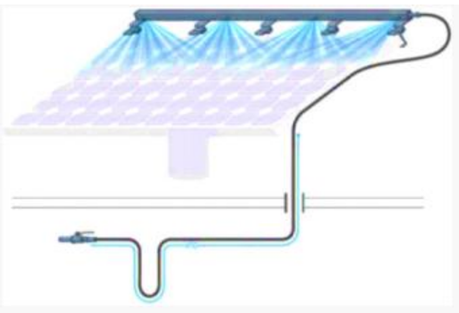


Figure 50: Water spraying installation [20]

4.1.3 Economic point of view

Whether or not it is interesting to install a cooling system requires a small calculation. According to paper [20], the electrical efficiency increases by 15% in extreme weather conditions. Assuming that extreme weather conditions take place during the summer months (high temperatures), the cooling system will only have to be used during the summer. By calculating how much extra electricity can be generated in the summer months (June, July, Augustus, and September) in the coming 20 years, it can be determined how much extra money the university can earn from it (formula 14 and 15). Based on this calculation it can be decided whether or not it is an economically sound choice to install a cooling system.

$Extra\ electricity = 0{,}15 * production\ without\ cooling\ system$ * 20 = 0,15 * 780.960kWh * 20 = 2.342.880 kWh (15)

$Extra\ money = \sum_{i=0}^{20} \frac{extra\ electricity}{20} * 0{,}0819 * 1{,}05^{i}$ = €342.694 (16)

The installation of a water spraying system also involves an additional investment cost. Sunbooster, a company that installs such installations is developing ever better water spraying installations. Sunbooster can make a water spraying installation in which the used water can be reused, filtered, and stored again. At the moment the installations they develop cost €250.000/MW, but this price will halve in the next two years between €100.000/MW and €150.000/MW [41].

In section 3.5.1, by taking the sum of, for example, the installations where the JKM390M-6RL3-B module is used, it can be calculated that the total installation is 4.5MW in size. The total installation cost of a water spray installation would therefore be around €346.625 at this time. So installing it is not relevant at the moment but maybe in the future.

4.2 Building-integrated PV (BIPV) and building applied PV (BAPV)

In section 2.5.1, we described the difference between BIPV and BAPV and what these two terms mean. In this section, we will take a closer look at the possibilities of applying BIPV or BAPV to the buildings of the Montilivi campus.

4.2.1 Possibilities BIPV

The Montilivi campus contains many modern buildings that were erected not long ago. When these buildings were erected, the possibility of using BIPV was not taken into account, which means that the possibilities are already limited.

<u>Possibility 1: photovoltaic curtain wall</u>

A first possibility that can be applied is to integrate solar panels in such a way that they can serve as a photovoltaic curtain wall. This is best done on façades facing south, south-east, or south-west. By replacing the standard curtain wall with a photovoltaic curtain wall, the building can generate electricity in this way as an additional benefit. Photovoltaic curtain walls are slightly more expensive than standard curtain walls (mainly the cabling makes photovoltaic curtain walls more expensive) but the extra costs are recouped within about 5 years [42].

There are different materials from which a photovoltaic curtain wall can be made: thin-film glass, polycrystalline glass, or monocrystalline glass. For a normal solar panel installation, crystalline solar panels are chosen because of their efficiency, but for a photovoltaic facade, the thin film is the best option for the following reasons [42]:

- better performance in low light conditions,
- better performance in shaded environments,
- performs better at extreme angles, façade has a tilt angle of 90°,
- can tolerate higher temperatures.

Replacing the existing curtain walls with photovoltaic curtain walls is a major investment. But since this investment cost can be recovered within about 5 years, it is certainly an opportunity to install photovoltaic facades on the Montilivi campus. Almost every building has curtain walls, which can significantly increase the electricity yield per building.

<u>Possibility 2: photovoltaic balustrades</u>

There are several places on the campus where food and drinks can be ordered. Two of these places have a terrace, which offers the possibility to consume the ordered drinks and/or food outside. One solution for generating additional solar energy is to place photovoltaic railings around these terraces. Besides generating energy, placing photovoltaic balustrades will also have the advantage that an attractive design will attract more students to have a drink on the terrace. This is a win-win situation for the Montilivi campus, more money will be made on two levels than without a photovoltaic balustrade.

4.2.2 Possibilities BAPV

In addition to placing PV modules on the roof, it is also possible to place PV modules on the walls of the various buildings on the Montilivi campus. However, two things should be noted here. First, it is not possible to place PV modules on every wall of each building because of the shadow. Secondly, the PV modules should always be placed on the wall where the sun will shine a lot. The red lines in Figure 51 indicate the most suitable walls for placing PV modules. All these solar panels are facing south-west (azimuth 206° on Figure 24).

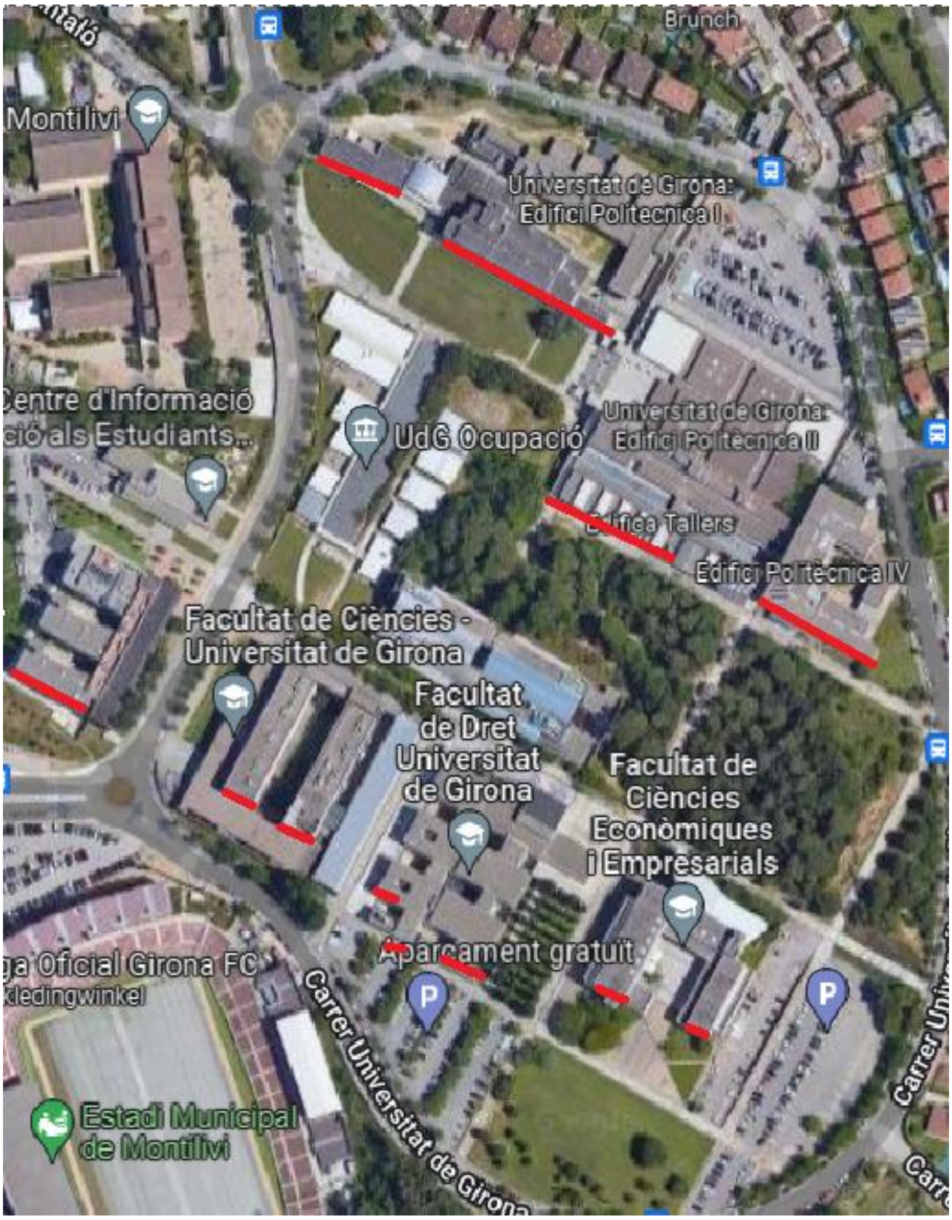


Figure 51: Possibilities to place PV modules on the walls

When PV modules are placed on the walls, they have a tilt angle of 90°. As discussed earlier, this is not the ideal angle at which a PV module in Girona should be positioned. To determine the difference in generation between a panel that is set up in an ideal position (tilt angle 36° and azimuth

180°) and a panel that is placed on a wall (tilt angle 90° and azimuth 206°), a simulation is carried out using Sunny Design. Figure 52 shows the results of this simulation.

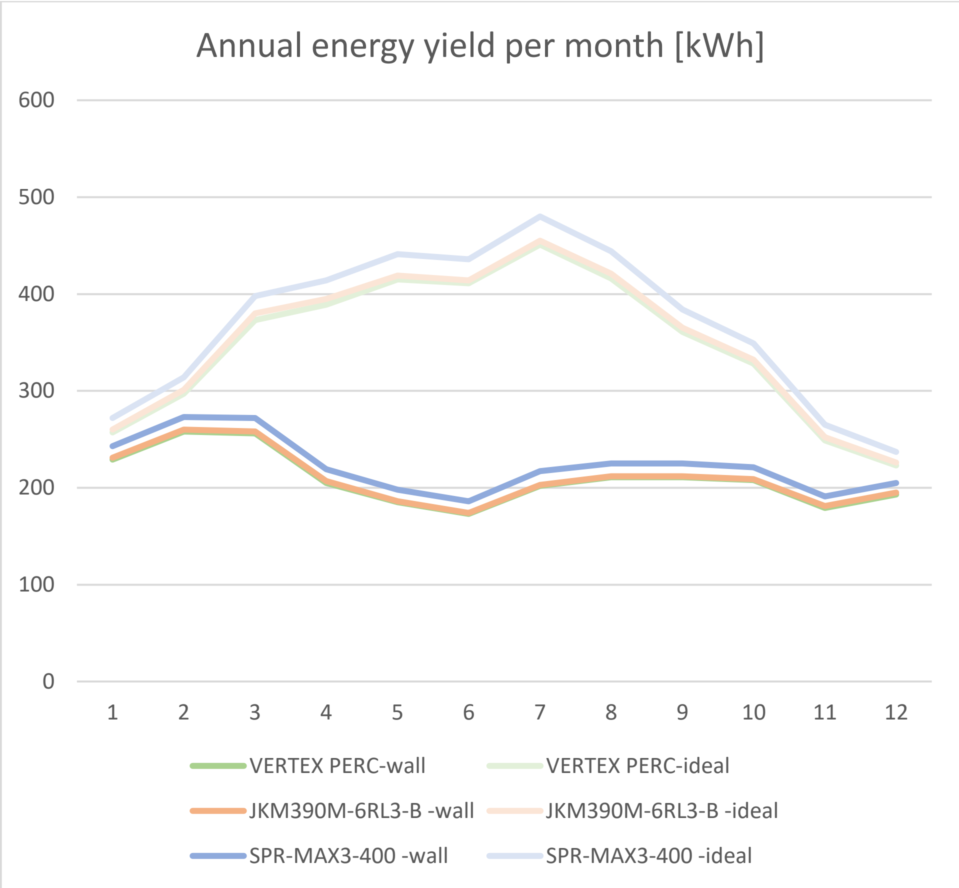


Figure 52: Comparison PV installation wall vs PV installation ideal situation

The simulations were carried out for installations between 2.7kWp and 2.8kWp. From Figure 52, it can be observed that a PV installation in the ideal situation will generate more energy than when a PV installation is installed on a wall of the Montilivi campus (±66% more per year). However, there is something remarkable to be seen in Figure 52. In the winter months, a PV installation installed on a wall will generate more energy than in the summer months. This can be explained by the fact that the sun is lower in the winter, which means that it shines more perpendicularly on the panel. During the winter months, the energy yield of an installation against a wall does not differ much from an installation in an ideal position. Finally, it can generally be concluded that a PV installation against a wall on the Montilivi campus generates less energy than an ideal PV installation. Therefore, the payback time of such installations will also be slightly longer. However, it is an additional way of generating electricity and in the long run, the University of Girona will benefit.

4.3 Solar charging station

Finally, how an EV can be charged with the help of a solar charging station is mentioned. Finally, the opportunity of installing solar charging stations on the Montilivi campus is discussed. In section 2.5.2 some examples were given of urban photovoltaics including an EV charging station with solar panels. This section will briefly review three parts. First, possible locations on the Montilivi campus where solar charging stations can be placed are mentioned. Then, some advantages of a solar charging station are discussed. Finally, how an EV can be charged with the help of a solar charging station is mentioned.

4.3.1 Possible locations for a solar charging station

There are some places on the Montilivi campus where charging points for electric vehicles can be provided. The number of charging points needed depends on the number of electric cars that currently circulate in Girona and how this will evaluate in the future. Figure 53 shows where charging stations can be provided. The yellow crosses represent charging station locations that can be used by students and any outsiders. The red crosses represent charging station locations that can be used by university staff.

Figure 53: Charging point locations

Figure 53 shows that there are many different places where charging stations can be installed. In some places, it is more difficult to place a solar charging station, like the charging stations near the Science building. At this location, there are a lot of shadows, which makes it impossible to place a solar charging station there.

4.3.2 Advantages

Charging EVs with solar panels has several advantages over charging EVs using the grid. The first advantage is that electricity from solar panels is cheaper than grid electricity. Every year the cost of grid electricity rises, while solar panels produce electricity without any increase in costs. In addition, solar panels are also less polluting than electricity. The CO2 emissions are much less (about 5 times less) than when charging from the grid [43]. Finally, when many EVs are connected at the same time to different charging stations, the network will be heavily burdened. Installing a solar charging station can prevent overloading the grid and thus support it.

4.3.3 How to charge an EV with a solar panel charging station

To charge an EV with the help of a solar charging station, four steps must be completed to have a properly functioning installation:

- step 1: determine the amount of kWh needed to charge the EV,
- step 2: determine the amount of solar panels that can supply this kWh,
- step 3: set up the PV installation,
- step 4: choosing a charging station.

Step 1:

Each EV consumes an x number of kWh per 100 km. Based on a database where the consumption of all different electric vehicles can be found, it appears that an electric vehicle consumes on average 201 Wh per km, which corresponds to 20.1 kWh per 100 km [44]. It is estimated that every Spaniard drives 32 km per day. It is assumed that each student/university staff member spends at least one hour at school and during that hour the EV is charged so that it can drive 32 km. Based on this assumption it can be determined how many kW the charging station should be. A distance of 32 km corresponds to 6.43 kWh (20.1/100*32). This means that it is best to choose a charging station that can deliver more than 6.43 kW.

Step 2:

The number of solar panels is installed based on the capacity of the charging station. Assuming that the sun would shine for a full hour, the PV installation has to deliver at least 6.43 kWp to meet the EV charging capacity. Depending on how much power the chosen panel will deliver, the number of PV modules will vary. With the formula below, the number of solar panels can be determined.

$$Number\ of\ solar\ panels = \frac{6{,}43\ [kW]}{panel\ power\ [kWp]} + 1 \qquad (17)$$

This formula takes 1 solar panel more than needed as a safety margin. The power of each solar panel deteriorates every year and so it was discussed earlier in section 3.5.1 that a PV plant will never deliver its installed kWp (because of clouds, shadows, etc.). This safety margin of 1 additional panel can also be extended to a safety margin of 2 or 3 additional panels, depending on what the university prefers.

Step 3:

A correct and complete PV installation can be set up by going through the steps in chapter 3 one by one. The best PV installation can be chosen for the solar charging station by going through all these different steps again.

Step 4:

In step 1, a charging station of at least 6.43kW should be chosen. A charge station that can deliver exactly this power does not exist. This is why we chose a charging station from EVbox that can deliver 7.4 kW. EVbox offers both single and double-wall charging stations. Depending on the location on the campus, you can choose between these two options. Figure x shows the EVbox charging station.

Figure 54: EVBox charging station [45]

5 Conclusion and future work

This thesis described the process how to select the most optimal PV installation for the Montilivi campus in Girona. Due to the high number of components in a PV installation, a roadmap was developed in this thesis to create the most efficient PV installation. This roadmap is integrally applied at the Montilivi campus in Girona and is useful for larger companies. In addition, this thesis examined how solar panels can be applied in other ways on the Montilivi campus. This shows interested parties whether or not it is a good choice to use solar panels differently at this moment.

In the first phase of the thesis, ten types of solar panels with high efficiency (>20%) and with a power of ±400Wp were compared. Based on datasheets, the SPR-MAX3-400, the JKM390M-6RL3-B, and the VERTEX PERC module showed the best properties. These three modules use monocrystalline cells.

In the second phase, the most optimal position for these three types of PV modules was determined based on the location and orientation of the buildings. Research and calculations showed that the panels worked most efficiently on the Montilivi campus when placed at an inclination of 36°, facing south. Because of this and because the university wanted the most efficient installation possible, this inclination and orientation were used in further simulations.

Subsequently, to model the most optimal PV installation, different types of inverters were compared. This showed that inverters of the brand SMA have the best properties (see Appendix E). In addition, data from PVGIS shows that inverters with a lower capacity (±13%) than the installed capacity are allowed for each configuration. Using Sunny Design, the number of inverters and strings was determined for each installation on the Montilivi campus based on the maximum generated output power of the different installations (see Appendix G).

In the fourth phase of the thesis, a support structure and the cables were dimensioned and chosen. First, a calculation was made for the minimum cable section for each string and then the cable length was calculated. The installations on the Montilivi campus require cables of 4 and 6mm², which can be purchased from the site "Elektrodproducten". These cables are then accompanied by connectors and protection devices. It was opted to order connectors on the site "Elektramat" and to provide fuses that ensure that the current in the cables is not exceeded (Appendix J).

In addition, there is being looked at what happens after the current is transformed by an inverter. Therefore, it was briefly touched on what to do with the AC cabling and how to manage the generated energy. Depending on whether or not there is a Sunny Tripower CORE2 placed in the installation, an SMA Data Manager M was used (If there is a Sunny Tripower CORE2, an SMA Data Manager M is required). Also, the question of whether or not to install a battery system after the inverter was considered. After citing some points, such as the consumption of the buildings, the opening time of the campus, and the price of the batteries, it was found that the use of a battery would not economically viable.

Moreover, an economic analysis was performed and discussed what the optimal PV system is for the Montilivi campus. Here it became clear that if the university chooses the most ecological option, the best option was to choose the installations that use the SPR-MAX3-400 module (2514tCO_2 and 2058tCO_2 more reduction than the JKM390M-6RL3-B and VERTEX PERC module, respectively). When the university looks at it more economically, in the long term the installations using the JKM390M-6RL3-B module are the best choice. These installations return 226930 and 172360 euros more after 20 years than installations using the SPR-MAX3-400 module and VERTEX PERC module, respectively. In the short term, on the other hand, the installations where the VERTEX PERC module is used are the most interesting. These installations have a 3.36 and 0.29 year faster payback than using the SPR-MAX3-400 module and JKM390M-6RL3-B module, respectively. From my insight, it was cited that the University of Girona best chooses installations with the JKM390M-6RL3-B panel because it is the most economically interesting in the long run and it never got the worst result out of all the parameters compared in sections 3.10 and 3.11.

Finally, some additional opportunities were considered for PV installations on the Montilivi campus. From this section, it was decided that a cooling system is not economically viable. There would be a loss of 3931 euros over 20 years. In addition, some possibilities for BIPV and BAPV on the campus were mentioned. It appeared that BIPV can be applied in the form of a photovoltaic curtain wall and photovoltaic balustrades. BAPV, on the other hand, is going to have up to 66% less energy generation than an ideal PV installation. It is also more expensive than BIPV. Finally, the possibility of installing a solar charging station on campus was looked at. This resulted in an EVbox charging station of 7.4kW being the optimal choice.

This thesis looked at the installations according to efficiency and economy. The solar panels were simulated so that each module can generate its maximum output. In future work, the possibility of placing the solar panels according to an East-West configuration can also be considered. This will lead to more output power but maybe economically less interesting. In addition, one can also look at placing the solar panels according to the orientation of the building.

Within this thesis, the prices for the different parts of the installation were looked up on internet. In future work, this can be done by contacting suppliers. This can give a more realistic picture of how much the installations cost on the Montilivi campus.

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Appendices

Appendix A: Specifications of 10 different solar panels

Table 17: Specifications of solar panels part 1

Manufacturer	Sun Power Maxeon	LG Electronics Inc.	Panasonic	REC Solar AS	REC Solar AS
Solar panel	SPR-MAX3-400	LG405Q1C-A6	EVPV380	REC 410 AA Pure (Alpha)	REC 400 AA Pure (Alpha)
Rated power (Pnom) (W)	400	405	380	410	400
Power tolerance (%)	5/0	3/0	10/0	5/0	5/0
Panel efficiency (%)	22,63	22,3	21,7	22,16	21,62
Max power voltage (Vmpp) (V)	65,8	35,4	38,1	42,7	42,1
Max. power current (lmpp) (A)	6,08	8,67	9,98	9,61	9,51
Open terminal voltage (Voc) (V)	75,6	41,9	44,3	49	48,8
Short circuit current (lsc) (A)	6,58	9,15	10,61	10,35	10,25
Max. system voltage (V IEC)	1000	1000	1000	1000	1000
Maximum fuses (A)	20	20	25	25	25
Temp. coefficient of power (%/°C)	-0,29	-0,29	-0,26	-0,26	-0,26
Temp. coefficient of voltage (mV/°C)	-176,8	-100,56	-106,32	-117,6	-117,1

Temp. coefficient of current (mA/°C)	2,9	3,66	4,244	4,14	4,1
Weight (kg)	19	18,5	19,5	20,5	20,5
Weight/rated power	0,0475	0,04568	0,051316	0,05	0,05125
Dimensions (L*B*H) (mm)	1690 * 1046*40	1740*1042*40	1721*1016*30	1821*1016*30	1821*1016*30
Price (€)	334	450	334	320	280
Price/Wp	0,835	1,11111	0,878947	0,780487805	0,7
Price/eff.	14,75916924	20,1794	15,39171	14,44043321	12,9509713
Power output in year 25 (%)	92	92,5	92	92	92

Table 18: Specifications solar panels part 2

Manufacturer	Silfab Solar	Risen energy	Trina solar	Jinko Solar	Deepblue 3.0
Solar panel	Elite	RSM40-8-410M	VERTEX PERC	JKM390M-6RL3-B	334
Rated power (Pnom) (W)	380	410	540	390	405
Power tolerance (%)	10/0	3/0	5/0	3/0	5/0
Panel efficiency (%)	21,4	21,33	20,7	20,43	20,7
Max power voltage (Vmpp) (V)	38,88	34,89	31,2	37,15	31,21
Max. power current (lmpp) (A)	9,79	11,76	17,33	10,5	12,98
Open terminal voltage (Voc) (V)	45,13	41,9	37,5	44,47	37,23
Short circuit current (lsc) (A)	10,5	12,47	18,14	11,32	13,87
Max. system voltage (V IEC)	1000	1500	1500	1000	1000
Maximum fuses (A)	20	20	30	20	25
Temp. coefficient of power (%/°C)	-0,377	-0,34	-0,34	-0,35	-0,35
Temp. coefficient of voltage (mV/°C)	-125,91	-104,75	-93,75	-122,5	-93,075
Temp. coefficient of current (mA/°C)	4,83	4,988	7,256	5,53	5,548
Weight (kg)	19	21	28,6	22,1	21,5
Weight/rated power	0,05	0,0512195	0,052963	0,056667	0,05309
Dimensions (L*B*H) (mm)	1795*990*38	1752*1096*30	2384*1096*35	1855*1029*50	1722*1134*30
Price (€)	286	450	224	168	235
Price/Wp	0,75263	1,097561	0,414815	0,430769	0,58025
Price/eff.	13,3645	21,097046	10,82126	8,223201	11,3527
Power output in year 25 (%)	85,1	84,8	84,8	83,1	83,1

Appendix B: Decision matrix

Table 19: Decision matrix part 1

Criteria	Weight (1-5)	SPR-MAX3-400		LG405Q1C-A6		EVPV380		REC 410 AA Pure (Alpha)		REC 400 AA Pure (Alpha)	
		Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Rated power (Pnom) (W)	2	3	6	3	6	3	6	3	6	3	6
Panel efficiency (%)	5	5	25	4	20	3	15	4	20	3	15
Weight/rated power	1	5	5	5	5	3	3	3	3	3	3
Price (€)	2	3	6	1	2	3	6	3	6	3	6
Price/Wp	4	3	12	1	4	2	8	3	12	3	12
Price/eff.	5	3	15	1	5	3	15	3	15	4	20
Power output in year 25 (%)	3	5	15	5	15	5	15	5	15	5	15
	Total		84		57		68		77		77

Table 20: Decision matrix part 2

Criteria	Elite		RSM40-8-410M		VERTEX PERC		JKM390M-6RL3-B		JAM54S30	
	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total	Score (1-5)	Total
Rated power (Pnom) (W)	3	6	3	6	5	10	3	6	3	6
Panel efficiency (%)	3	15	3	15	2	10	2	10	2	10
Weight/rated power	3	3	3	3	3	3	2	2	3	3
Price (€)	3	6	1	2	4	8	5	10	4	8
Price/Wp	3	12	1	4	5	20	5	20	5	20
Price/eff.	3	15	1	5	4	20	5	25	4	20
Power output in year 25 (%)	3	9	3	9	3	9	2	6	2	6
		66		44		80		79		73

Appendix C: Landscape vs portrait format

Table 21: Landscape and portrait installation of the SPR-MAX3-400 PV module

SPR-MAX3-400	Landscape	Portrait
Number of panels [/]	257	262
Peak power [kWp]	102,8	104,8
IRR [%]	11,7	12,1
Annual energy yield [MWh]	141,96	147,72
Expected payback period [Year]	7,4	7,2
Feed-in tariff after 20 Years [EUR]	270.831	281.810
Electricity production costs for 20 years [EUR/kWh]	0,048	0,047
CO2 reduction after 20 years [t]	953	992
Total investment [EUR]	92.130	93.863

Table 22: Landscape and portrait installation of the VERTEX PERC PV module

VERTEX PERC	Landscape	Portrait
Number of panels [/]	156	166
Peak power [kWp]	84,24	89,64
IRR [%]	28	27,5
Annual energy yield [MWh]	125,07	129,95
Expected payback period [Year]	3,5	3,6
Feed-in tariff after 20 Years [EUR]	238,614	247.915
Electricity production costs for 20 years [EUR/kWh]	0,024	0,025
CO2 reduction after 20 years [t]	840	873
Total investment [EUR]	41.299	43.479

Table 23: Landscape and portrait installation of the JKM390M-6RL3-B PV module

JKM390M-6RL3-B	Landscape	Portrait
Number of panels [/]	235	232
Peak power [kWp]	91,65	90,48
IRR [%]	26,3	28,4
Annual energy yield [MWh]	119,06	126,19
Expected payback period [Year]	3,7	3,5
Feed-in tariff after 20 Years [EUR]	227,136	240,749
Electricity production costs for 20 years [EUR/kWh]	0,026	0,024
CO2 reduction after 20 years [t]	800	847
Total investment [EUR]	41.545	41.095

Appendix D: Configuration of the solar panels for each building

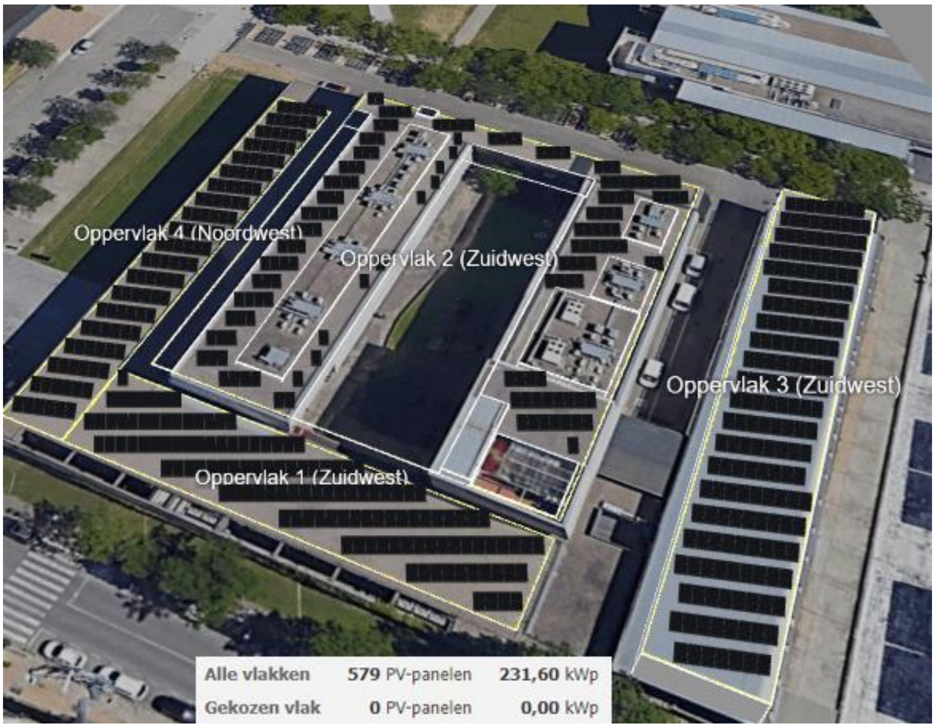


Figure 55: Configuration Science building_ SPR-MAX3-400

Figure 56: Configuration Science building_ JKM390M-6RL3-B

Figure 57: Configuration Science building_ VERTEX PERC

Figure 58: Configuration P1 building_ SPR-MAX3-400

Figure 59: Configuration P1 building_ JKM390M-6RL3-B

Figure 60: Configuration P1 building_ VERTEX PERC

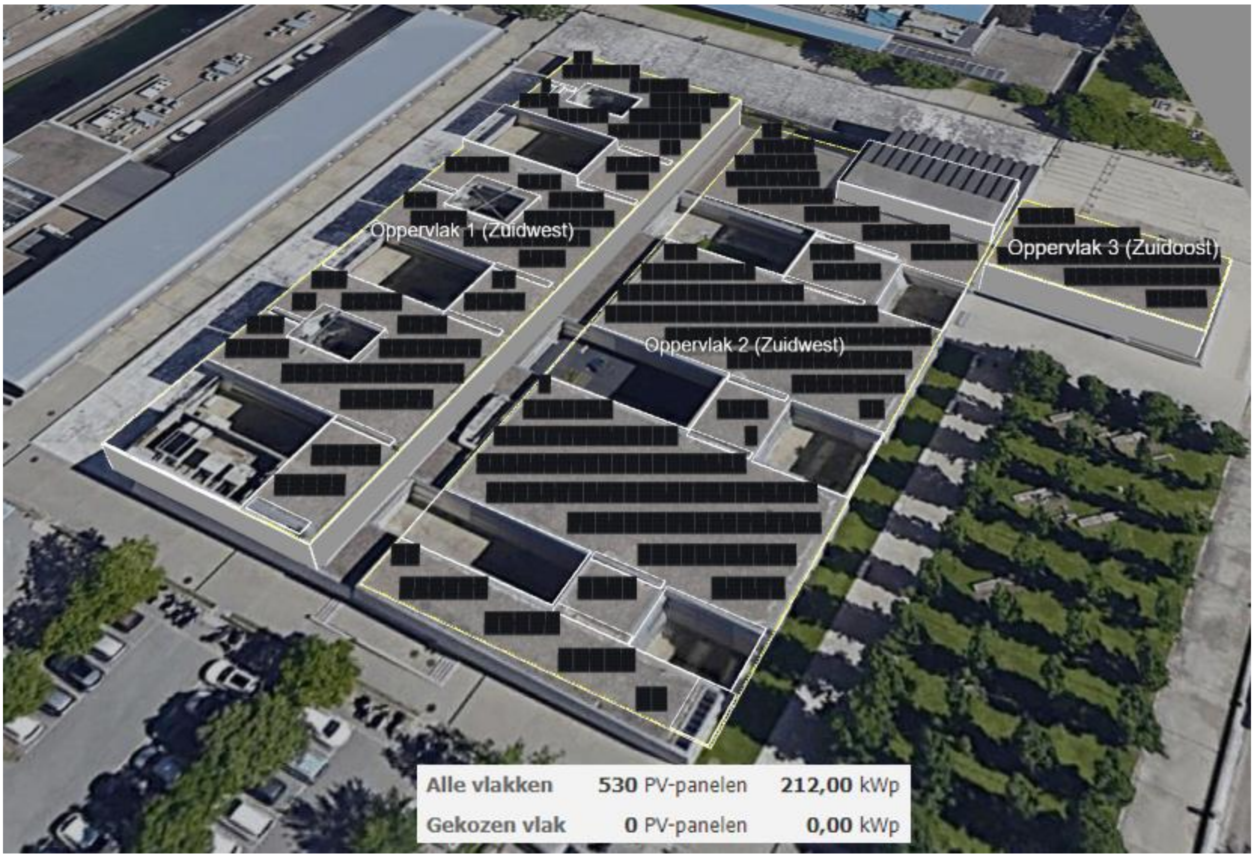


Figure 61: Configuration law building_ SPR-MAX3-400

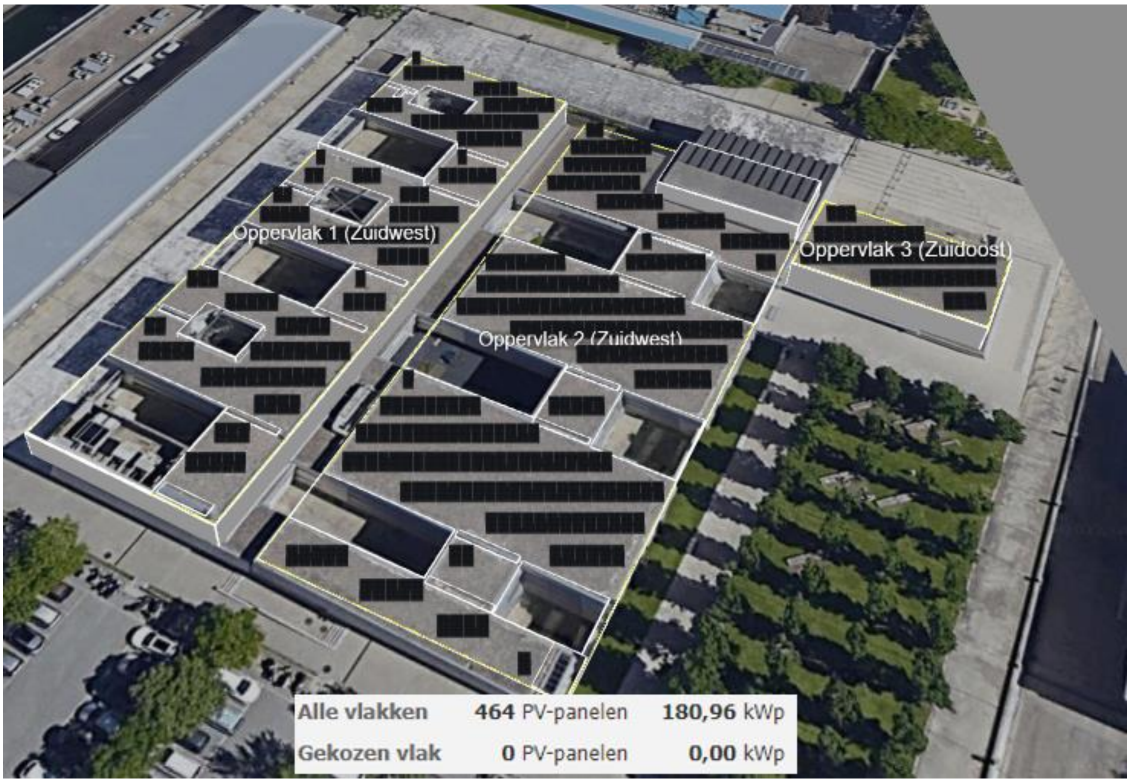


Figure 62: Configuration law building_ JKM390M-6RL3-B

Figure 63: Configuration law building_ VERTEX PERC

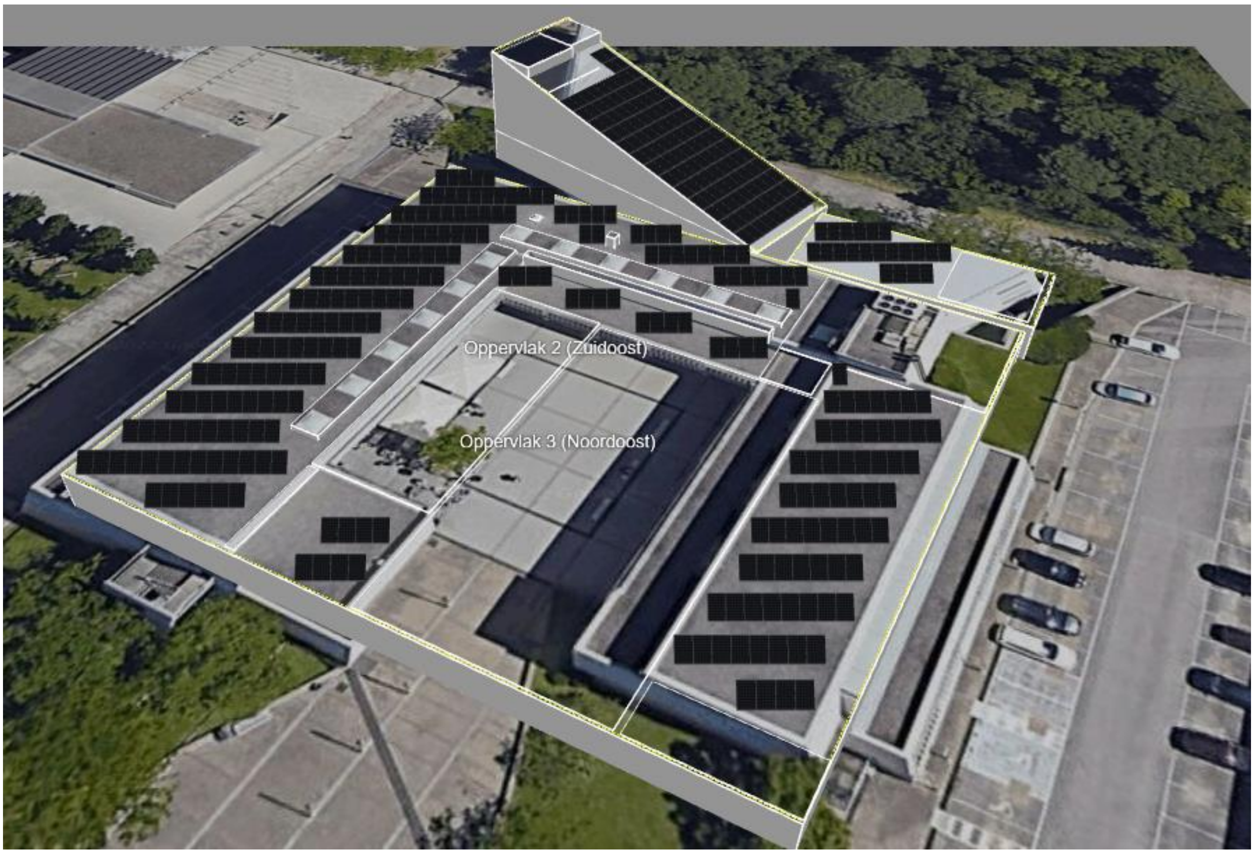


Figure 64: Configuration economics building_ SPR-MAX3-400

Figure 65: Configuration economics building_ JKM390M-6RL3-B

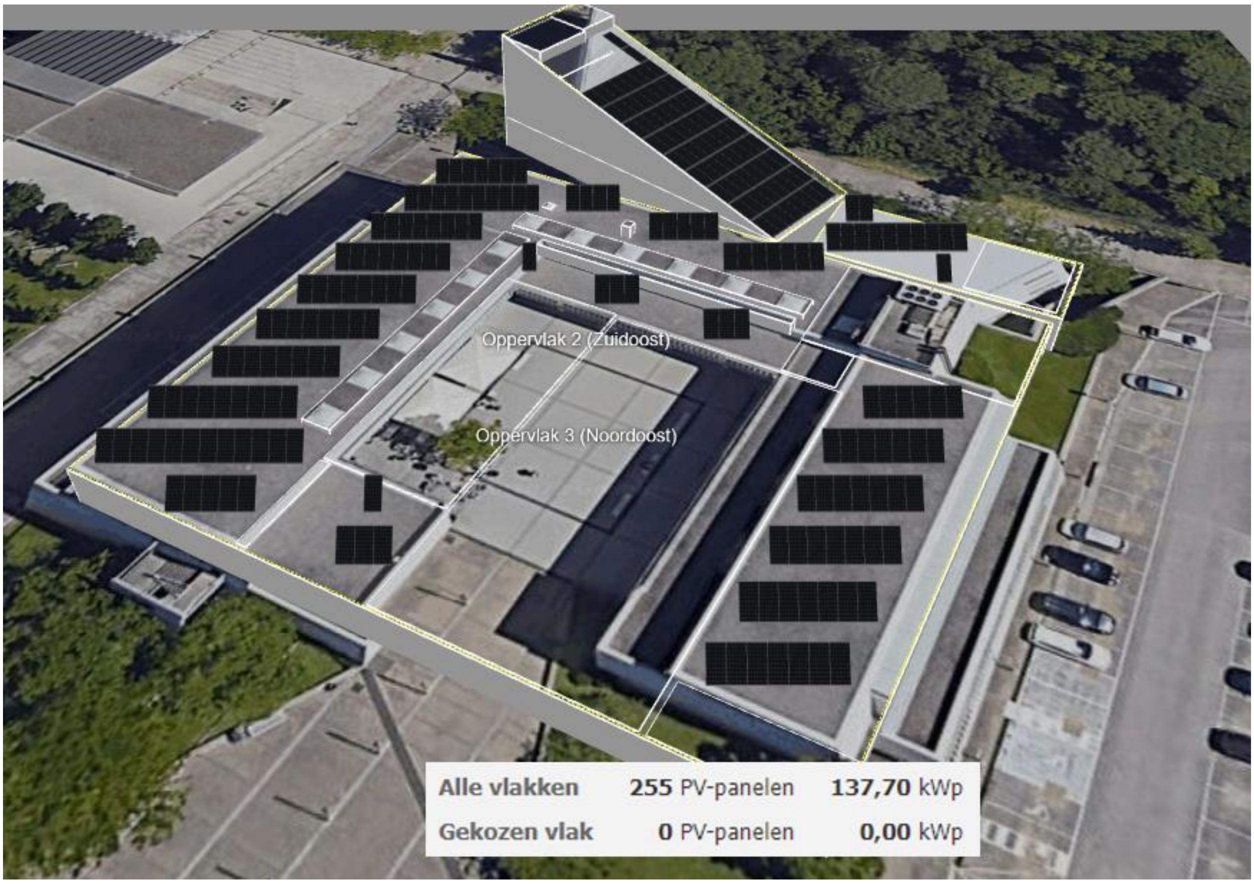


Figure 66: Configuration economics building_ VERTEX PERC

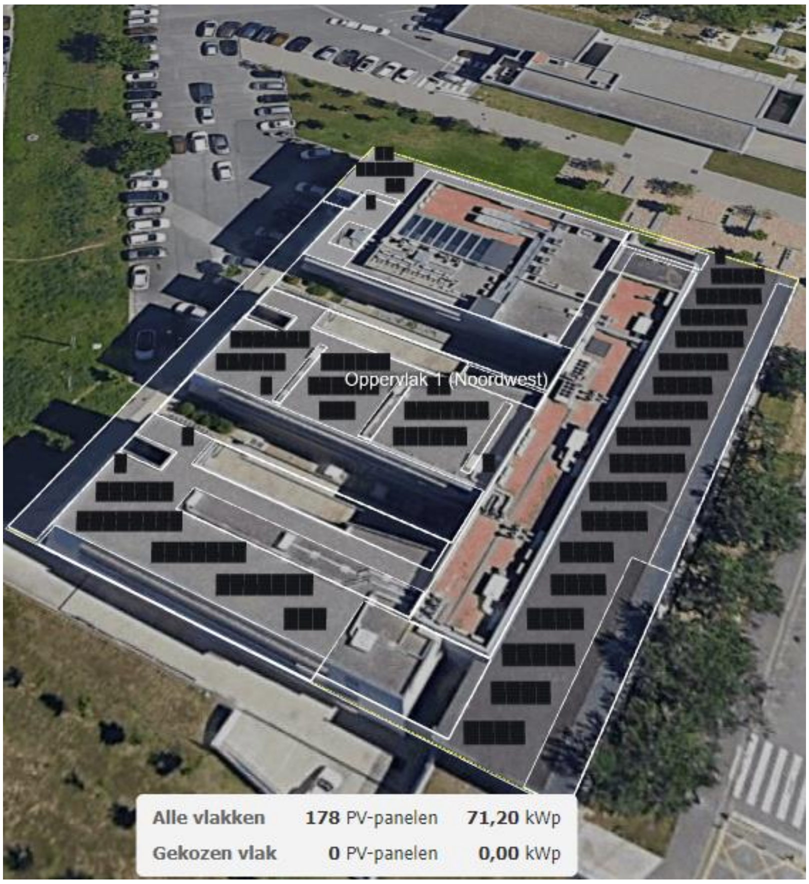


Figure 67: Configuration shared classrooms_ SPR-MAX3-400

Figure 68: Configuration shared classrooms _ JKM390M-6RL3-B

Figure 69: Configuration shared classrooms_ VERTEX PERC

Figure 70: Configuration P2+P4+workshops_ SPR-MAX3-400

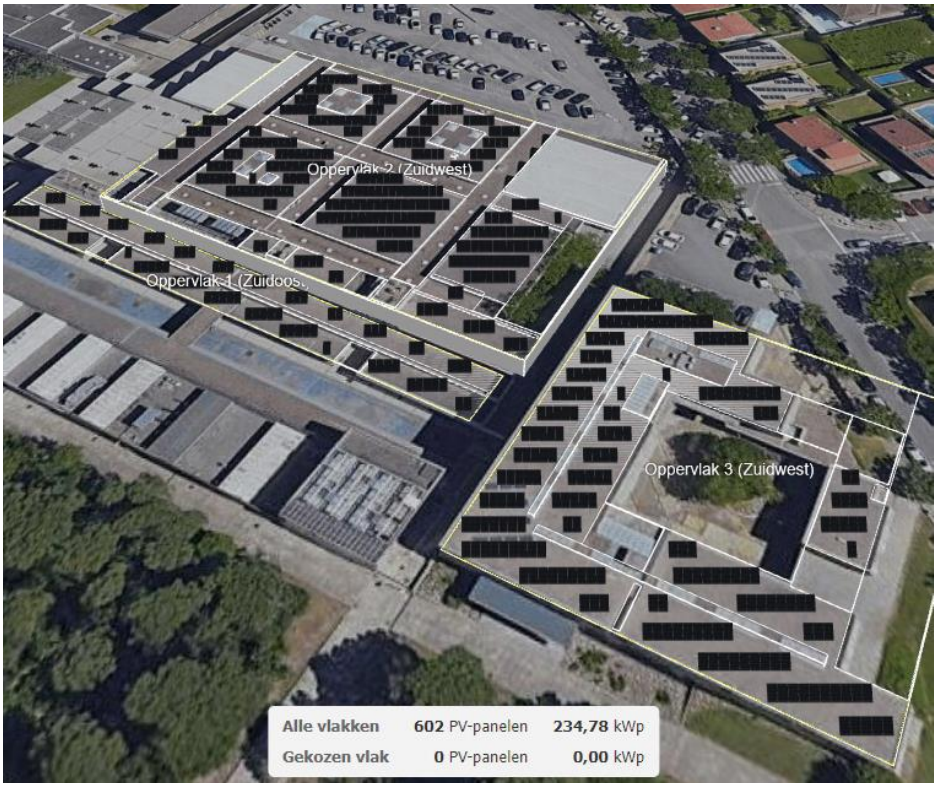


Figure 71: Configuration P2+P4+workshops_ JKM390M-6RL3-B

Figure 72: Configuration P2+P4+workshops_ VERTEC PERC

Figure 73: Configuration library_ SPR-MAX3-400

Figure 74: Configuration library_ JKM390M-6RL3-B

Figure 75: Configuration library_ VERTEC PERC

Figure 76: Configuration CIAE building_ SPR-MAX3-400

Figure 77: Configuration CIAE building_ JKM390M-6RL3-B

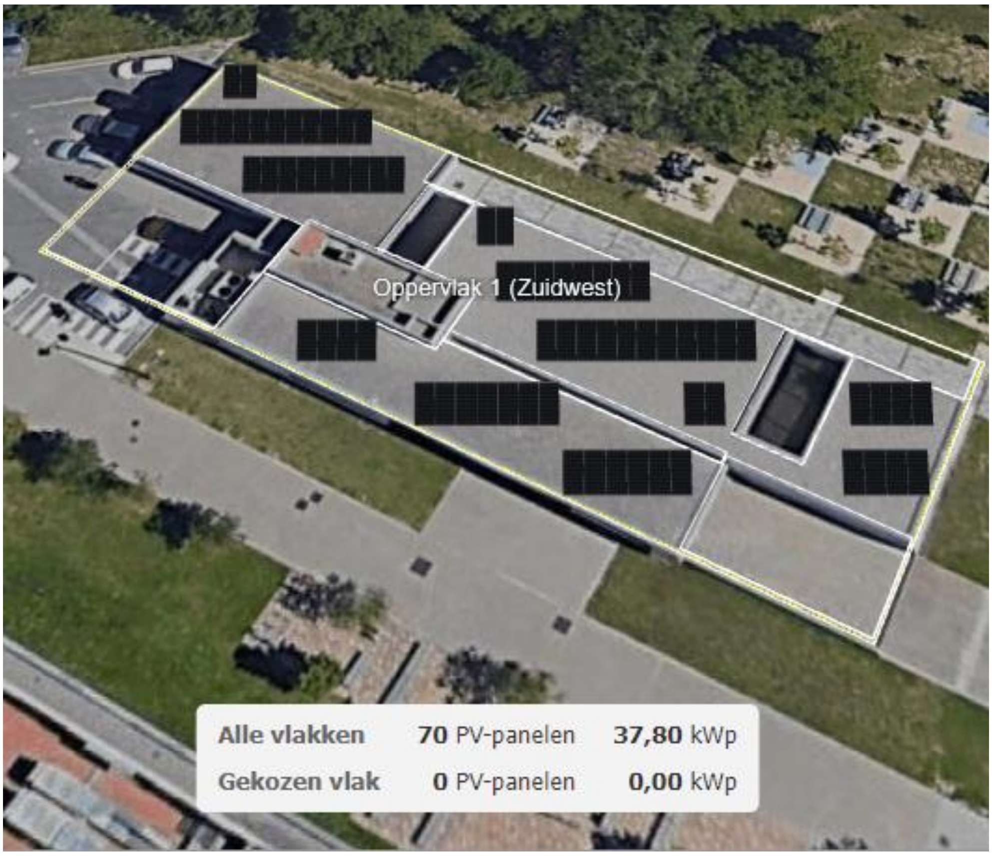


Figure 78: Configuration CIAE building_ VERTEC PERC

Figure 79: Configuration P3 building_ SPR-MAX3-400

Figure 80: Configuration P3 building_ JKM390M-6RL3-B

Figure 81: Configuration P3 building_ VERTEC PERC

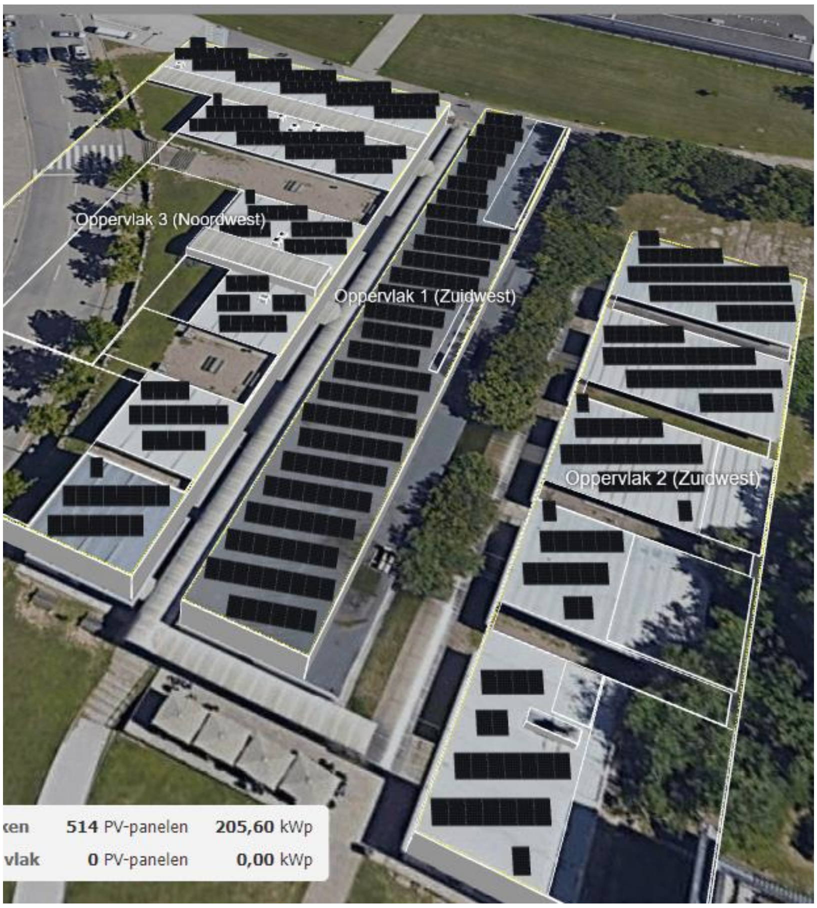


Figure 82: Configuration central modules_ SPR-MAX3-400

Figure 83: Configuration central modules_ JKM390M-6RL3-B

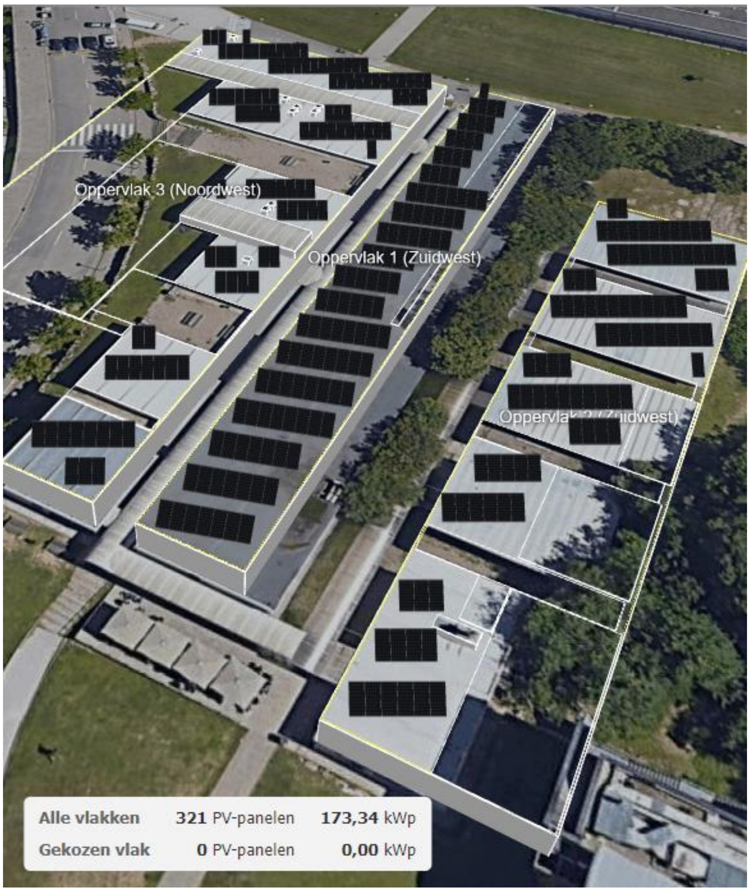


Figure 84: Configuration central modules_ VERTEC PERC

Appendix E: Comparison inverters

Table 24: Comparison of different inverter models

Manufacturer	Fronius	SolarEdge	SMA	Fronius	SolarEdge	SMA
Model	Primo 3.0-1	SE4k	Sunny boy 3.0	Primo 6.0-3	SE6k	Sunny Tripower 6.0
Max power of the PV generator (Wp)	4500	5400	5500	12000	8100	9000
MPP- voltage range (V)	200-800	…-9000	110-500	195-800	…-900	260-800
Maximum input voltage (V)	/	900	850	/	900	850
Minimum input voltage (V)	80	/	125	200	/	125
Rated AC power (W)	3000	4000	3000	6000	6000	
Maximum efficiency (%)	97,9	98	97	97,9	98	98,2
Price	998	1079	920	1419	1437	1325

Manufacturer	Fronius	SolarEdge	SMA	Fronius	SolarEdge	SMA
Model	Symo 10.0-3-M	SE10k	Sunny Tripower 10.0	Symo 15.0-3-M	SE15k	Sunny Tripower 15000TL
Max power of the PV generator (Wp)	15500	13500	15000	22500	20250	27000
MPP- voltage range (V)	270-800	…-900	320-800	370-800	…-900	240-800
Maximum input voltage (V)	/	900	1000	/	900	1000
Minimum input voltage (V)	200	/	125	200	/	150
Rated AC power (W)	10000	10000	10000	15000	15000	15000
Maximum efficiency (%)	97,7	98	98,3	97,9	98	98,4
Price	1869	1665	1784	2369	1844	2379

Manufacturer	Fronius	SolarEdge	SMA	Fronius	SolarEdge	SMA
Model	Symo 20.0-3-M	/	Sunny Tripower 20000TL	/	SE27.6K	Sunny Tripower CORE2
Max power of the PV generator (Wp)	30000	/	36000	/	37250	165000
MPP- voltage range (V)	320-800	/	320-800	/	…-900	500-800
Maximum input voltage (V)	/	/	1000	/	900	1100
Minimum input voltage (V)	200	/	150	/	/	200
Rated AC power (W)	20000	/	20000	/	27500	110000
Maximum efficiency (%)	97,7	/	98,4	/	98,3	98,6
Price	2639	/	2599	/	2100	5660

Appendix F: Datasheet inverters [46] [47]

SUNNY TRIPOWER CORE2
STP 110-60

SMA

More flexibility
- For large rooftop and ground-mounted systems up to the MW range
- 12 MPP trackers
- 24 strings with 1100 VDC Sunclix connector

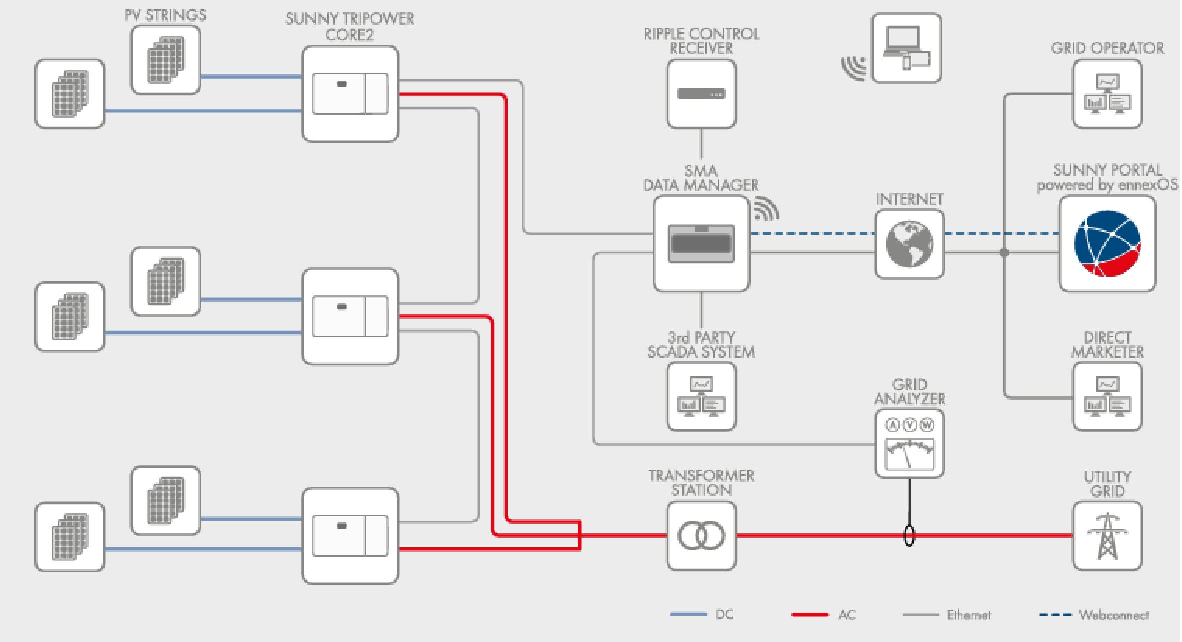
More power
- 110 kW for standard 400 VAC
- Fast commissioning without additional DC combiners
- Peak efficiency of 98.6%

More yield
- Premium monitoring service for reliable system performance
- Maximum yields thanks to the integrated software solution SMA ShadeFix

More system integration
- Flexible and future-proof expansion in the SMA Energy System Business
- Holistic energy management with ennexOS
- High IT security

SUNNY TRIPOWER CORE2
Flexible system design and highest yields thanks to integrated features

Flexible system design for larger commercial PV systems: The Sunny Tripower CORE2 is the ideal inverter for decentralized system structures up to the megawatt range. With 110 kilowatts, 24 strings and 12 MPP trackers, the Sunny Tripower CORE2 allows for a particularly high solar coverage in ground-mounted PV systems as well as at different roof pitches during the day. The integrated SMA ShadeFix software solution automatically optimizes system performance anytime, even with partially shaded modules. The automatic monitoring service SMA Smart Connected also ensures maximum PV system yields by detecting failures as fast as possible.
With the Sunny Tripower CORE2 as a central component of the SMA Energy System Business, installers and PV system operators will benefit from the high-quality components from a single source and future-proof options to expand their systems by SMA storage solutions.



Technical data	Sunny Tripower CORE2
Input (DC)	
Max. PV array power	165000 Wp STC
Max. input voltage	1100 V
MPP voltage range	500 V to 800 V
Rated input voltage	585 V
Min. input voltage / Start input voltage	200 V / 250 V
Max. input current per MPP tracker / Max. short-circuit current per MPP tracker	26 A / 40 A
Number of independent MPP trackers / Strings per MPP tracker	12 / 2
Output (AC)	
Rated power at nominal voltage	110000 W
Max. apparent AC power	110000 VA
Nominal AC voltage	400 V
AC voltage range	320 V to 460 V
AC grid frequency / range	50 Hz / 45 Hz to 55 Hz 60 Hz / 55 Hz to 65 Hz
Rated grid frequency	50 Hz
Max. output current	159 A
Power factor at rated power / displacement power factor adjustable	1 / 0.8 overexcited to 0.8 underexcited
Harmonic (THD)	< 3%
Feed-in phases / AC connection	3 / 3-PE
Efficiency	
Max. efficiency / European efficiency	98.6% / 98.4%
Protective devices	
Input-side disconnection device	●
Ground fault monitoring / grid monitoring / DC reverse polarity protection	● / ● / ●
AC short-circuit current capability / galvanically isolated	● / —
All-pole sensitive residual-current monitoring unit	●
Monitored surge arrester (type II) AC / DC	● / ●
Protection class (according to IEC 62109-1) / surge category (according to IEC 62109-1)	I / AC: III; DC: II
General data	
Dimensions (W / H /D)	1117 mm / 682 mm / 363 mm (44.0 in / 26.9 in / 14.3 in)
Weight	93.5 kg (206.1 lbs)
Operating temperature range	−30 °C to +60 °C (−22 °F to +140 °F)
Noise emission, typical	< 65 db(A)
Self-consumption (at night)	< 5 W
Topology / cooling concept	Transformerless / active cooling
Degree of protection (according to IEC 60529)	IP66
Max. permissible value for relative humidity (non-condensing)	100%
Features / functions / accessories	
DC connection / AC connection	Sunclix / terminal lug (up to 240 mm²)
LED display (Status / Fault / Communication)	●
Ethernet interface	● (2 ports)
Data interface	Web Interface / Modbus SunSpec
Mounting type	Wall mounting / rack mounting
Warranty: 5 / 10 / 15 / 20 years	● / ○ / ○ / ○
Certificates and approvals (selection)	IEC 62109-1/-2, EN50549-1/-2:2018, VDE-AR-N 4105/4110/4120:2018, IEC 62116, IEC 61727, C10/C11 LV2/MV1:2018, CEI 0-16:2019, AS/NZS 4777.2, SI 4777, TOR Generator Typ A/B
● Standard features ○ Optional features — not available Data at nominal conditions Status 03/2020	
Type designation	STP 110-60

Efficient

- Maximum efficiency of 98.4%
- Yield increase without installation effort due to integrated shade management SMA ShadeFix

Safe

- DC surge arrester (SPD type II) can be integrated

Flexible

- DC input voltage of up to 1000 V
- Multistring capability for optimum system design
- Optional display

Innovative

- Cutting-edge grid management functions with Integrated Plant Control
- Reactive power available 24/7 (Q on Demand 24/7)

SUNNY TRIPOWER 15000TL / 20000TL / 25000TL

The versatile specialist for large-scale commercial plants and solar power plants

The Sunny Tripower is the ideal inverter for large-scale commercial and industrial plants. Not only does it deliver extraordinary high yields with an efficiency of 98.4%, but it also offers enormous design flexibility and compatibility with many PV modules thanks to its multistring capabilities and wide input voltage range.
The future is now: the Sunny Tripower comes with cutting-edge grid management functions such as Integrated Plant Control, which allows the inverter to regulate reactive power at the point of common coupling. Separate controllers are no longer needed, lowering system costs. Another new feature—reactive power provision on demand (Q on Demand 24/7).

SMA SMART CONNECTED

The integrated service for ease and comfort

SMA Smart Connected* is the free monitoring of the inverter via the SMA Sunny Portal. If there is an inverter fault, SMA proactively informs the PV system operator and the installer. This saves valuable working time and costs.

With SMA Smart Connected, the installer benefits from rapid diagnoses by SMA. They can thus quickly rectify the fault and score points with the customer thanks to the attraction of additional services.

ACTIVATION OF SMA SMART CONNECTED

During registration of the system in the Sunny Portal, the installer activates SMA Smart Connected and benefits from the automatic inverter monitoring by SMA.

AUTOMATIC INVERTER MONITORING

SMA takes on the job of inverter monitoring with SMA Smart Connected. SMA automatically checks the individual inverters for anomalies around the clock during operation. Every customer thus benefits from SMA's long years of experience.

PROACTIVE COMMUNICATION IN THE EVENT OF FAULTS

After a fault has been diagnosed and analyzed, SMA informs the installer and end customer immediately by e-mail. Everyone is thus optimally prepared for the troubleshooting. This minimizes the downtime and saves time and money. The regular power reports also provide valuable information about the overall system.

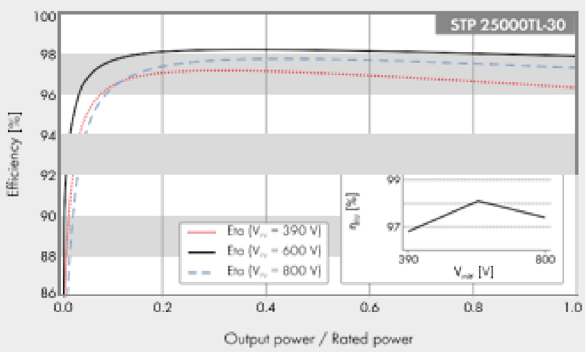
REPLACEMENT SERVICE

If a replacement device is necessary, SMA automatically supplies a new inverter within one to three days of the fault diagnosis. The installer can contact the PV system operator of their own accord and replace the inverter.

PERFORMANCE SERVICE

The PV system operator can claim compensation from SMA if the replacement inverter cannot be delivered within three days.

Efficiency Curve



Accessory

RS485 interface
DM-485CB-10

PowerControlModule
PWCMOD-10

DC surge arrester Typ II, inputs A and B
DCSPD KIT3-10

Multifunction relay
MFR01-10

● Standard features ○ Optional features — Not available
Data at nominal conditions
Status: 02/2021

Technical Data	Sunny Tripower 15000TL	Sunny Tripower 20000TL	Sunny Tripower 25000TL
Input (DC)			
Max. generator power	27000 Wp	36000 Wp	45000 Wp
DC rated power	15330 W	20440 W	25550 W
Max. input voltage	1000 V	1000 V	1000 V
MPP voltage range / rated input voltage	240 V to 800 V / 600 V	320 V to 800 V / 600 V	390 V to 800 V / 600 V
Min. input voltage / start input voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current input A / input B	33 A / 33 A	33 A / 33 A	33 A / 33 A
Max. DC short-circuit current input A/input B	43 A / 43 A	43 A / 43 A	43 A / 43 A
Number of independent MPP inputs / strings per MPP input	2 / A:3; B:3	2 / A:3; B:3	2 / A:3; B:3
Output (AC)			
Rated power (at 230 V, 50 Hz)	15000 W	20000 W	25000 W
Max. AC apparent power	15000 VA	20000 VA	25000 VA
AC nominal voltage	3 / N / PE; 220 V / 380 V 3 / N / PE; 230 V / 400 V 3 / N / PE; 240 V / 415 V		
AC voltage range	180 V to 280 V		
AC grid frequency / range	50 Hz / 44 Hz to 55 Hz 60 Hz / 54 Hz to 65 Hz		
Rated power frequency / rated grid voltage	50 Hz / 230 V		
Max. output current / Rated output current	29 A / 21.7 A	29 A / 29 A	36.2 A / 36.2 A
Power factor at rated power / Adjustable displacement power factor	1 / 0 overexcited to 0 underexcited		
THD	≤ 3%		
Feed-in phases / connection phases	3 / 3		
Efficiency			
Max. efficiency / European Efficiency	98.4% / 98.0%	98.4% / 98.0%	98.3% / 98.1%
Protective devices			
DC-side disconnection device	●		
Ground fault monitoring / grid monitoring	● / ●		
DC surge arrester (Type II) can be integrated	○		
DC reverse polarity protection / AC short-circuit current capability / galvanically isolated	● / ● / —		
All-pole sensitive residual-current monitoring unit	●		
Protection class (according to IEC 62109-1) / overvoltage category (according to IEC 62109-1)	I / AC: III; DC: II		
General data			
Dimensions (W / H / D)	661 / 682 / 264 mm (26.0 / 26.9 / 10.4 inch)		
Weight	61 kg (134.48 lb)		
Operating temperature range	–25 °C to +60 °C (–13 °F to +140 °F)		
Noise emission (typical)	51 dB(A)		
Self-consumption (at night)	1 W		
Topology / cooling concept	Transformerless / Opticool		
Degree of protection (as per IEC 60529)	IP65		
Climatic category (according to IEC 60721-3-4)	4K4H		
Maximum permissible value for relative humidity (non-condensing)	100%		
Features / function / Accessories			
DC connection / AC connection	SUNCLIX / spring-cage terminal		
Display	○		
Interface: RS485, Speedwire/Webconnect	○ / ●		
Data interface: SMA Modbus / SunSpec Modbus	● / ●		
Multifunction relay / Power Control Module	○ / ○		
Shade management SMA ShadeFix / Integrated Plant Control / Q on Demand 24/7	● / ● / ●		
Off-Grid capable / SMA Fuel Save Controller compatible	● / ●		
Guarantee: 5 / 10 / 15 / 20 years	● / ○ / ○ / ○		
Certificates and permits (more available on request) * Does not apply to all national appendices of EN 50438	AS 4777, BDEW 2008, C10/11, CE, CEI 0-16, CEI 0-21, CNS 15382, CNS 15426, DEWA 2.0, DK1, DK2, EN 50549-1, EN 50549-2, G99/1, EN 50438:2013*, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, IS 16221-1/2, IS 16169, MEA 2013, NBR 16149, NEN EN 50438, NRS 097-2-1, PEA 2013, NTS, PPC, RD 1699/413, RD 661/2007, Res. n°7:2013, RfG compliant, SI4777, TOR generator, UTE C15-712-1, VDE 0126-1-1, VDE-AR-N 4105, VDE-AR-N 4110, VFR 2014		
Type designation	STP 15000TL-30	STP 20000TL-30	STP 25000TL-30

Appendix G: Inverter and string configuration of the different PV installations

Type	PV-generator PV-panelen	# 1 126/126	# 2 150/150	# 3 183/183	# 4 120/120	Configuratie
3 x STP 15000TL-30 PV-generator/omvormer compatibel		A: 3 x 7 B: 3 x 7				cos φ: 1,00 $P_{AC,max}$: 15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 50,40 kWp	Nom. vermogensverhouding: 91 %		Energierendementsfactor: 99,9 %			
2 x STP 25000TL-30 PV-generator/omvormer compatibel					A: 3 x 10 B: 3 x 10	cos φ: 1,00 $P_{AC,max}$: 25,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 48,00 kWp	Nom. vermogensverhouding: 106 %		Energierendementsfactor: 100 %			
1 x STP110-60 (CORE2) PV-generator/omvormer beperkt compatibel			H: 3 x 10 I: 3 x 10 J: 3 x 10 K: 3 x 10 L: 3 x 10	A: 5 x 5 B: 5 x 5 C: 5 x 5 D: 5 x 5 E: 5 x 5 F: 5 x 5 G: 3 x 11		cos φ: 1,00 $P_{AC,max}$: 110,00 kW
Mededelingen en oplossingsvoorstellen (3 mededelingen)						
Piekvermogen: 133,20 kWp	Nom. vermogensverhouding: 84 %		Energierendementsfactor: 99,2 %			

Figure 85: Inverter and string configuration science building_SPR-MAX3-400

Type	PV-generator PV-panelen	# 1 116/116	# 2 141/141	# 3 169/169	# 4 105/105	Configuratie
1 x STP 20000TL-30 PV-generator/omvormer compatibel					A: 3 x 18 B: 1 x 5	cos φ: 1,00 $P_{AC,max}$: 20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 23,01 kWp	Nom. vermogensverhouding: 89 %		Energierendementsfactor: 99,8 %			
1 x STP 15000TL-30 PV-generator/omvormer compatibel					A: 2 x 18 B: 1 x 10	cos φ: 1,00 $P_{AC,max}$: 15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 17,94 kWp	Nom. vermogensverhouding: 85 %		Energierendementsfactor: 99,5 %			
5 x STP10.0-3AV-40 PV-generator/omvormer compatibel				A ‖ B: 2 x 15		cos φ: 1,00 $P_{AC,max}$: 10,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 58,50 kWp	Nom. vermogensverhouding: 87 %		Energierendementsfactor: 99,7 %			
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel		H: 1 x 23 I: 1 x 23 J: 1 x 23 K: 1 x 23 L: 2 x 12	B: 1 x 23 C: 1 x 23 D: 1 x 23 E: 1 x 23 F: 1 x 23 G: 2 x 13	A: 1 x 19		cos φ: 1,00 $P_{AC,max}$: 110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 107,64 kWp	Nom. vermogensverhouding: 104 %		Energierendementsfactor: 100 %			

Figure 86: Inverter and string configuration science building_ JKM390M-6RL3-B

Type	PV-generator PV-panelen	# 1 83/83	# 2 86/86	# 3 125/125	# 4 71/71	Configuratie
1 x STP 20000TL-30 PV-generator/omvormer compatibel		A: 1 x 21 B: 1 x 21				cos φ: 1,00 $P_{AC,max}$: 20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 22,68 kWp	**Nom. vermogensverhouding: 90 %**			**Energierendementsfactor: 99,9 %**		
1 x STP 15000TL-30 PV-generator/omvormer compatibel					A: 1 x 21 B: 1 x 10	cos φ: 1,00 $P_{AC,max}$: 15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 16,74 kWp	**Nom. vermogensverhouding: 92 %**			**Energierendementsfactor: 99,9 %**		
1 x STP 15000TL-30 PV-generator/omvormer compatibel		A: 1 x 22		B: 1 x 11		cos φ: 1,00 $P_{AC,max}$: 15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 17,82 kWp	**Nom. vermogensverhouding: 86 %**			**Energierendementsfactor: 99,6 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel		L: 1 x 19	A: 1 x 17 B: 1 x 17 C: 1 x 17 D: 1 x 17 E: 1 x 18	F: 1 x 19 G: 1 x 19 H: 1 x 19 I: 1 x 19 J: 1 x 19 K: 1 x 19		cos φ: 1,00 $P_{AC,max}$: 110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 118,26 kWp	**Nom. vermogensverhouding: 95 %**			**Energierendementsfactor: 100 %**		
1 x STP 20000TL-30 PV-generator/omvormer compatibel					A: 1 x 20 B: 1 x 20	cos φ: 1,00 $P_{AC,max}$: 20,00 kW

Figure 87: Inverter and string configuration science building _ VERTEX PERC

Type	Gebouw 2: Oppervlak 1 (Zuidwest) 269/269	Gebouw 3: Oppervlak 2 (Zuidwest) 180/180	Gebouw 1: Oppervlak 3 (Zuidwest) 32/32	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
2 x STP 25000TL-30 Neem het maximale aantal aansluitingen in acht!		A: 4 x 11	B: 2 x 8	1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 48,00 kWp	**Nom. vermogensverhouding: 106 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer beperkt compatibel	A: 4 x 7 B: 4 x 7 C: 4 x 7 D: 4 x 7 E: 4 x 7 F: 4 x 7 G: 4 x 7 H: 4 x 7 I: 5 x 9	J: 3 x 10 K: 3 x 10 L: 4 x 8		1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (3 mededelingen)					
Piekvermogen: 144,40 kWp	**Nom. vermogensverhouding: 77 %**		**Energierendementsfactor: 97,8 %**		

Figure 88: Inverter and string configuration P1 building_SPR-MAX3-400

Type	Gebouw 2: Oppervlak 1 (Zuidwest) 246/246	Gebouw 3: Oppervlak 2 (Zuidwest) 161/161	Gebouw 1: Oppervlak 3 (Zuidwest) 29/29	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP10.0-3AV-40 PV-generator/omvormer compatibel			A: 1 x 17 B: 1 x 12	1,00	10,00 kW

Mededelingen en oplossingsvoorstellen (1 mededeling)

Piekvermogen: 11,31 kWp **Nom. vermogensverhouding: 90 %** **Energierendementsfactor: 99,9 %**

Type	Gebouw 2: Oppervlak 1 (Zuidwest)	Gebouw 3: Oppervlak 2 (Zuidwest)	Gebouw 1: Oppervlak 3 (Zuidwest)	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP110-60 (CORE2) PV-generator/omvormer beperkt compatibel	F: 2 x 17 G: 2 x 17 H: 2 x 17 I: 2 x 17 J: 2 x 17 K: 2 x 17 L: 2 x 21	A: 2 x 16 B: 2 x 16 C: 2 x 16 D: 2 x 16 E: 3 x 11		1,00	110,00 kW

Mededelingen en oplossingsvoorstellen (3 mededelingen)

Piekvermogen: 158,73 kWp **Nom. vermogensverhouding: 70 %** **Energierendementsfactor: 95,7 %**

Figure 89: Inverter and string configuration P1 building_ JKM390M-6RL3-B

Type	Gebouw 2: Oppervlak 1 (Zuidwest) 168/168	Gebouw 3: Oppervlak 2 (Zuidwest) 106/106	Gebouw 1: Oppervlak 3 (Zuidwest) 21/21	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 20000TL-30 PV-generator/omvormer compatibel		B: 1 x 21	A: 1 x 21	1,00	20,00 kW

Mededelingen en oplossingsvoorstellen (1 mededeling)

Piekvermogen: 22,68 kWp **Nom. vermogensverhouding: 90 %** **Energierendementsfactor: 99,9 %**

Type	Gebouw 2: Oppervlak 1 (Zuidwest)	Gebouw 3: Oppervlak 2 (Zuidwest)	Gebouw 1: Oppervlak 3 (Zuidwest)	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP110-60 (CORE2) PV-generator/omvormer beperkt compatibel	A: 1 x 21 B: 1 x 21 C: 1 x 21 D: 1 x 21 E: 1 x 21 F: 1 x 21 G: 1 x 21 H: 1 x 21	I: 1 x 21 J: 1 x 21 K: 1 x 21 L: 1 x 22		1,00	110,00 kW

Mededelingen en oplossingsvoorstellen (2 mededelingen)

Piekvermogen: 136,62 kWp **Nom. vermogensverhouding: 82 %** **Energierendementsfactor: 99 %**

Figure 90: Inverter and string configuration P1 building _ VERTEX PERC

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 176/176	Gebouw 2: Oppervlak 2 (Zuidwest) 301/301	Gebouw 3: Oppervlak 3 (Zuidoost) 53/53	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
4 x STP 20000TL-30 Neem het maximale aantal aansluitingen in acht!	A: 4 x 11	B: 3 x 5		1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 94,40 kWp	**Nom. vermogensverhouding: 87 %**		**Energierendementsfactor: 99,6 %**		
1 x STP110-60 (CORE2) Neem het maximale aantal aansluitingen in acht!		C: 2 x 12 D: 2 x 12 E: 2 x 12 F: 2 x 12 G: 2 x 12 H: 2 x 12 I: 2 x 12 J: 2 x 12 K: 2 x 12 L: 5 x 5	A: 5 x 5 B: 4 x 7	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 117,60 kWp	**Nom. vermogensverhouding: 95 %**		**Energierendementsfactor: 99,8 %**		

Figure 91: Inverter and string configuration law building_SPR-MAX3-400

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 150/150	Gebouw 2: Oppervlak 2 (Zuidwest) 265/265	Gebouw 3: Oppervlak 3 (Zuidoost) 49/49	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 20000TL-30 PV-generator/omvormer compatibel			A: 2 x 18 B: 1 x 13	1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 19,11 kWp	**Nom. vermogensverhouding: 107 %**		**Energierendementsfactor: 100 %**		
2 x STP 25000TL-30 PV-generator/omvormer compatibel	A: 3 x 19 B: 1 x 18			1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 58,50 kWp	**Nom. vermogensverhouding: 87 %**		**Energierendementsfactor: 99,8 %**		
5 x STP 20000TL-30 PV-generator/omvormer compatibel		A: 2 x 18 B: 1 x 17		1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 103,35 kWp	**Nom. vermogensverhouding: 99 %**		**Energierendementsfactor: 100 %**		

Figure 92: Inverter and string configuration law building_ JKM390M-6RL3-B

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 101/101	Gebouw 2: Oppervlak 2 (Zuidwest) 188/188	Gebouw 3: Oppervlak 3 (Zuidoost) 34/34	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
2 x STP 20000TL-30 PV-generator/omvormer compatibel		B: 1 x 23	A: 1 x 17	1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 43,20 kWp	**Nom. vermogensverhouding: 95 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel	A: 1 x 20 B: 1 x 20 C: 1 x 20 D: 1 x 20 E: 1 x 21	F: 1 x 20 G: 1 x 20 H: 1 x 20 I: 1 x 20 J: 1 x 20 K: 1 x 20 L: 1 x 22		1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 131,22 kWp	**Nom. vermogensverhouding: 85 %**		**Energierendementsfactor: 99,5 %**		

Figure 93: Inverter and string configuration law building _ VERTEX PERC

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 21/21	Gebouw 3: Oppervlak 2 (Zuidoost) 121/121	Gebouw 2: Oppervlak 3 (Noordoost) 266/266	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
3 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 1 x 7		B: 2 x 12	1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 37,20 kWp	**Nom. vermogensverhouding: 124 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) Neem het maximale aantal aansluitingen in acht!		A: 2 x 12 B: 2 x 12 C: 2 x 12 D: 2 x 12 E: 5 x 5	F: 3 x 9 G: 3 x 9 H: 3 x 9 I: 3 x 9 J: 3 x 9 K: 3 x 9 L: 4 x 8	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 126,00 kWp	**Nom. vermogensverhouding: 89 %**		**Energierendementsfactor: 99,9 %**		

Figure 94: Inverter and string configuration economics building_SPR-MAX3-400

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 17/17	Gebouw 3: Oppervlak 2 (Zuidoost) 110/110	Gebouw 2: Oppervlak 3 (Noordoost) 241/241	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 1 x 17	B: 1 x 20		1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 14,43 kWp	**Nom. vermogensverhouding: 106 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) Neem het maximale aantal aansluitingen in acht!		A: 2 x 15 B: 2 x 15 C: 2 x 15	D: 2 x 13 E: 2 x 13 F: 2 x 13 G: 2 x 13 H: 2 x 13 I: 2 x 13 J: 2 x 13 K: 2 x 13 L: 3 x 11	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 129,09 kWp	**Nom. vermogensverhouding: 87 %**		**Energierendementsfactor: 99,8 %**		

Figure 95: Inverter and string configuration economics building_ JKM390M-6RL3-B

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 13/13	Gebouw 3: Oppervlak 2 (Zuidoost) 74/74	Gebouw 2: Oppervlak 3 (Noordoost) 168/168	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 1 x 13		B: 1 x 13	1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 14,04 kWp	**Nom. vermogensverhouding: 109 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel		I: 1 x 18 J: 1 x 18 K: 1 x 18 L: 1 x 20	A: 1 x 19 B: 1 x 19 C: 1 x 19 D: 1 x 19 E: 1 x 19 F: 1 x 19 G: 1 x 19 H: 1 x 22	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 123,66 kWp	**Nom. vermogensverhouding: 90 %**		**Energierendementsfactor: 100 %**		

Figure 96: Inverter and string configuration economics building _VERTEX PERC

Type	Gebouw 1: Oppervlak 1 (Noordwest) 178/178			Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
2 x STP 25000TL-30 Neem het maximale aantal aansluitingen in acht!	A: 4 x 10 B: 3 x 9			1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 53,60 kWp	**Nom. vermogensverhouding: 95 %**		**Energierendementsfactor: 100 %**		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 2 x 11 B: 2 x 11			1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 17,60 kWp	**Nom. vermogensverhouding: 87 %**		**Energierendementsfactor: 99,6 %**		

Figure 97: Inverter and string configuration shared classrooms_SPR-MAX3-400

Type	Gebouw 1: Oppervlak 1 (Noordwest) 160/160			Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
2 x STP 20000TL-30 PV-generator/omvormer compatibel	A: 3 x 19			1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 44,46 kWp	Nom. vermogensverhouding: 92 %		Energierendementsfactor: 99,9 %		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 2 x 18 B: 1 x 10			1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 17,94 kWp	Nom. vermogensverhouding: 85 %		Energierendementsfactor: 99,6 %		

Figure 98: Inverter and string configuration shared classrooms_ JKM390M-6RL3-B

Type	Gebouw 1: Oppervlak 1 (Noordwest) 113/113			Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
2 x STP 20000TL-30 PV-generator/omvormer compatibel	A: 1 x 20 B: 1 x 20			1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 43,20 kWp	Nom. vermogensverhouding: 95 %		Energierendementsfactor: 100 %		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 1 x 20 B: 1 x 13			1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 17,82 kWp	Nom. vermogensverhouding: 86 %		Energierendementsfactor: 99,6 %		

Figure 99: Inverter and string configuration shared classrooms _VERTEX PERC

Type	Gebouw 2: Oppervlak 1 (Zuidoost) 97/97	Gebouw 1: Oppervlak 2 (Zuidwest) 339/339	Gebouw 3: Oppervlak 3 (Zuidwest) 231/231	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
7 x STP 20000TL-30 PV-generator/omvormer compatibel		B: 1 x 9	A: 3 x 11	1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 117,60 kWp	Nom. vermogensverhouding: 122 %		Energierendementsfactor: 100 %		
1 x STP110-60 (CORE2) PV-generator/omvormer beperkt compatibel	A: 4 x 8 B: 4 x 8 C: 3 x 11	D: 3 x 10 E: 3 x 10 F: 3 x 10 G: 3 x 10 H: 3 x 10 I: 3 x 10 J: 3 x 10 K: 3 x 10 L: 3 x 12		1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (3 mededelingen)					
Piekvermogen: 149,20 kWp	Nom. vermogensverhouding: 75 %		Energierendementsfactor: 96,9 %		

Figure 100: Inverter and string configuration P2+P4+workshop_SPR-MAX3-400

Type	Gebouw 2: Oppervlak 1 (Zuidoost) 83/83	Gebouw 1: Oppervlak 2 (Zuidwest) 311/311	Gebouw 3: Oppervlak 3 (Zuidwest) 208/208	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
8 x STP 25000TL-30 PV-generator/omvormer compatibel		A: 2 x 19	B: 2 x 13	1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 199,68 kWp	**Nom. vermogensverhouding: 102 %**		**Energierendementsfactor: 100 %**		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	B: 2 x 19	A: 1 x 7		1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 17,55 kWp	**Nom. vermogensverhouding: 87 %**		**Energierendementsfactor: 99,7 %**		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 2 x 18 B: 1 x 9			1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 17,55 kWp	**Nom. vermogensverhouding: 87 %**		**Energierendementsfactor: 99,7 %**		

Figure 101: Inverter and string configuration P2+P4+workshops_ JKM390M-6RL3-B

Type	Gebouw 2: Oppervlak 1 (Zuidoost) 50/50	Gebouw 1: Oppervlak 2 (Zuidwest) 202/202	Gebouw 3: Oppervlak 3 (Zuidwest) 137/137	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
5 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 1 x 10		B: 1 x 21	1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 83,70 kWp	**Nom. vermogensverhouding: 92 %**		**Energierendementsfactor: 99,9 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel		A: 1 x 20 B: 1 x 20 C: 1 x 20 D: 1 x 20 E: 1 x 20 F: 1 x 20 G: 1 x 20 H: 1 x 20 I: 1 x 20 J: 1 x 22	K: 1 x 16 L: 1 x 16	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 126,36 kWp	**Nom. vermogensverhouding: 88 %**		**Energierendementsfactor: 99,8 %**		

Figure 102: Inverter and string configuration P2+P4+workshops _ VERTEX PERC

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 216/216	Gebouw 2: Oppervlak 2 (Zuidwest) 60/60	Gebouw 3: Oppervlak 3 (Zuidoost) 91/91	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 25000TL-30 PV-generator/omvormer compatibel		A: 3 x 10 B: 3 x 10		1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 24,00 kWp	**Nom. vermogensverhouding: 106 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) Neem het maximale aantal aansluitingen in acht!	E: 3 x 9 F: 3 x 9 G: 3 x 9 H: 3 x 9 I: 3 x 9 J: 3 x 9 K: 3 x 9 L: 3 x 9		A: 2 x 11 B: 2 x 11 C: 2 x 11 D: 5 x 5	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 122,80 kWp	**Nom. vermogensverhouding: 91 %**		**Energierendementsfactor: 99,9 %**		

Figure 103: Inverter and string configuration library_SPR-MAX3-400

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 198/198	Gebouw 2: Oppervlak 2 (Zuidwest) 54/54	Gebouw 3: Oppervlak 3 (Zuidoost) 80/80	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP110-60 (CORE2) Neem het maximale aantal aansluitingen in acht!	A: 2 x 14 B: 2 x 14 C: 2 x 14 D: 2 x 14 E: 2 x 14 F: 2 x 14 G: 2 x 15	H: 3 x 9 I: 3 x 9	J: 2 x 13 K: 2 x 13 L: 2 x 14	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 129,48 kWp	**Nom. vermogensverhouding: 86 %**		**Energierendementsfactor: 99,7 %**		

Figure 104: Inverter and string configuration library_ JKM390M-6RL3-B

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 138/138	Gebouw 2: Oppervlak 2 (Zuidwest) 33/33	Gebouw 3: Oppervlak 3 (Zuidoost) 50/50	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel	C: 1 x 19 D: 1 x 19 E: 1 x 19 F: 1 x 19 G: 1 x 19 H: 1 x 19 I: 1 x 24	A: 1 x 16 B: 1 x 17	J: 1 x 16 K: 1 x 16 L: 1 x 18	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 119,34 kWp	**Nom. vermogensverhouding: 94 %**		**Energierendementsfactor: 100 %**		

Figure 105: Inverter and string configuration library_ VERTEX PERC

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 111/111			Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 25000TL-30 Neem het maximale aantal aansluitingen in acht!	A: 4 x 10 B: 3 x 11			1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)					
Piekvermogen: 29,20 kWp	Nom. vermogensverhouding: 88 %		Energierendementsfactor: 99,6 %		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 2 x 10 B: 2 x 9			1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 15,20 kWp	Nom. vermogensverhouding: 101 %		Energierendementsfactor: 100 %		

Figure 106: Inverter and string configuration CIAE building_SPR-MAX3-400

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 103/103			Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 20000TL-30 PV-generator/omvormer compatibel	A: 2 x 18 B: 1 x 17			1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 20,67 kWp	Nom. vermogensverhouding: 99 %		Energierendementsfactor: 100 %		
1 x STP 20000TL-30 PV-generator/omvormer compatibel	A: 2 x 18 B: 1 x 14			1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 19,50 kWp	Nom. vermogensverhouding: 105 %		Energierendementsfactor: 100 %		

Figure 107: Inverter and string configuration CIAE building_ JKM390M-6RL3-B

Type	Gebouw 1: Oppervlak 1 (Zuidwest) 70/70			Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
1 x STP 20000TL-30 PV-generator/omvormer compatibel	A: 1 x 21 B: 1 x 20			1,00	20,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 22,14 kWp	Nom. vermogensverhouding: 92 %		Energierendementsfactor: 99,9 %		
1 x STP 15000TL-30 PV-generator/omvormer compatibel	A: 1 x 21 B: 1 x 8			1,00	15,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)					
Piekvermogen: 15,66 kWp	Nom. vermogensverhouding: 98 %		Energierendementsfactor: 100 %		

Figure 108: Inverter and string configuration CIAE building_ VERTEX PERC

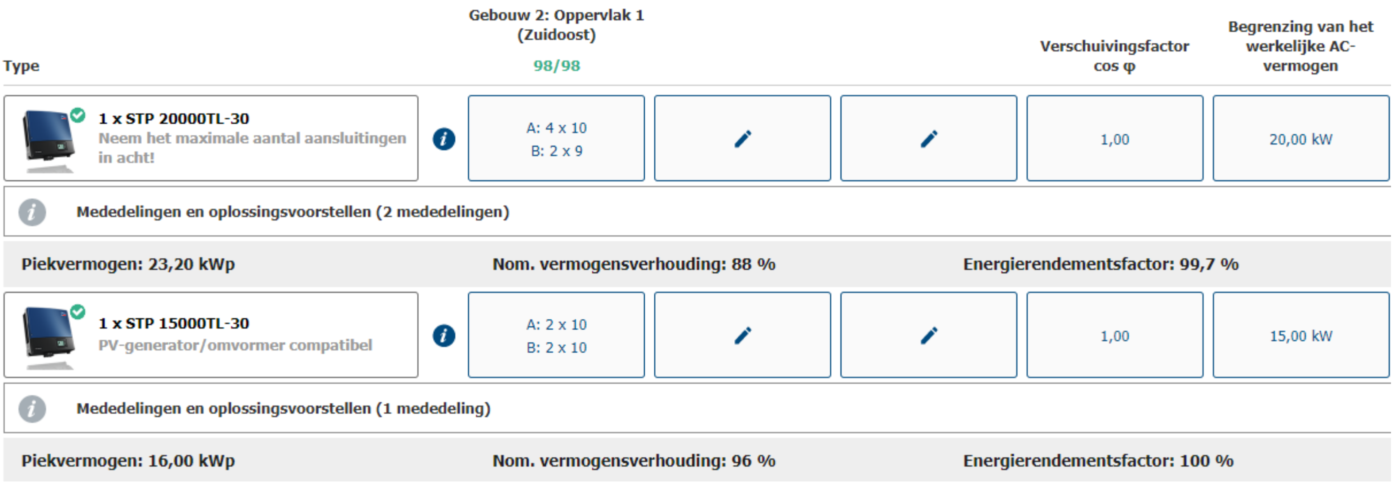


Figure 109: Inverter and string configuration P3 building_SPR-MAX3-400

Figure 110: Inverter and string configuration P3 building_ JKM390M-6RL3-B

Figure 111: Inverter and string configuration P3 building_ VERTEX PERC

Type		Gebouw 1: Oppervlak 1 (Zuidwest) 174/174	Gebouw 2: Oppervlak 2 (Zuidwest) 148/148	Gebouw 3: Oppervlak 3 (Noordwest) 192/192	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
3 x STP 25000TL-30 Neem het maximale aantal aansluitingen in acht!	i	A: 4 x 10 B: 2 x 9			1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (2 mededelingen)						
Piekvermogen: 69,60 kWp		**Nom. vermogensverhouding: 110 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer beperkt compatibel	i		A: 4 x 7 B: 4 x 7 C: 4 x 7 D: 4 x 7 E: 3 x 12	F: 3 x 9 G: 3 x 9 H: 3 x 9 I: 3 x 9 J: 3 x 9 K: 3 x 9 L: 3 x 10	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (3 mededelingen)						
Piekvermogen: 136,00 kWp		**Nom. vermogensverhouding: 82 %**		**Energierendementsfactor: 98,9 %**		

Figure 112: Inverter and string configuration central modules_SPR-MAX3-400

Type		Gebouw 1: Oppervlak 1 (Zuidwest) 161/161	Gebouw 2: Oppervlak 2 (Zuidwest) 138/138	Gebouw 3: Oppervlak 3 (Noordwest) 171/171	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
3 x STP 25000TL-30 PV-generator/omvormer compatibel	i	B: 1 x 19		A: 3 x 19	1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 88,92 kWp		**Nom. vermogensverhouding: 86 %**		**Energierendementsfactor: 99,7 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel	i	A: 1 x 20 B: 1 x 20 C: 1 x 20 D: 1 x 20 E: 2 x 12	F: 1 x 19 G: 1 x 19 H: 1 x 19 I: 1 x 19 J: 1 x 19 K: 1 x 19 L: 2 x 12		1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 94,38 kWp		**Nom. vermogensverhouding: 118 %**		**Energierendementsfactor: 100 %**		

Figure 113: Inverter and string configuration central modules_ JKM390M-6RL3-B

Type		Gebouw 1: Oppervlak 1 (Zuidwest) 113/113	Gebouw 2: Oppervlak 2 (Zuidwest) 96/96	Gebouw 3: Oppervlak 3 (Noordwest) 112/112	Verschuivingsfactor cos φ	Begrenzing van het werkelijke AC-vermogen
2 x STP 25000TL-30 PV-generator/omvormer compatibel	i		A: 1 x 24 B: 1 x 24		1,00	25,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 51,84 kWp		**Nom. vermogensverhouding: 99 %**		**Energierendementsfactor: 100 %**		
1 x STP110-60 (CORE2) PV-generator/omvormer compatibel	i	A: 1 x 18 B: 1 x 18 C: 1 x 18 D: 1 x 18 E: 1 x 18 F: 1 x 23		G: 1 x 18 H: 1 x 18 I: 1 x 18 J: 1 x 18 K: 1 x 18 L: 1 x 22	1,00	110,00 kW
Mededelingen en oplossingsvoorstellen (1 mededeling)						
Piekvermogen: 121,50 kWp		**Nom. vermogensverhouding: 92 %**		**Energierendementsfactor: 99,9 %**		

Figure 114: Inverter and string configuration central modules_ VERTEX PERC

Appendix H: Cable length for each configuration

Table 25: Cable length for each configuration

	Science				P1	
	4mm² cable (m)	6mm² cable (m)			4mm² cable (m)	6mm² cable (m)
SPR-MAX3-400	600	360		SPR-MAX3-400	900	60
JKM390M-6RL3-B	1200	60		JKM390M-6RL3-B	780	60
VERTEX PERC	840	0		VERTEX PERC	600	0
	Law				Economics	
	4mm² cable (m)	6mm² cable (m)			4mm² cable (m)	6mm² cable (m)
SPR-MAX3-400	1080	120		SPR-MAX3-400	1020	60
JKM390M-6RL3-B	840	120		JKM390M-6RL3-B	780	60
VERTEX PERC	960	0		VERTEX PERC	840	0
	Shared classroom				P2+P4+workshops	
	4mm² cable (m)	6mm² cable (m)			4mm² cable (m)	6mm² cable (m)
SPR-MAX3-400	360	0		SPR-MAX3-400	1560	0
JKM390M-6RL3-B	120	120		JKM390M-6RL3-B	1200	0
VERTEX PERC	360	0		VERTEX PERC	1320	0
	Library				CIAE	
	4mm² cable (m)	6mm² cable (m)			4mm² cable (m)	6mm² cable (m)
SPR-MAX3-400	780	60		SPR-MAX3-400	240	0
JKM390M-6RL3-B	720	0		JKM390M-6RL3-B	240	0
VERTEX PERC	720	0		VERTEX PERC	240	0
	P3				Central modules	
	4mm² cable (m)	6mm² cable (m)			4mm² cable (m)	6mm² cable (m)
SPR-MAX3-400	240	0		SPR-MAX3-400	1080	0
JKM390M-6RL3-B	240	0		JKM390M-6RL3-B	900	180
VERTEX PERC	240	0		VERTEX PERC	960	0

Appendix I: Number of connectors for each configuration

Table 26: Number of connectors per installation

	Science			P1
	# connectors			# connectors
SPR-MAX3-400	32		SPR-MAX3-400	32
JKM390M-6RL3-B	42		JKM390M-6RL3-B	28
VERTEX PERC	28		VERTEX PERC	20
	Law			Economics
	# connectors			# connectors
SPR-MAX3-400	40		SPR-MAX3-400	36
JKM390M-6RL3-B	32		JKM390M-6RL3-B	28
VERTEX PERC	32		VERTEX PERC	28
	Shared classroom			P2+P4+workshops
	# connectors			# connectors
SPR-MAX3-400	12		SPR-MAX3-400	52
JKM390M-6RL3-B	8		JKM390M-6RL3-B	40
VERTEX PERC	12		VERTEX PERC	44
	Library			CIAE
	# connectors			# connectors
SPR-MAX3-400	28		SPR-MAX3-400	32
JKM390M-6RL3-B	24		JKM390M-6RL3-B	28
VERTEX PERC	24		VERTEX PERC	20
	P3			Central modules
	# connectors			# connectors
SPR-MAX3-400	8		SPR-MAX3-400	36
JKM390M-6RL3-B	8		JKM390M-6RL3-B	36
VERTEX PERC	8		VERTEX PERC	32

Appendix J: Datasheet DC protection

Fuse 22x58 40A

Product no.: 381267

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Built to standards IEC60269-1, EN60269-1, IEC60269-2 and EN60269-2.

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DYFUS holder 100A T-2 22x58 ZRB

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DYFUS ZRB 50 A (690V) sectionable fuse holder with SC screw fixing for industrial size 22x58 cylindrical fuses.

Built according to IEC60269-1, IEC60269-2, EN60269-1, EN60269-2, IEC60947-3 and EN60947-3 standards.