Expansion of an existing 3 MW photovoltaic power plant without exceeding a limited power

Imanol Matanza

Master Thesis 2019

Expansion of an existing 3 MW photovoltaic power plant without exceeding a limited power

Master Thesis

Author: Imanol Matanza

411975

21/10/2019

Chair for Energy Systems and Energy Management

Examiner: Prof. Dr.-Ing. Wolfram H. Wellßow

Supervisor: M. SC. Marco Weisenstein

Declaration of academic honesty

Hereby I declare that the present thesis is drawn up after DPO/BPO/MPO Elektrotechnik und Informationstechnik by myself without help of third parties but the support of my supervisor, that all used sources and tools including the internet are completely and exactly mentioned, and that everything is marked which is taken unchanged, shortened or analogous from other literature.

Abstract (English)

The photovoltaic power plants have a big issue on their production profile; the parabolic shape of their daily power output affects and obliges to oversize in many cases the surrounding grid. However, the orientation and tilting of the photovoltaic modules allow slightly changing or moving their production. The following report shows an existing 3 MWp photovoltaic power plant built in an old military base with bunkers where the modules have a South orientation and where the power can be increased. It exist an accorded maximum power injection of 2,900 kW with the grid operator. Nonetheless, the degradation during the years of the current modules and the time when the peak power occurs, allow adding more photovoltaic modules by varying their orientation and tilting on the surface of the bunkers. With this purpose a simulation program was used to analyze different building configurations and how the production profiles change depending on the tilting and orientation. Different results have been obtained where the importance of the sun path was demonstrated. Moreover, an extra addition of around 1,000 modules (370 kW) can be performed. Finally, a short economic approach was realized in order to prove the feasibility of the project.

Abstract (German)

Die Photovoltaikkraftwerke haben ein großes Problem mit ihrem Produktionsprofil; die parabolische Form ihrer täglichen Leistung beeinflusst und zwingt in vielen Fällen dazu, das umgebende Netz zu überdimensionieren. Die Ausrichtung und Neigung der Photovoltaik-module ermöglicht jedoch eine geringfügige Änderung oder Verlagerung ihrer Produktion. Der folgende Bericht zeigt ein bestehendes 3-MWp-Photovoltaik-Kraftwerk, das in einem alten Militärstützpunkt mit Bunkern errichtet wurde, in denen die Module nach Süden ausgerichtet sind und in denen die Leistung erhöht werden kann. Es besteht eine vereinbarte maximale Einspeiseleistung von 2.900 kW beim Netzbetreiber. Die Verschlechterung während der Jahre der gegenwärtigen Module und der Zeitpunkt, zu dem die Spitzenleistung auftritt, ermöglichen es jedoch, mehr Photovoltaikmodule hinzuzufügen, indem ihre Ausrichtung variiert und die Oberfläche der Bunker geneigt wird. Zu diesem Zweck wurde ein Simulationsprogramm verwendet, um verschiedene Gebäudekonfigurationen zu analysieren und zu analysieren, wie sich die Produktionsprofile in Abhängigkeit von der Neigung und Ausrichtung ändern. Es wurden verschiedene Ergebnisse erzielt, bei denen die Bedeutung des Sonnenwegs nachgewiesen wurde. Darüber hinaus können rund 1.000 Module (370 kW) nachgerüstet werden. Schließlich wurde der kurze wirtschaftliche Ansatz verwirklicht, um die Machbarkeit des Projekts zu beweisen.

CONTENTS

1. Introduction

Situated in the municipality of Clausen in Südwestpfalz district, in Rhineland-Palatinate, western Germany, an open-air photovoltaic power plant was finished and started to produce clean and carbon free energy the 27th of October of 2013. With a peak power of 3121.82 kWp, a total amount of 13,604 modules and 216 inverters, it has generated a total amount of 18,122.88 TWh and helped to avoid the emission of 16,297.85 tons of CO2.

Surrounded in red, it is shown the denomination of the bunkers, in order to make an idea during the report:

Fig 1.1: Bird's eye view from the 3 MW Photovoltaic power plant.

It was built in an old American base where nerve gas was left under military bunkers. After the removal of the gas in 1990 the base was emptied and unused. A german company called "Solarprojekte Gmbh" bought the terrain and installed the actual photovoltaic panels.

The main purpose of this report is to evaluate the actual energy yield, checking the accorded power injection in the middle voltage grid and try to investigate the possibility of increasing the production by adding more modules on top of the bunker´s roofs.

All conventional modules (monocrystalline and polycristallyne) degrade year by year, reducing their efficiency. In addition to this degradation, the photovoltaic energy has an hourly production similar to convex parable, with the peak power around midway (with south configurations). The objective is to analyze different building configurations and afterwards study how the tilting and orientation of the modules affect to their production profile.

The network-operator of the grid is “Pfalzwerke Netzgesellschaft Gmbh”. Both companies agreed on a power injection of 2,900 kW to the medium voltage grid of 20 kV. The photovoltaic generators produce the electricity on DC and it is transformed to a 400 V AC three phased low voltage grid. This current is then derived to three different transformers of 1 MVA capacity each to increase the voltage to the 20 kV of the middle voltage grid.

The main advantage of the project is that the total accorded power will not be exceeded, this means that:

- There will be no need on buying new transformers, which are normally an expensive part of the power plants.
- The required civil work will not require of a big expenditure apart from the trenches of the low voltage lines. Just cleaning the vegetation from the surface of the bunkers.
- The paperwork with the grid operator will not be as strict as in a new power plant, probably some notifications of the new added power.

The efforts of the report will be destined to the irradiation study of the installation, therefore, the expenditure of different features will not be precise, but just an approximation to consider or have a first idea of how much could cost the addition of extra panels. Finally the benefits that could generate to the owner of the power plant will be calculated.

To accomplish objectives these are the most important steps that will be followed:

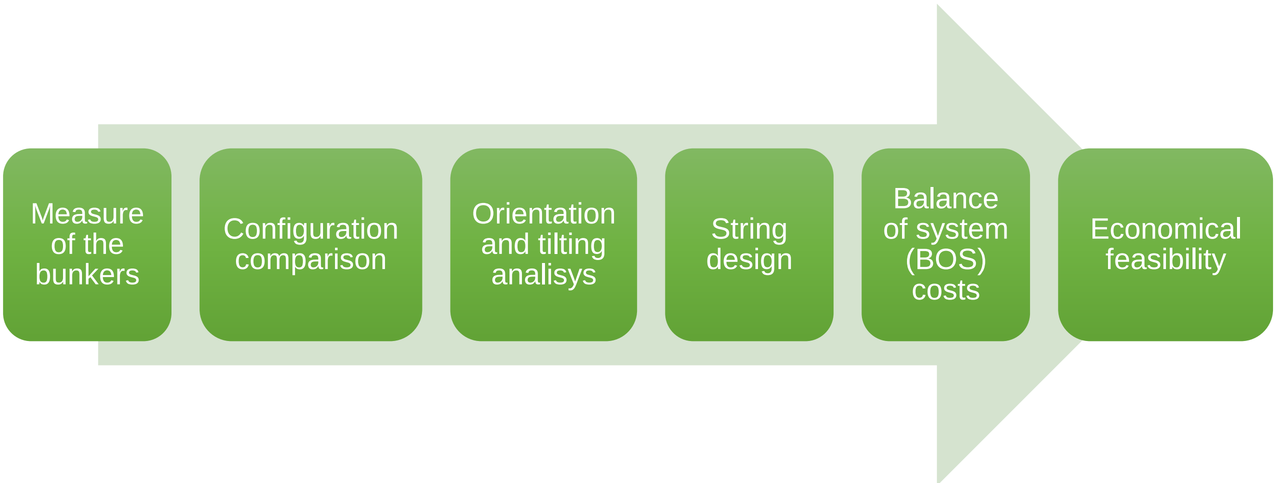


Fig 1.2: Followed procedure.

2. State of the art

2.1. Main components of a photovoltaic power plant

Normally the photovoltaic powerplants are one of the simpliest ways of producing electricity. They offer the possibility of being installed in big or few quantities, creating small installation of few kW to really big power plants of hundreds of MW. It does not matter how much power is installed that the main components will continue being the same:

a) PV generator; formed by the photovoltaic modules, here is were the Sun irradiation is transformed into electricity.
b) Inverter; the modules produce the electricity in DC, so the inverter is the device in charge of transforming the electricity into AC.
c) Structure; the photovoltaic panels require of a structure to hold them in the same position of their whole lifetime. These could be placed on houseroofs or on the ground.
d) Cables; to connect the PV array with the inverter and the inverter with the local grid.
e) Protections; these will be in charge of the security and safety of all the components of the installation.
f) There are possible components that can be added as batteries to storage the excess energy, transformers to change the voltage before injecting it to the grid, trackers to follow the movement of the Sun...

In this project nothing from the last point will be used, the use of chemical batteries will not be considerated and neither the trackers for a better production, because the modules will be tilt-fixed on the bunkers. Moreover, the transformers are not required, so just a slight explanation will be given to understand their task.

In the next section a brief look into the general market will be made, in order to have an overall idea of which kind of prices and efficiencies can be found in it. Finally, the final decision of each component will be explained.

2.2. Election of the components

Before making the election of the photovoltaic model and the inverter it is important to analyze the actual solar market. Even if both components are the main or at least the most evident part from a photovoltaic installation, there are other components which will strongly affect to the final budget of the project, such us the cables, montage system, civil work, designing time, salaries…

The National Renewable Energy Laboratory (NREL) from the United States prepared a report analyzing market prices for all the components of the photovoltaic plants, not just the modules, the inverters and the structure, but also the soft costs (install labor, land acquisition, taxes…). The report gather information from 2010 till 2018 of photovoltaic systems, accounting for all system and project-development costs incurred during the installation to model the costs for residential, commercial, and utility-scale systems.

In the past, great part of the budget was composed by the solar modules, making unfeasible in many cases the construction of photovoltaic power plants without subsidies from the national governments or local support. However, several improvements in production processes and the increase on the production in China have pulled down the prices, making the photovoltaic energy production without incentives appealing (Fu, Feldman, & Margolis, 2018).

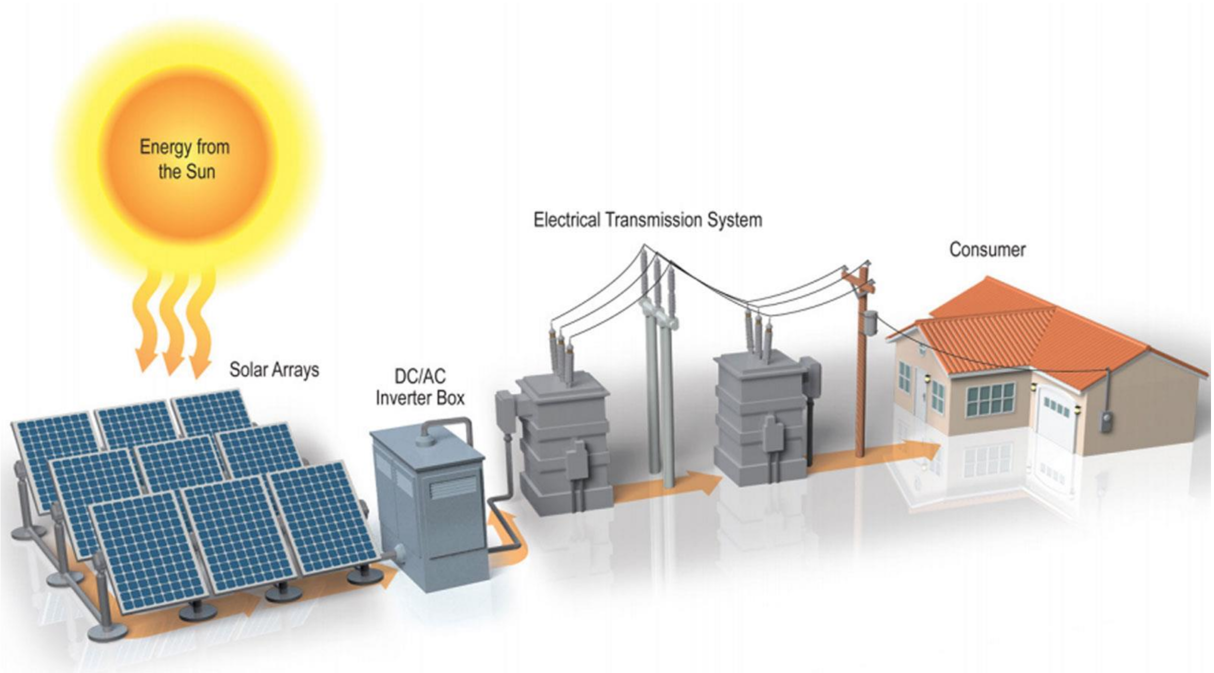


Fig 2.1: Equipment required in a solar farm. (Renew Wisconsin)

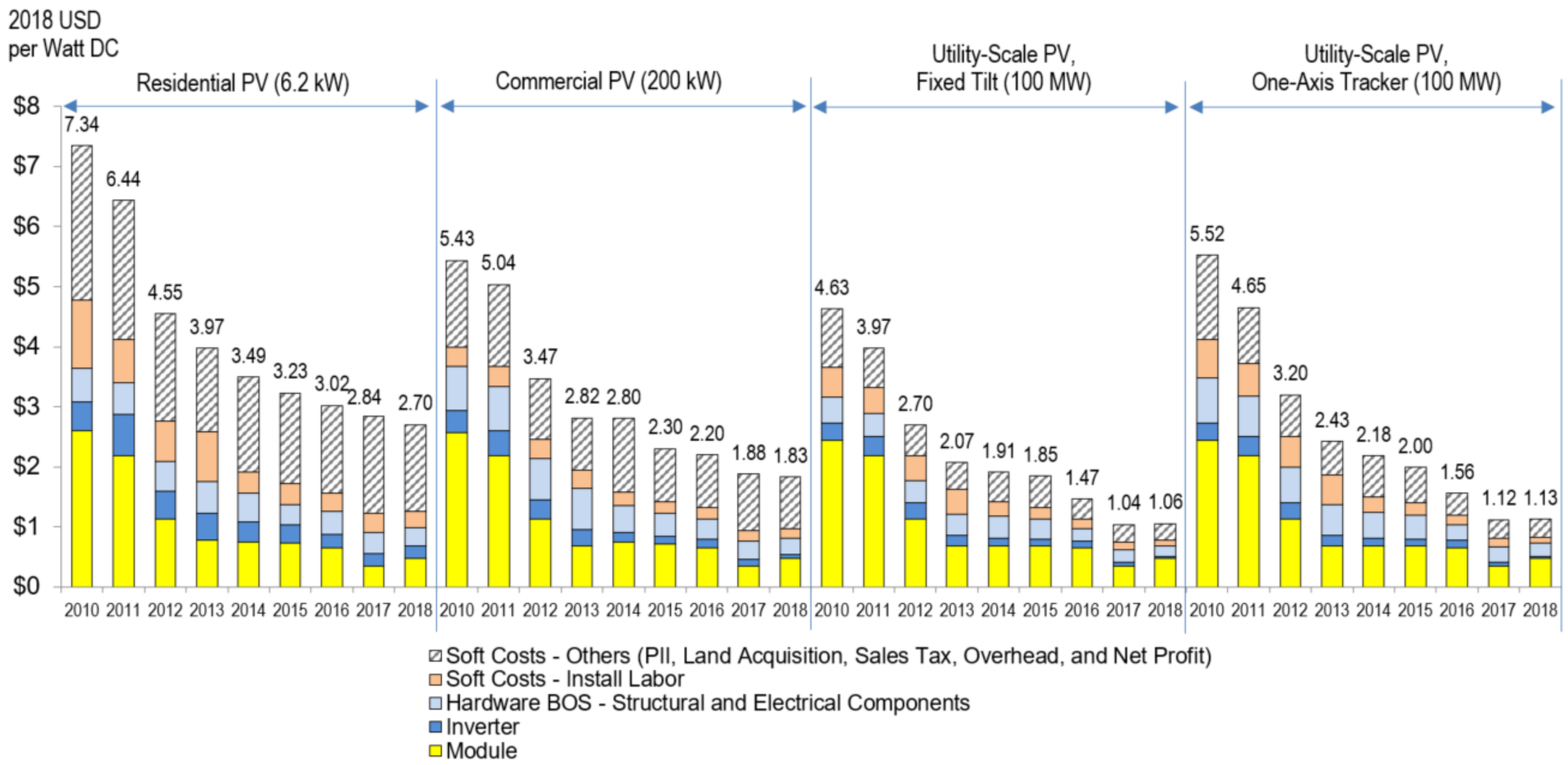


Fig 2.2: The costs break down per Watt DC for different photovoltaic system (Fu, Feldman, & Margolis, 2018).

2.2.1. Photovoltaic module

Another fact to take under consideration is that normally the module manufacturers are offering a warranty of approximately 25 years of production. The production of modules is not going to be as perfect as in the beginning of their operability lives, but they commonly assure a linear degradation, reaching around 80% of performance (comparing with the first year) after 20 years of lifetime.

Plenty of PV manufactures companies from USA and Europe have been declared on bankruptcy since China started producing cheaper technology than their competitors (Bastasch, 2014).

For all these reasons it is important to choose reliable solar module and inverter brands. Even when the installation is properly designed to last for 20-30 years, it is sure that failures are going to appear someday. It is recommended to rely on a liable company so that when these failures occur, replacements will be available and the warranties can be put to use.

With this purpose Bloomberg New Energy Finances (BNEF) makes an analysis helping people and companies gaining a clear perspective on the financial, economic, and policy implications of industry-transforming trends and technologies to drive to a cleaner, more competitive future. In latest analysis the brand “LONGI solar” has reached record bankability rating (Yang, 2019).

LONGI has also ranked as the most creditworthy module manufacturer. BNEF uses the Altman-Z score - a combination of financial ratios - to access the creditworthiness of manufacturers. It is an indicator of the risk of a company filing for bankruptcy in the next 2 years. LONGI was accessed at a score of 3.1 which indicates strong financial health and bankruptcy to be highly unlikely. LONGI's Altman-Z score is the highest among pure play module manufactures.

2.2.2. Inverter

The inverter will take care of switching the Direct Current (DC) coming from the generator to Alternate Current (AC) to inject it on the grid. Most of the manufacturers offer similar characteristics such as a 98% of efficiency and around a 5 years warranty. While solar modules are not prone of breaking, the inverters can fail due to improper design and sizing or because they are not installed in ventilated and warm areas.

Inverters are composed of: passive electronic components, such as capacitors, inductors, transformers, wires; active electronic components, such as power transistors, diodes, and integrated circuits; and electromechanical components, such as relays, switches, connectors, and fans. The electromechanical components are more likely to fail sooner than the other component types. However, capacitors and the inverter bridge are not immune to aging, stress, usage beyond their operational limit, and thermal shock and overload. “The inverter can also have computer components that can fail (Ireland, 2009).

Analyzing the inverter market it comes out that the three main manufacturers are Huawei, Sungrow and SMA in this order. In comparison to the decades-long warranty for the cells, mean time to first failure (MTFF) for inverters is estimated to be between 5 and 10 years. The inverters are really the item that is more probable to fail from the normal life of the installation.

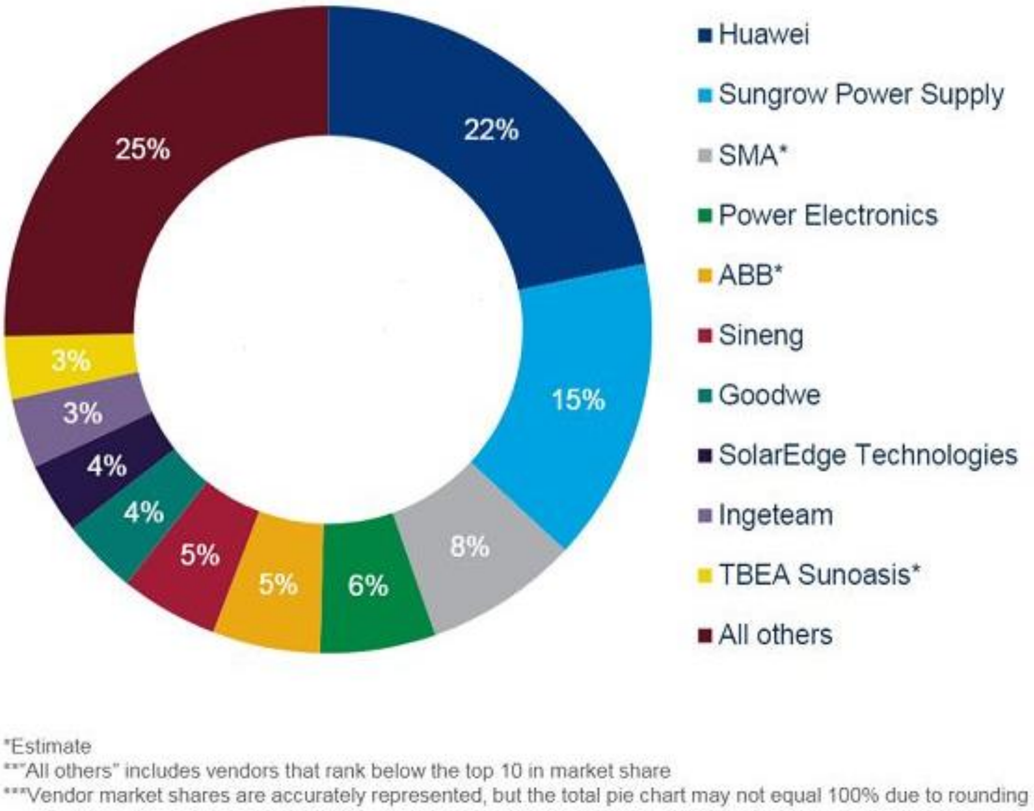


Fig 2.3: Global PV inverter market shares for 2018 (PV magazine, 2019).

As a final comment about the inverters, most of them have a similar price per Watt and are offering same services such as an online portal for remote controlling and some years warranty (Svarc, 2019). For this reason the selection of the inverter will not be so critical, and the selection will be done for experience reasons.

2.2.3. Cables and wires

Even if cables and wires sound almost the same there is a difference between them, while wires are just formed by a single conductor, whereas the cables are formed by at least two different conductors. Moreover, these conductors can be formed in different ways, basically they are usually made of copper or aluminum, both of which have very good conductivity, malleability, and ductility:

- The single or solid wire is a single conductor, which is either bare or insulated by a protective sheath. It is used in static applications, such as in-home applications as electrical wiring, which is plastered inside. Solid wires are cheaper and have a more compact diameter for the same current carrying ability as stranded wires. However, they are available only in small gauges.
- Stranded wire is composed of multiple thin strands of wires twisted together to form one single wire core. They are suitable for applications in which they are subject to frequent movement or even vibrations (i.e., robotics or vehicular applications). Stranded wires are more straightforward to route, but they have a larger diameter for the same carrying capacity as solid wires and are also more expensive.

In the installation the cables are divided in two main parts, the low voltage and the middle voltage cables. On the one hand there will be no need on buying middle voltage cables, these ones are coming out from the transformers and they connect the power plant to the local grid. They were sized for a peak power of 2900 kW, and the main point is to add more power along the day, but without never exceeding the accorded amount. This means that the maximum injected power will be mainteined, so the middle voltage cables will still stand the extra electricity. On the contrary, low DC voltage cables to connect the PV array to the inverter will be required and also low AC voltage cables to connect the inverters with the transformers.

In the case of three-phase inverters, the connection to the low voltage grid is made using a five-core AC cables (three live wires for the three phases that carry the current, a neutral wire carry current away from the device and ground wire (safety wire) that connects the casing of the device to the ground).

The size of the wire to be used depends upon:

- The generating capacity of the Solar Panel (larger the current generated, bigger the size).

- The distance of the solar panel system to the loads (greater the distance, bigger the size).

2.2.4. Final selection

After making a short analysis from the actual solar components market, the final decision can be carried out. The company which could accomplish the upgrade of the photovoltaic power plant has a long business relationship with “IBC Solar“. This company is a relieable solar energy solutions provider, from individual solar modules to entire solar parks. Moreover, because of this close relation, the company is offering a 40% of discount in most of his products. So after comparing these prices with offers from other providers, the inverters and the modules are going to be obtained from this big provider.

Observing their website, there is just one solar module from “LONGI solar” LR6-72PE-370M with a power of 370 Watt and a total price of 114.67€, which makes a cost of 0.310 €/Watt. On the side of the inverter the chosen has been the SMA CORE-1 STP 50-40 with a total power of 50 kW and a price of 3,629.29€, making a 0.073 €/Watt.

3. Vegetation removal

As seen in the Fig. 1.1. the bunkers are completely covered by a big layer of vegetation. In some of them there are even little trees, this will make the cleaning of the area a little bit more difficult. In the following sections it will be showed the required tools and a time approach to accomplish the task.

3.1. Measuring of the area

Google maps has been used to measure the roof area of the bunkers. It is true that the roofs are not flat. However, this is just an approach to know how much time will be needed, so the obtained values will be considered as valid. Here we have the surface:

Bunker 1: 911.64 m^2	Bunker 5: 643.68 m^2	Bunker 9: 863.53 m^2
Bunker 2: 1052.15 m^2	Bunker 6: 771.13 m^2	Bunker 10: 777.72 m^2
Bunker 3: 1084.21 m^2	Bunker 7: 754.14 m^2	Bunker 11: 700.25 m^2
Bunker 4: 1093.14 m^2	Bunker 8: 963.62 m^2	Bunker 12: 511.43 m^2

This makes a total of approximately: 10126.64 m^2

3.2. Time approach

In order to obtain a first approach of the needed time, the vegetation of a little house garden was cut. In the following pictures it is shown the total surface of the respective garden together with some pictures to make an idea:

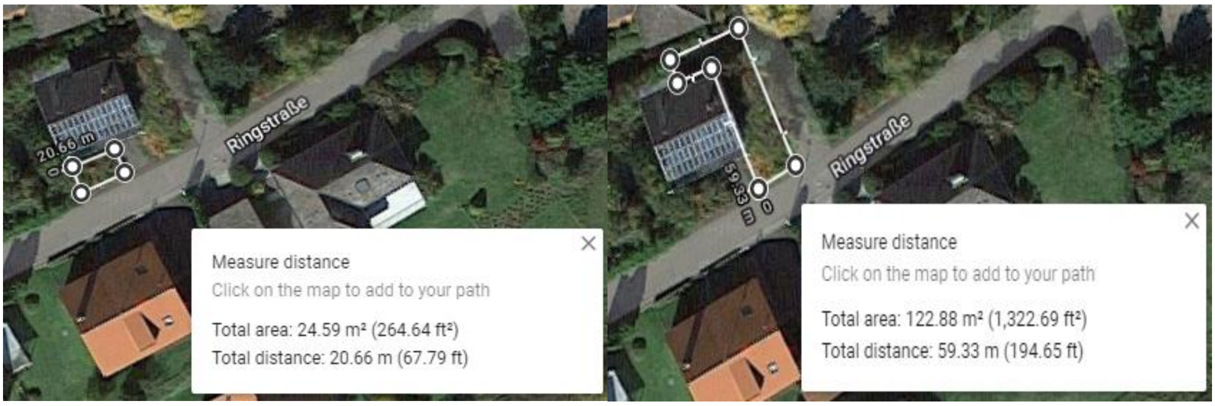


Fig. 3.1: Measuring of the cut garden

The garden as seen in the pictures is composed by 147.47 m^2. The time needed to remove all the plants was 1h 15', including the required time to start the machines. The work was made by three workers, but the task could be done just by two workers with the appropriate machinery. Therefore, it will take approximately a complete day of gardening per bunker.

3.3. Required machinery

After the experience of the garden, this is the considered machinery to remove all as fast as possible:

- Chainsaw: to cut the little trees and big plants.
- Hand mower with blade: once the trees are removed this is the fastest option to continue with the task.
- Blower: to remove the wastes downhill.

Fig. 3.2: Required machinery

4. Configurations study

The main objective of this section is to analyze several design options and to choose one among them. With this purpose a 3D model example of the bunkers will be generated. The chosen programs therefore are:

- SketchUp 2019: This is a 3D design software which allows to geolocate the installation and which can show the shape of the terrain.
- BIMsolar: This is an innovative project supported by InnoEnergy and a free software that helps designing a photovoltaic installation, either BAPV (standard PV modules set on a roof), or BIPV (integrated PV on a curtain wall / window). The BIMsolar software is developed by EnerBIMto.

After modeling in SketchUp the bunkers in the photovoltaic power plant, the file will be exported to BIMsolar, where different cases of study will be considered. BIMsolar has a whole data bank of weather forecasts all over Europe available to use, allowing the user to choose the closer or more similar one to the photovoltaic plant. In this case, the closest one is situated in Mannheim.

4.1. Creation of the 3D model

SketchUp is a really powerful 3D software which allows creating incredible and realistic models. However, in this case just an approach is required, for that reason just some of the offered options were used. The most important is the one that allows geolocating the installation, using a bird’s eye view from the surrounding area and then showing the shape of the terrain.

Additionally, as the real measures of the bunkers are not available and due to the difficulty and time required to obtain them, the model will just be an approach of the reality. The procedure to modelling them was:

1- Creation of a rectangle with the same shape obtained thanks to the bird’s eye view.
2- The height of the entrances is around 4 meters. Knowing this, the rectangles where extruded until this height.
3- Finally the curved shape was given to the cubes.

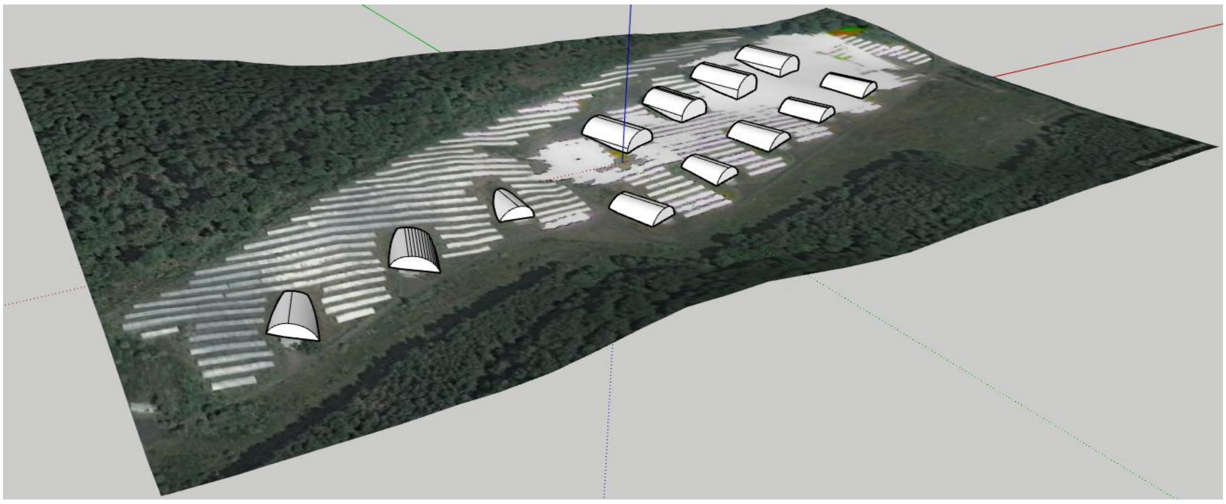


Fig 4.1: Final 3D model

4.2. Cases of study

As seen in the Fig. 1.1. the bunkers are not perfectly oriented to the south. East bunkers are slightly facing the South-East and West bunkers the South-West. When designing a photo-voltaic plant two main possible configurations are the most typical ones: Place all the modules directly facing the South or an East-West configuration.

Having these things in mind, there will be three different cases of study:

- Option A: Placing the modules on the same direction of the bunkers, letting some distance between the different lines. Inside this option different tilts will be also analyzed.
- Option B: Using just one face of the bunker, the one which is facing slightly the South.
- Option C: Using the other side of the bunker, the one facing slightly the North.

For the following study different tilting possibilities where analyzed, with this purpose measures of the bunker where made, with a resulting inclination, orientation and possible surface showed as module of:

- Bunker 1: I=14.93º; O=70º (240 modules)
- Bunker 2: I=15.94º; O=70º (189 modules)
- Bunker 3: I=21.80º; O=70º (120 modules)
- Bunker 4: I=15.94º; O=70º (217 modules)
- Bunker 5: I=19.98º; O=90º (144 modules)
- Bunker 6: I=15.94º; O=-70º (133 modules)
- Bunker 7: I=15.95º; O=-70º (119 modules)
- Bunker 8: I=17.10º; O=70º (175 modules)
- Bunker 9: I=15.94º; O=70º (119 modules)
- Bunker 10: I=14.93º; O=70º (160 modules)
- Bunker 11: I=17.10º; O=70º (147 modules)
- Bunker 12: I=17.10º; O=70º (84 modules)

As it can be appreciated, the inclination of the bunkers goes from 14.93º in the flattest one, to an inclination of 19.98º on the most inclined one. This means that lower inclinations for the modules can not be achieved. However, increasing the height of the modules using the structure to hold them, some more meters can be gained. Hence, the following studies will consider tilting angles from 15º to 30º.

4.2.1. Option A (modules facing the south)

Placing the modules facing the south is normally the best productive configuration among all the options, because the photovoltaic panels will be all the time under the Sun. However, several disadvantages can also be found, some of the most critical ones are:

- Tilting the modules can generate shadows on the back lines. Therefore is important to know the appropriate distance between the different lines. As higher the tilting angle is, longer the distance between panels should be, reducing the filling rate of the total surface and the total power.
- Because of the curved shape of the bunkers shadows will appear on the lower modules due to the top modules.
- Moreover, this curved shape can make of the montage-system a difficult task. Normally the aluminum bars are straight and not curved, so this could add an additional cost to the structure.
- More fixing points to the bunker will be needed, so more digging time will be required.
- The bunkers do not really have a cylindrical shape, while having a look at them from the top it can be appreciated that some of them are not completely straight, this means that the modules can not be placed one behind the other.

In order to choose the best inclination angle for the modules, the BIMsolar program has been used. Here it could be analyzed the electricity production of a module in different ranges of 5º from 0º to 60º.

Normally, the higher the tilting angle is, the higher the produced energy will be during winter months. However, this increase is much smaller than the loss of energy during summer months, making of big angles a bad idea from the point of view of maximizing the production. Accordingly to the next table, the angle where more electricity is generated by the module is the 35º. All this data were obtained using meteorological data from Mannheim, so using data from a different city with different latitude, could divers from them:

Month	0º	5º	10º	15º	20º	25º	30º	35º	40º	45º	50º	55º	60º
January	4,6	4,8	5,0	5,2	5,4	5,5	5,7	5,8	5,8	5,9	6,0	6,0	6,0
February	8,6	9,0	9,4	9,8	10,1	10,4	10,7	10,9	11,1	11,2	11,3	11,3	11,3

March	18,2	19,0	19,8	20,4	21,0	21,5	21,9	22,2	22,5	22,5	22,7	22,5	22,3
April	24,6	25,2	25,6	26,0	26,3	26,5	26,6	26,6	26,5	26,3	26,1	25,6	25,1
May	32,1	32,6	32,9	33,1	33,2	33,2	33,1	32,8	32,5	31,9	31,5	30,7	29,8
June	29,4	29,6	29,7	29,7	29,6	29,5	29,2	28,8	28,4	27,8	27,4	26,5	25,8
July	35,3	35,8	36,0	36,2	36,3	36,2	36,0	35,6	35,2	34,5	34,0	33,0	32,1
August	30,4	31,0	31,6	32,0	32,3	32,5	32,5	32,4	32,3	31,8	31,5	30,8	30,1
September	20,8	21,6	22,3	22,9	23,4	23,8	24,1	24,3	24,4	24,3	24,3	24,1	23,7
October	12,6	13,2	13,7	14,2	14,6	15,0	15,3	15,5	15,7	15,8	15,9	15,8	15,8
November	5,4	5,7	5,9	6,1	6,3	6,5	6,7	6,8	6,9	7,0	7,1	7,0	7,0
December	4,0	4,3	4,5	4,8	5,0	5,3	5,5	5,6	5,8	5,9	6,0	6,1	6,1
Total (kWh)	226,1	231,8	236,6	240,5	243,7	246,0	247,2	247,5	247,0	245,0	243,8	239,4	235,1

Table 4.1: Produced energy for different tilting angles. Configuration A.

Once the desire angle has been chosen is important to measure the shadow loses related to consequently distances between lines. Once again, the data will be obtained from BIMsolar with different spacing from 0.5 meters till 2 meters.

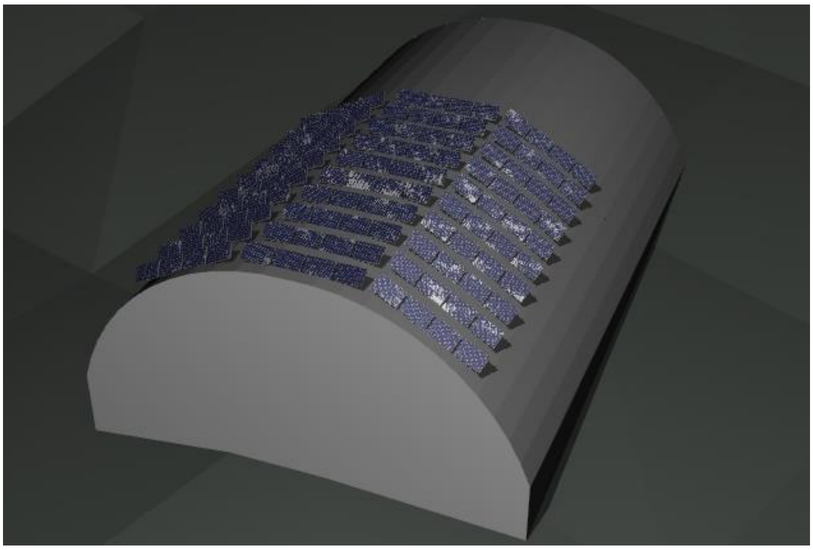


Fig 4.2: Configuration A. Panels facing the south with the direction of the bunkers.

As seen in the Fig 4.2 the production and shadow losses study was carried out for a total amount of 120 random panels along the bunker in groups of 4.

	0,5m		0,75m		1m		1,25m		1,5m		1,75m		2m	
Month	Produced	Losses	Produced	Losses	Produced	Losses	Produced	Losses	Produced	Losses	Produced	Losses	Produced	Losses
January	513,91	100,34	563,21	51,29	583,10	33,01	589,37	27,87	605,54	14,89	605,07	17,60	611,10	14,08
February	1039,42	135,41	1099,13	77,56	1140,38	40,39	1145,93	37,53	1169,59	19,30	1165,56	26,85	1173,40	23,40
March	2253,85	116,56	2285,81	89,65	2358,19	27,63	2370,46	22,47	2385,09	18,47	2393,55	18,05	2402,18	16,83
April	2754,38	82,55	2796,00	48,38	2837,80	19,50	2855,63	11,78	2874,67	6,84	2887,86	4,82	2898,31	4,12
May	3422,69	77,62	3476,63	36,17	3512,20	18,44	3533,15	11,11	3560,67	2,02	3575,73	0,89	3587,28	0,83
June	2996,01	77,57	3050,01	33,58	3086,06	13,78	3106,94	5,82	3128,50	2,10	3143,38	0,82	3154,75	0,78
July	3723,70	69,49	3779,28	29,64	3816,86	13,00	3838,95	6,68	3862,85	2,51	3880,55	0,30	3892,73	0,28
August	3424,73	74,77	3479,45	33,55	3510,95	19,44	3529,30	14,09	3551,05	8,22	3566,96	4,75	3578,86	3,34
September	2514,62	90,73	2567,48	45,32	2591,32	31,97	2612,13	21,11	2625,74	18,78	2635,45	18,11	2646,69	14,84
October	1564,21	99,54	1606,02	60,70	1620,76	51,17	1647,33	30,09	1656,23	28,33	1664,55	25,86	1675,27	21,61
November	613,33	120,69	663,74	70,83	684,75	51,56	700,78	37,03	712,15	29,20	716,34	27,55	723,04	23,53
December	446,96	155,72	514,38	88,86	549,01	55,51	555,51	50,00	578,70	29,60	582,29	27,88	585,72	26,31
Total	25267,80	1200,97	25881,14	665,52	26291,36	375,41	26485,47	275,57	26710,77	180,26	26817,28	173,47	26929,33	149,94
Shadow losses	4,54%		2,51%		1,41%		1,03%		0,67%		0,64%		0,55%	

Table 4.2: Produced energy and shadow losses for different spacing between lines

As it can be appreciated in the table, as bigger the separation between lines the lowest the shadow losses will be. However, an arrangement between separation and production should be done. As much as the shadow losses are decreased the better, but it is important to understand that by increasing the spacing the less peak power could be installed. The last line of the table shows the percentage of shadow losses from the total amount of energy which could be produced.

It is notorious that from 0,75m to 1m the shadow losses are almost the half and the subsequently increases to 1,25m and 1,5m allow decreasing the shadow losses around a 35% respectively for each of them. Furthermore, increasing another 0,25m the spacing will decrease the losses in just a 4%. The desired distance will be therefore between 1m and 1,5m.

4.2.2. Option B (Using just one side, the most appropriate)

Using one side of the bunkers will make much easier the design for the strings, because it will exist just one surface. Additionally, as the wires will be underneath the panels will not be needed so many channels or tubes to protect the cables. Moreover, it will make much easier the installation of the mounting system. However, the energy yield per module will not be as high as in the Option A.

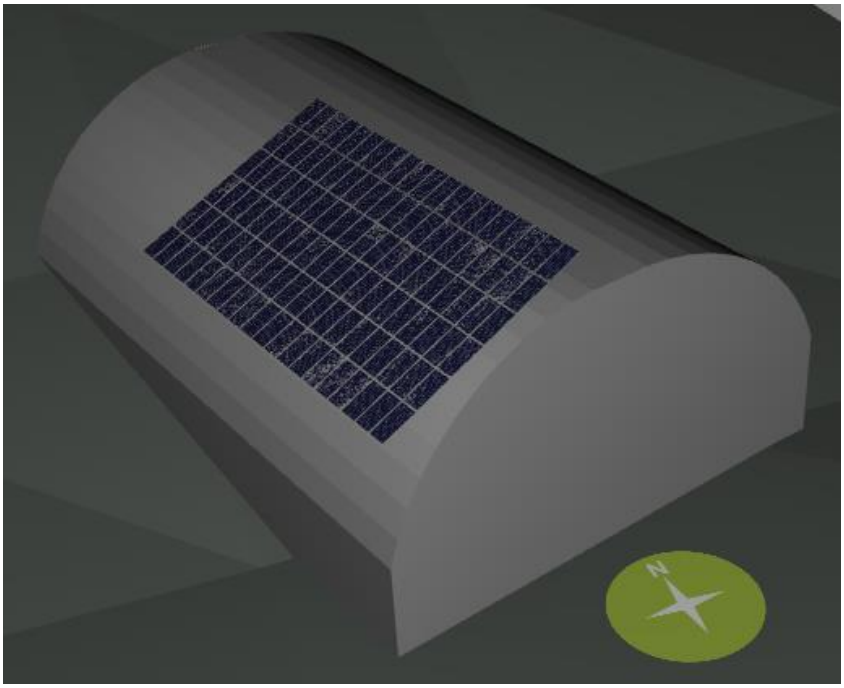


Fig 4.3: Configuration B. Panels leaning on the South-West side of the bunker 3.

In this case the orientation of the surface can not be changed, which means, that just the tilting of the panels can be varied. Using the same software, different tilting cases were figured out. For this purpose the bunker number 3 was chosen, which has an orientation of 70º on its South-West face and -110º on the Noth-East face. Here, 120 of the picked modules can be placed.

The results here observed are different from the obtained ones of the Configuration A (facing the south). The reason is that the orientation is completely critical. As the modules are facing almost the West, when they are looking directly the Sun, this is about to disappear. The angle between the earth and the Sun rays is the lower, so bigger inclinations of the modules will be beneficial for the production. The next table shows data of the energy yield for each month of the year:

	15º	20º	25º	30º
January	688,115	687,244	684,428	678,939
February	1284,566	1279,268	1270,957	1258,563
March	2804,984	2794,848	2780,207	2758,535
April	3763,713	3727,174	3687,408	3633,484
May	4944,522	4879,939	4808,417	4715,199
June	4487,445	4422,544	4351,282	4258,952
July	5486,882	5412,896	5329,559	5223,014
August	4686,679	4617,519	4541,667	4455,463
September	3207,12	3179,835	3146,754	3105,898
October	1918,509	1910,281	1897,897	1876,074
November	796,696	792,272	787,214	779,793
December	598,949	600,248	599,717	596,088
Total	34668,18	34304,068	33885,507	33340,002

Table 4.3: Produced energy for different tilting angles. Configuration B.

4.2.3. Option C (Using both sides of the bunker)

The last considered option will evaluate the possibility of adding a second surface with modules on the other side of the bunker, even if they are starting to face the North. Once more, same type and module number where used for the production study as it can be appreciated on the Fig 4.4.

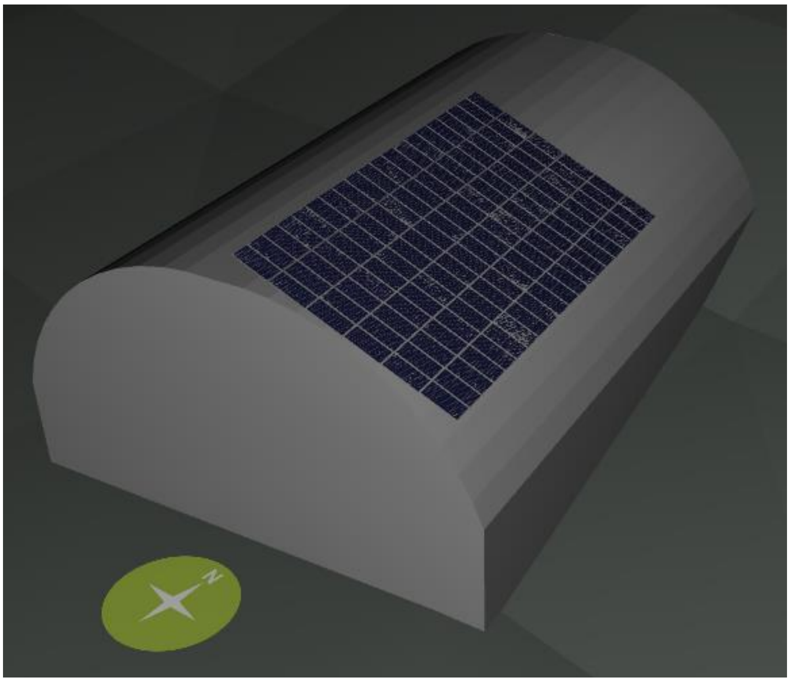


Fig 4.4: Configuration B. Panels leaning on the North-East side of the bunker 3.

	15º	20º	25º	30º
January	656,9	646,7	636,0	624,8
February	1242,0	1225,1	1206,5	1184,8
March	2657,7	2612,7	2559,3	2498,7
April	3718,3	3670,0	3607,2	3535,8
May	4981,6	4925,2	4848,7	4756,1
June	4588,0	4549,7	4491,4	4419,2
July	5526,3	5461,1	5373,9	5268,3
August	4777,3	4732,6	4668,9	4585,4
September	3159,7	3119,9	3068,4	3011,4
October	1854,4	1828,0	1794,9	1760,2
November	781,1	773,8	764,2	753,8
December	554,6	543,2	531,8	521,4
Total	34498,0	34088,2	33551,2	32920,0

Table 4.4: Produced energy for different tilting angles. Configuration C.

In this case, lower tilting angles help to increase the total amount of output energy from the panels. The results prove the contrast with the previous case. The reason behind it is in the Fig 4.5, increasing the angle when the modules are facing the North it means showing their back to the Sun rays during midday, which is the most productive part of the day.

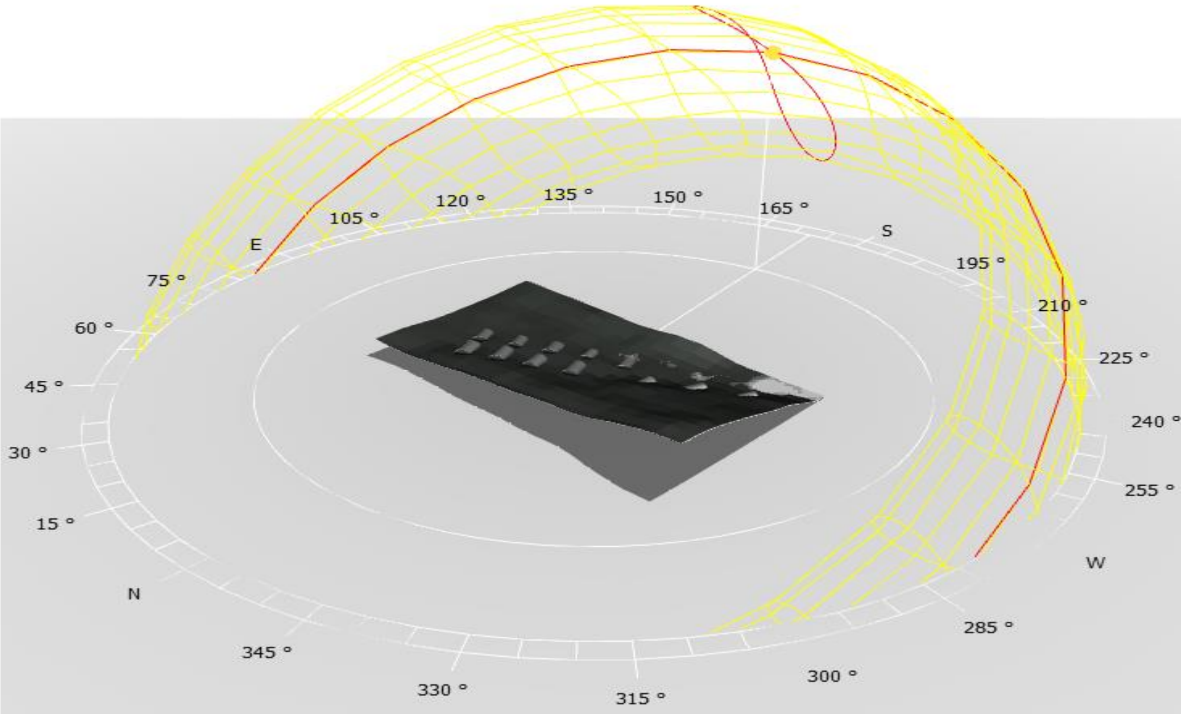


Fig 4.5: Sun paths during the year for latitude of 49º (Mannheim).

Comparing the values with the Option B it can be observed that the difference is not so high for low tiltings, even if the modules are slightly looking to the North. And as commented before, big inclinations angles may increase the difference between both scenarios.

	15º	20º	25º	30º
North-East	34498,0	34088,2	33551,2	32920,0
South-West	34668,2	34304,1	33885,5	33340,0
Difference	0,49%	0,63%	0,99%	1,26%

Table 4.5: Comparison between both sides of the bunkers

4.3. Conclusion and decision

After analyzing all the possible options it is time to compare them and make a decision. The following table gathers the best scenario for each configuration, the results from the South configuration may divers from the previously mentioned because of selected modules for each analysis are different. In this one, all the configurations were proved with the same module type (LONGI 370 W). Whereas the simulations done in the section 4.2.1. were done before the election of the photovoltaic module.

	South-West	North-East	South
January	688,115	656,879	770,837
February	1284,566	1241,991	1518,174
March	2804,984	2657,713	3158,906
April	3763,713	3718,304	3827,786
May	4944,522	4981,636	4784,625
June	4487,445	4588,044	4152,105
July	5486,882	5526,276	5227,285
August	4686,679	4777,339	4848,597
September	3207,12	3159,705	3542,443
October	1918,509	1854,413	2193,971
November	796,696	781,061	905,897
December	598,949	554,618	729,277
Total	34668,18	34497,979	35659,903

Table 4.6: Comparison of the three best configurations.

It is reasonable that the Configuration A (almost south orientation) is the most productive one. However, as it will be proved in the next sections the influence of when occurs the peak power will be crucial for the final selection.

5. Irradiation study, tilting and orientation influence

As mentioned at the introduction, the photovoltaic power plant is just allowed to inject a maximum amount of 2,900 kW to the middle voltage grid. Therefore, it is critical to understand how the tilting and the orientation of the new added modules will affect to the new protduction, not just to control the injected power, but also to maximize the obtained energy with the lower possible expenditure.

So the first step would be to know which the real energy production of the actual modules is. The power plant is equipped with a datalogger called webbox (from the brand SMA) to make the control and maintenance of the whole installation. This datalogger is in charge of recording and uploading the energy yield of each standing inverter, allowing the company to check easily and remotely when any of them is not working properly. All the data is then uploaded to “Sunny Portal“ where the energy production per hour can be checked.

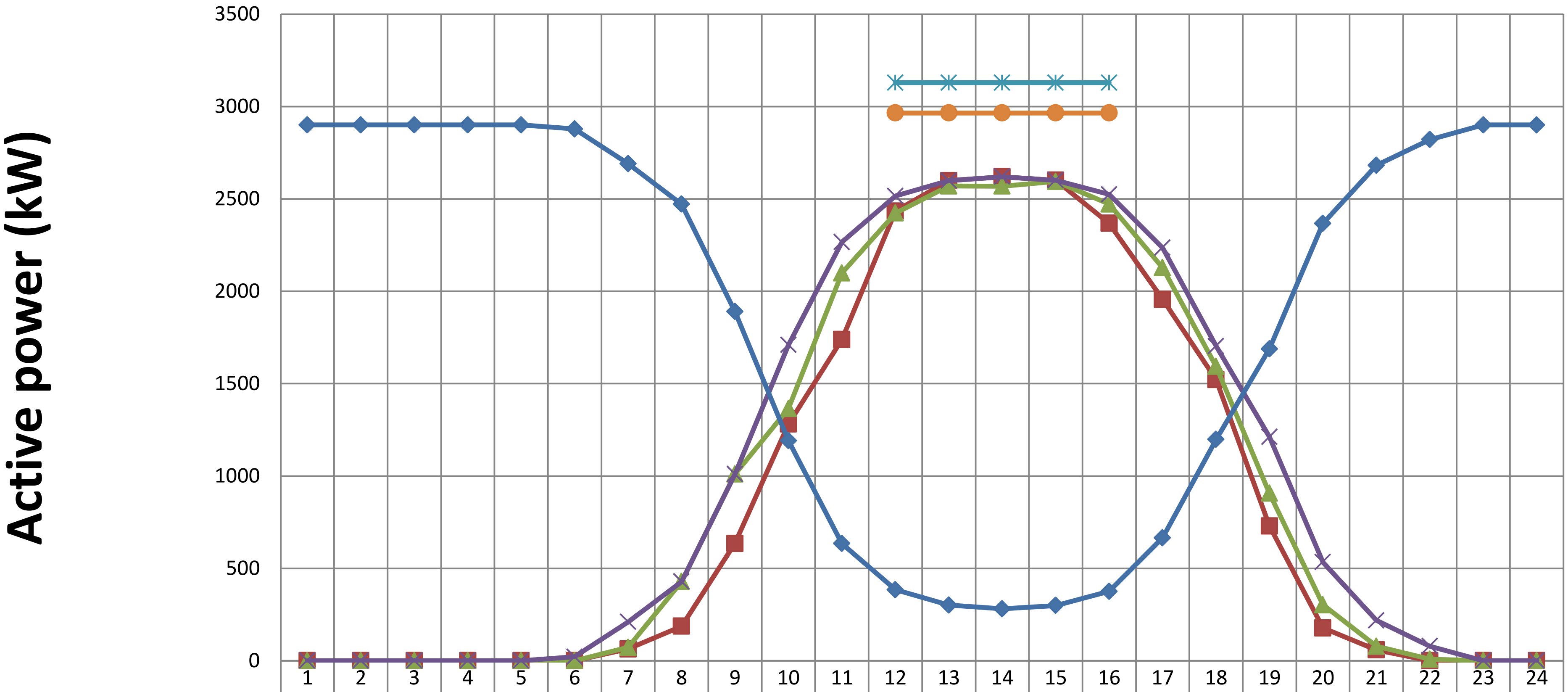
5.1. Actual production

The available data is since 2014 registered. However, just the values from 2018 and the current 2019 will be used. The reason for not using all the available data is that along the lifetime of the PV generator the efficiency is been reduced year per year. On the one hand, the used modules are from “Chaori Solar”, a chinese brand that went into bankruptcy some years ago, so their datasheet could not be found on the internet. On the other hand, the chosen module from “Longi Solar” has a degradation or loss of 0.55%/year, when normally monocrystallines and polycrystalline have a 0.5%/year of loss (Energy Informative, 2014).

After obtaining all the hourly productions, three different profiles were taken:

- Maximal kW: This shows the daily profile of the highest peak power.
- Maximal daily production: This sketches the daily profile of the most productive day.
- Maximal hourly: This draws the highest power for each hour.
- Added power possibility: The last graphic is the difference between the maximal injected power (2,900 kW) and the worst scenario (Maximal hourly).

As it can be appreciated, at around 14 the graphic shows the lowest value, at this moment just an extra 280.5 kW of active power can be injected to the grid. However, the main objective of this section is to vary the tilting and the orientation of the added modules so that the peak power of the added modules is delayed comparing to the actual production.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Maximal kW	0	0	0	0	0	0	63,74	186,5	634,8	1281	1739	2434	2599	2620	2601	2367	1956	1521	729,6	177	58,38	0	0	0
Max. Daily production	0	0	0	0	0	0	72,39	428,6	1010	1364	2099	2423	2569	2569	2594	2472	2127	1593	906,8	302,5	78,44	8,54	0	0
Max. Hour	0	0	0	0	0	21,33	209,7	428,6	1010	1709	2266	2516	2599	2620	2601	2525	2235	1702	1212	533,1	218,3	79,1	0,15	0
Added power possibility	2900	2900	2900	2900	2900	2879	2690	2471	1890	1191	633,7	384,2	301,1	280,5	299,1	375,4	665	1198	1688	2367	2682	2821	2900	2900
Power under STC												3129	3129	3129	3129	3129								
Maximal inverter power												2965	2965	2965	2965	2965								

Table 5.1: Actual production profiles and maximal power that could be added.

5.2. Tilting and orientation influence

The orientation of the photovoltaic panels affects not only on the energy yield, but also on when appears the peak power during the day. South orientations are the most productive ones when there are no shadow losses, but sometimes it is better to sacrifice a little bit of energy in order to decrease and move the peak power to a different time during the day. The amount of photovoltaic plants that are being installed all over the world can cause a variety of different problems in grid operation, especially in the grid voltage. A suboptimal orientation decreases the capacity factor, but on the other hand the decrease of the peak power can be beneficial in case of voltage problems and asset overloading.

In an East/West oriented PV system, power gradients are lower and the energy production therefore smoother, which leads to a reduced need for conventional power plant or other flexibility options to follow the gradients. This configuration achieves higher area utilization and yield per surface area. Moreover, the correlation of production and consumption of PV systems not facing south is worse while south oriented systems have the best correlation (Tröster & Schmidt).

Regarding the tilting of the modules, as it was observed in the table 5.1 of the section 5.2.1, a bigger angle increases the energy production during winter, but it makes lower the production in summer. The best correlation appears with a tilting angle of 35º, remarked with yellow.

The inclinations of all the bunkers are between 15º and 20º, but using the montage system the tilting of the modules could be varied. In the worst scenario, where the inclination is the lowest (bunker 1 and 10 with 14.93º), increasing the inclination till 30º, would suppose to add another 4.66 m from the top of the bunker.

Therefore, the following analysis shows the hourly production of a "Longi Solar" module for orientations from 0º to 90º (in ranges of 10º each) and different tilting from 15º/20º/25º/30º. The orientation angles are taken as 0º for south configurations and positive while turning to southwest configurations. Afterwards, the highest power of each hour was obtained to draw the most productive profile. The final step was to compare these profiles with the maximum added power possibility. Hence, the worst production scenario for the current installation was compared with the worst production scenario of the new modules. As the graphics that depict the obtained results require a lot of space, these have been placed at the last section called as "Annexes". However a summary will be shown:

	Nº modules				Energy yield per module (kWh)				Total yearly production (kWh)			
	15º	20º	25º	30º	15º	20º	25º	30º	15º	20º	25º	30º
0º	968	948	948	923	312,5	317,3	320,2	322,4	302519,4	300790,0	297498,3	297545,7
10º	968	951	935	932	311,4	315,9	318,0	320,6	301417,8	300384,8	297300,1	298816,9
20º	978	958	954	948	309,7	313,6	315,8	316,9	302898,3	300405,8	301281,8	300409,8
30º	988	974	964	964	307,6	309,8	311,7	311,3	303931,5	301774,4	300464,3	300120,2
40º	1002	992	985	995	305,2	306,5	307,0	306,8	305858,5	304092,6	302442,3	305315,7
50º	1013	1006	1013	1017	301,8	302,2	302,6	300,4	305696,0	303994,1	306550,0	305517,0
60º	1028	1035	1039	1050	297,7	297,7	296,5	293,4	306072,6	308171,2	308082,2	308068,9
70º	1047	1059	1071	1076	294,7	292,6	289,9	287,0	308570,8	309908,9	310536,4	308785,1
80º	1067	1088	1104	1116	291,1	288,0	283,4	279,4	310595,2	313367,9	312847,1	311866,2
90º	1083	1113	1142	1146	287,4	283,3	278,6	272,7	311269,4	315363,0	318128,1	312570,4
-110	1083	1105	1127	1169	290,7	286,7	281,6	276,8	314823,8	316759,3	317395,9	323575,7
-70	1009	1002	1006	1017	304,6	305,0	305,6	305,6	307384,8	305593,0	307430,6	310750,5
						MAX	322,368			MAX	318128,08	

Table 5.2: Tilting and orientation results.

The number of modules that can be added to the actual installation are between 938 (I 30º and O 30º) to 1075 (I 30º and O 90º). However, it is not about the modules that can be added to the power plant, but the energy that they can produce. The efficiency of the modules is the highest for I 30º and O 0º, while the maximum energy that be produced occurs for I 15º and O 0º.

The problem of this method is that is just taking into account the maximal production of each hour, without considering when these peak powers happen. As the orientation and the tilting are different for the current modules and the new ones, it is impossible that both peaks occur at the same time. Taking a look on the north-east orientation (-110º) two main results can be extracted from the table 6.2.,

a) As higher the tilting is, the lower the energy yield per module. Whereas with south facing panels the energy yield per module increases as they approach the optimal inclination angle (35º). This easy to understand, because increasing the inclination of the panels, it means that they will be turning their back to the Sun.
b) Another important fact is that this orientation allows the modules to produce more power per year than the ones looking to the West (90º). It can be thought that the modules as closer to a south orientation are the higher should be their production. Nonetheless, as in the Fig 4.5 shows, the dawn is not always on the East and the sunset is not always on the West. The Fig 5.1 shows how during summer months (when there are more sunny hours and the irradiance is the higher), the sunlight is favorable for angles higher than the 90º. Fig 5.2 shows this phenomenon, how production is bigger during summer months and slightly lower during the rest of

the year. In theory this should not happen, as it can be appreciated in the Fig. 5.2, for the same tilting, loses decrease as the face the South. Explanation could be the afternoon clouds and increase of the cell temperature along the day. It is explained more widely in the following paragraphs.

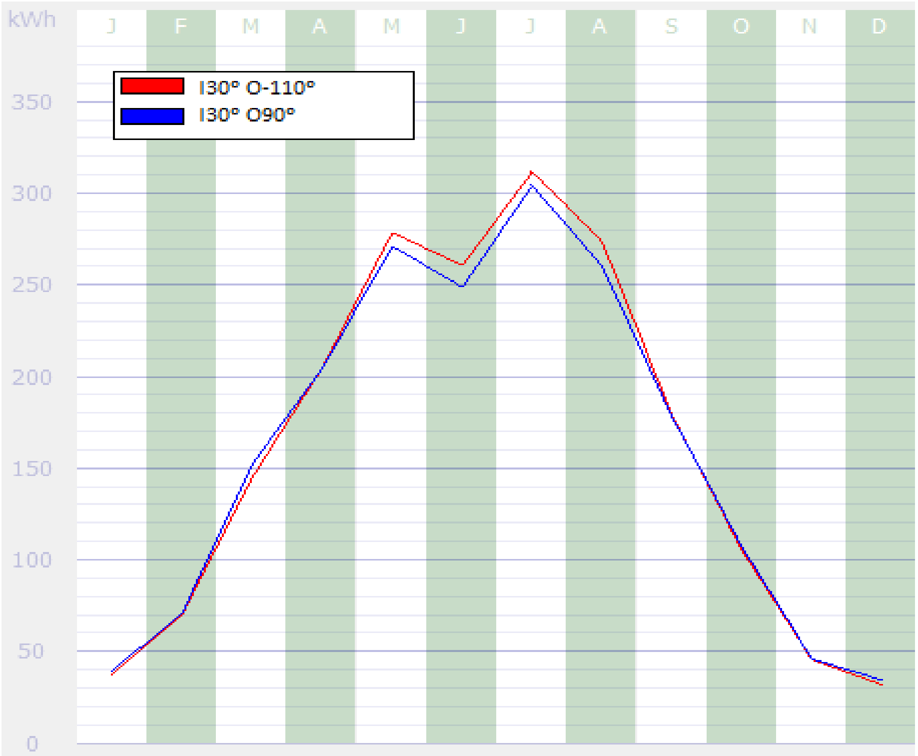


Fig 5.1: Monthly production for Northeast (-110º) and West (90º) configuration.

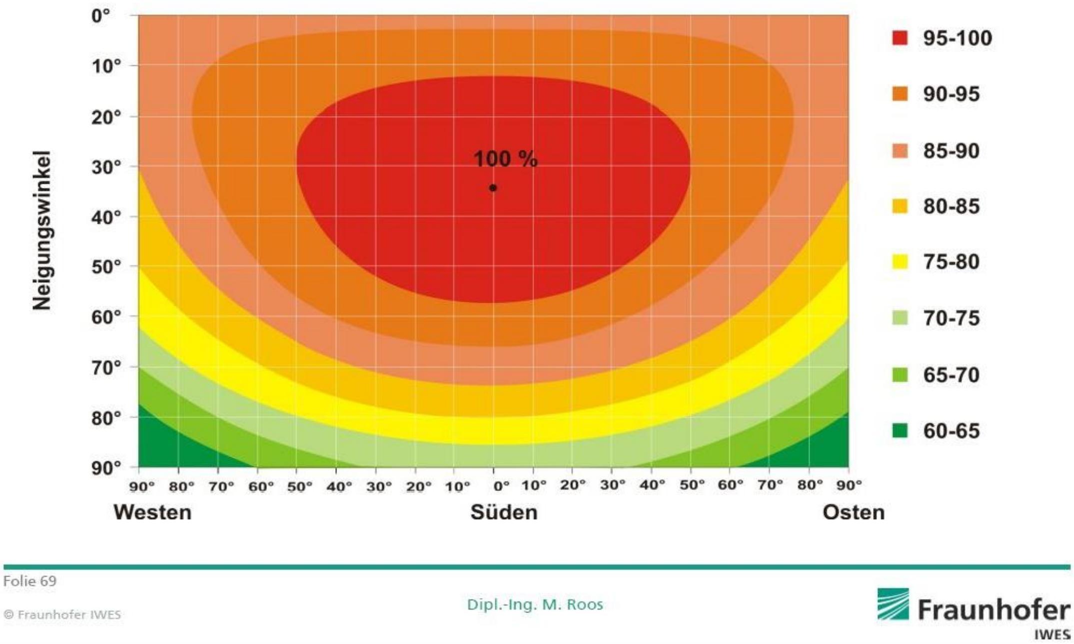


Fig 5.2: Orientation and tilting losses for German latitude.

Another curious fact is how the production for 70º and -70º is different in both cases. As it could be expected, under the same deviation from the south, the energy yield should be equal because the irradiance coming from the Sun should be the same. Nonetheless there are two aspects to be considered.

The first one comes by observing the irradiance coming to the surface of each panel. As said before, it could be expected the same energy arriving to both panels. However, Fig. 5.3 shows clearly how the incoming energy divers for both of them during the whole year. The main reason behind would be:

“Above the oceans at low latitudes, moreover, morning clouds are more common than afternoon clouds, and the early ones are the most reflective of the day. Over land there are more clouds, with higher reflectivity, in the afternoon.” (National Aeronautics and Space Administration (NASA), 2018).

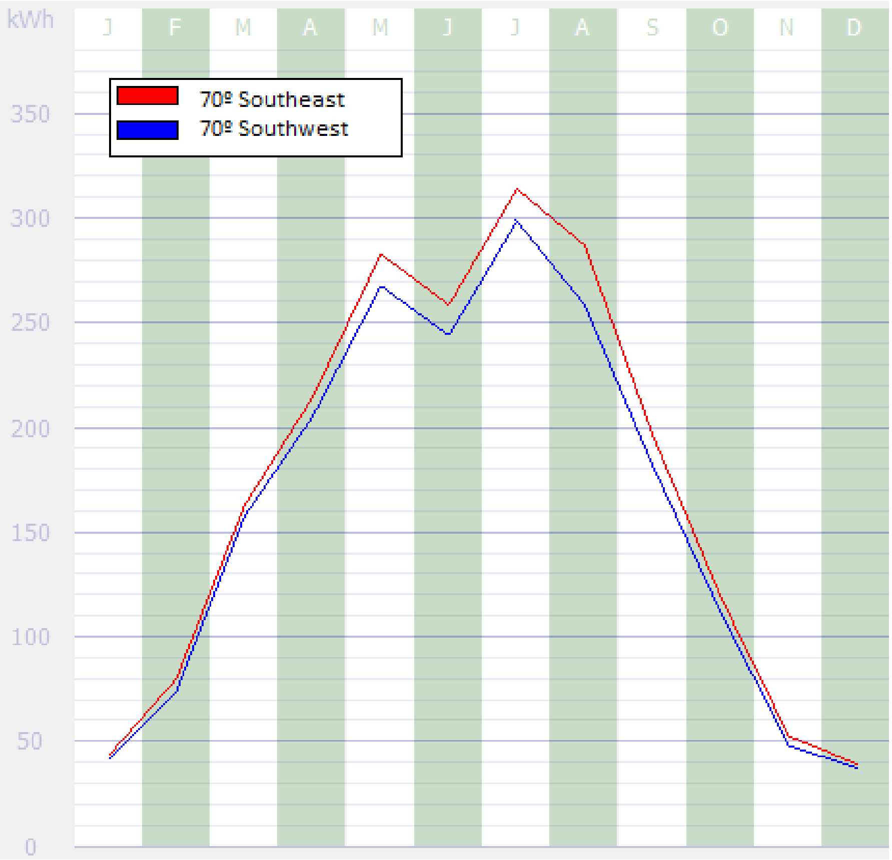


Fig 5.3: Irradiance on the surface of a Southeast and Southwest module.

The second fact that pushes down the production of a Southwest module is the cell temperature (and with the increase of the cell temperature it decreases the working voltage). It must be remembered that the optimal production will occur earlier for the Southeast module than for the Southeast panel. Moreover, the cell temperature will be increasing hour per hour. This explains how the cell temperature will be higher at the optimal production time of the South-west modules, making bigger the production losses due to the temperature.

The Fig. 5.4 depicts the production loss by temperature for each month of the year. Being bigger the loss during summer and spring months due to a higher incoming radiation from the Sun.

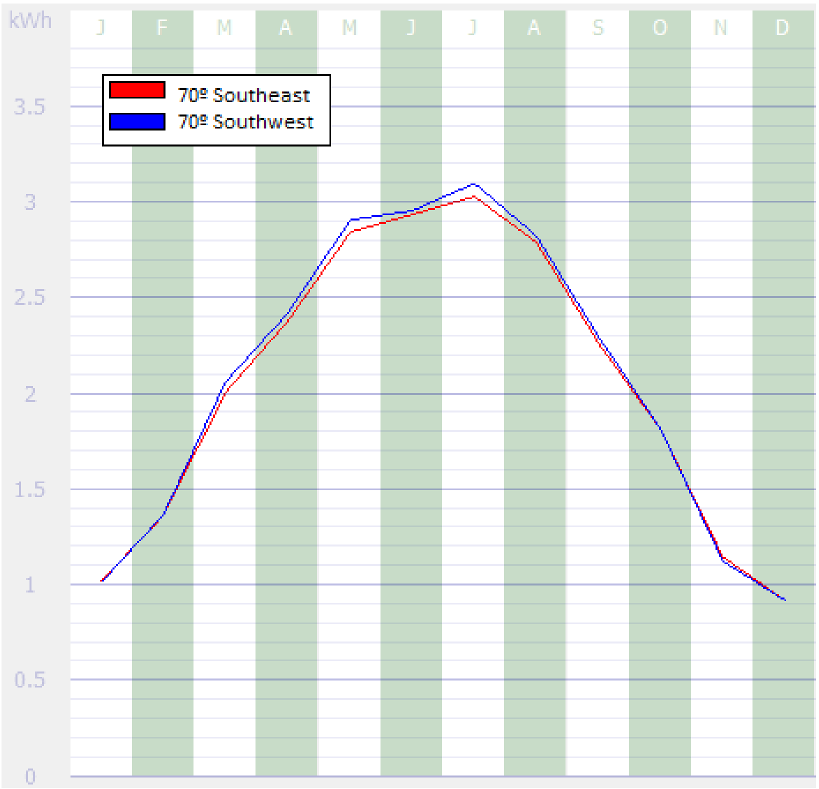


Fig 5.4: Production loss by temperature for of a Southeast and Southwest module.

5.3. Economic approach for each orientation and tilting

To make an approach of the generation costs for each scenario it was used the following formula, cable loses were not taking into account because this is just a comparison method, and the losses in the cables will be quite similar in all the cases, nonetheless they will be considered in the chosen scenario:

$$Generation\ cost\ \left(€/_{kWh}\right) = \frac{(Nº\ modules * 370\ W) * 0.65\ €/_{W_{dc}} + Nº\ inverters}{\frac{E_p + E_p * 87.60\%}{2} * 98\% * 25\ years}$$

Where:

- E_p: represents the energy production for the first year.
- 370 W: is the peak power of the module under STC.
- 87.60%: the module has linear degradation of 0.55%/per year. This means that after 25 years the produced energy will be 87.60%.
- 98%: is the efficiency of the inverters.
- 25 years of considered lifetime for the modules.
- 0.65 €/W_{dc}: is the sum for the costs of the module, inverter and BOS costs explained in the section 7.

$$0.723\ €/_{W_{dc}} = 0.310\ €/_{W_{dc}}\ (Module) + 0.340\ €/_{W_{dc}}\ (BOS)$$

- The number of inverters is obtained by the number of modules. To each inverter an amount of 202 modules can be connected as it was calculated in the section 6. So this makes 5 inverters of orientations of 0 º, 30 º and -70º, while the rest will require 6 inverters.

	15º	20º	25º	30º
0º	0,0361	0,0356	0,0360	0,0351
30º	0,0366	0,0364	0,0362	0,0362
60º	0,0382	0,0382	0,0384	0,0387
70º	0,0386	0,0388	0,0391	0,0395
90º	0,0395	0,0399	0,0405	0,0414
-110	0,0390	0,0395	0,0401	0,0407
-70	0,0369	0,0369	0,0368	0,0368
			MIN	0,0351

Table 5.3: Costs of generation for each scenario €/kWh.

With this first approach a general idea of which is the best option can be made. First of all, with grey color are printed the possible tilting and orientations (orientation of the bunkers). It can be appreciated that -70º is the best option. However, this orientation exist just for bunkers 6 and 7, where a total amount of 252 modules can be placed.

As the number of modules of all the scenarios is around 1000 photovoltaic panels, just 5 inverters will be placed on the field (this makes a total amount of 1010 panels). It makes no sense adding one more inverter to connect just some couple of modules more. Furthermore, it will reduce the risk of surpassing the accorded injection power.

Then, 202 modules will be placed on the bunkers 6 and 7 with 25º tilting, because all the tilting results are similar. However, 25º has the biggest energy yield per modules and will make more difficult the dust to deposit on the modules. Moreover, 30º tilting could generate shadow problems on the old modules.

The other 808 modules will be placed with a 70º orientation and 15º tilting:

- 404 on the bunkers 1 and 8, close to the transformer 3.
- 404 on the bunkers 4, 11 and 12, close to the transformer 2.

5.4. Cloud and Albeldo enhancement impact on solar irradiance

Normally the photovoltaic modules are tested inside laboratories under certain conditions. Their power output depend strongly on the module temperatura and the irradiance. There are two main ways of proving the manufactured panels:

- STC: Standard Testing Conditions, irradiance 1000 W/m^2, cell temperature 25 ºC and Spectra at AM1.5.
- NOCT: Nominal Operating Cell temperature, irradiance 800 W/m^2, ambient temperature 20 ºC, Spectra at AM1.5 and wind speed 1 m/s.

The first one shows the ideal working conditions for the panels, whereas the second the normal working conditions, because as higher the irradiance is, the higher the cell temperature is. Moreover, a higher cell temperatura decreases the voltage of the module and as the power is the product of current and voltage, this decreases in the same order. This means that is really hard having the power output shown in the datasheet of the product.

The solar constant is the amount of solar electromagnetic radiation per unit of area that incide on the atmosphere of the Earth and has an average value of 1361 W/m^2 (measured by the NASA). This does not mean that this is the maximum value that reaches the surface of the Earth, because the atmosphere absorbs part of this radiation.

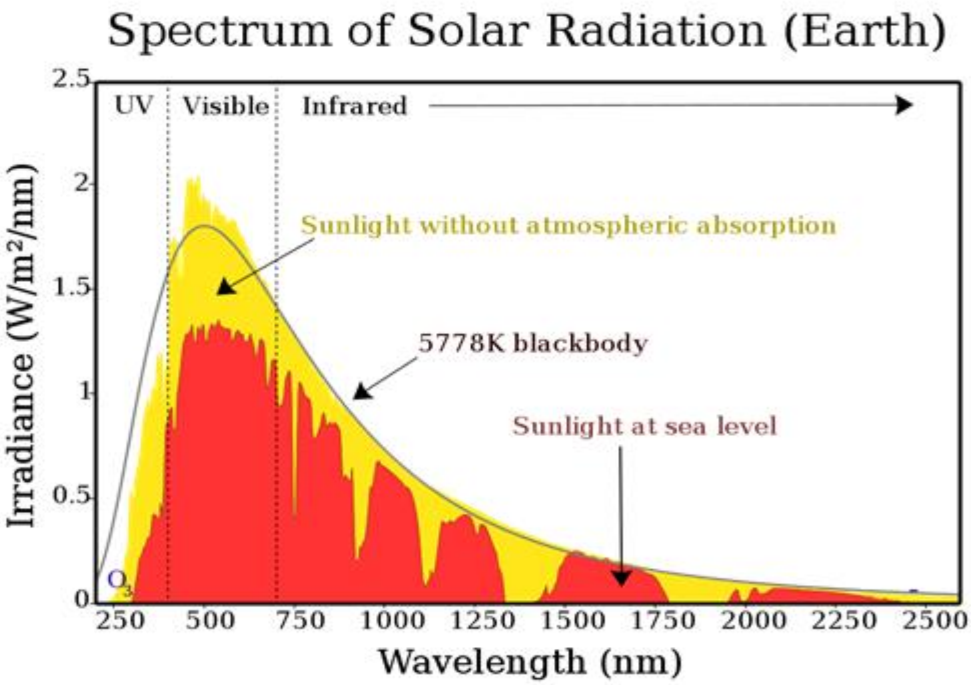


Fig 5.5: Solar irradiance spectrum above atmosphere and at surface (Wikipedia).

Moreover, the radiation is also influenced by the clearness of the sky. The parameter that measures this fact is:

$$K_t = {}^{GHI}/_{ETH} \;;$$

$$where\ GHI: Global\ horizontal\ irradiance\ and\ ETH: horizontal\ extraterrestrial\ irradiance$$

The clearness index is a measure of the clearness of the atmosphere. It is the fraction of the solar radiation that is transmitted through the atmosphere to strike the surface of the Earth. It is a dimensionless number between 0 and 1, defined as the surface radiation divided by the extraterrestrial radiation.

However there are two phenomenons that can push this value and the GHI up. They are known as the Cloud and Albedo enhancements (CE and AE). On the one hand, these are beneficial occurrences that can increase the power production. On the other hand, the increase of the irradiance above the 1000 W/m^2 of the STC can endanger the PV array. The simulations used in the previous sections were obtained in an hourly basis, so they are not taking into account increasing peaks that could be happening for some minutes during each hour.

With the objective of analyzing these two effects Christian A. Gueymard gathered information about them from other studies and he realized a new one in California, using a photodiode and a thermopile as measuring instruments. The next table puts together all of them:

Reference	GHI (W/m^2)	K_T	Location	Elev. (m)	Resolution (s)
Almeida et al. (2014)	1590	1.14	Brazil	760	1
de Andrade and Tiba (2016)	1648	N/S	Brazil	127	60
de Andrade and Tiba (2016)	1551	N/S	Brazil	593	60
Emck and Richter (2008)	**1832**	**1.34**	Ecuador	3400	300
Emck and Richter (2008)	1630	1.24	Ecuador	1970	300
Hansen et al. (2010)	≈1450	N/S	New Mexico, USA	1657	60
Inman et al. (2016)	1396	1.10	California, USA	N/S	30
Inman et al. (2016)	1380	1.04	Hawaii, USA	N/S	30
Pfister et al. (2003)	1450	N/S	New Zealand	370	60
Piacentini et al. (2003)	1528	1.13	Argentina	3900	5
Piacentini et al. (2011)	1477	1.09	Brazil	4	N/S
Piedehierro et al. (2014)	1244	1.10	Spain	680	60
Ramgolam and Soyjaudah (2014)	1532	1.09	Mauritius	200	30
Tapakis and Charalambides (2014)	1533	1.19	Cyprus	360	5
Walker (2000)	≈1350	N/S	Australia	40	60
This study	1546	1.30	Colorado, USA	1829	60
This study	1634	1.37	Colorado, USA	1829	60
This study	**1891**	**1.62**	Colorado, USA	1829	1

Table 5.4: Compilation of record GHI values reported in the literature.

As explained before, these values can increase momentarily the power output of the photovoltaic modules more than expected (considering that the irradiance is higher than 1000 W/m^2 and that the cell temperature is still 25 ºC). Nonetheless, the report also shows the evolution of GHI for different measuring instrumentation, with 1-min resolution for the thermopile and a 1-s resolution for the photodiode. This allows comparison between both of them.

As it can be acknowledged in the Fig 5.6, in most of the cases the duration of the irradiances peaks are between minutes and seconds. It is important to appreciate that the worst case among all of them took around 15 minutes.

Moreover, the measuring instrumentation has a really small size comparing to a whole photovoltaic module. It is critical to consider that all the cells of the photovoltaic module are connected in serie and when any of them is under the shadow or damaged, it will push down the power output of the whole module. Normally the panels are connected in large strings to increase the voltage, which allows decreasing the Joule losses, the gauge of the wires and the length of the wires. It is therefore, that each string has hundreds of cells connected in serie. The probability of having this peaks of irradiance on the whole string are almost null.

Furthermore, the production of the inverter is limited by its capacity, so even if all the modules connected to the same inverter are under high radiation, the inverter will act as a protection against this unexpected irradiance.

In addition for the previous considerations, the extra added power will have a distinct tilting and orientation, so when the old modules would be affected by CE and AE, the new ones would not be under the same effects. The existence of clouds would also lead to shadow on other parts of the power plant.

To conclude, after analyzing the CE and AE, they will not be considered as a critical fact that can influence on the limited power.

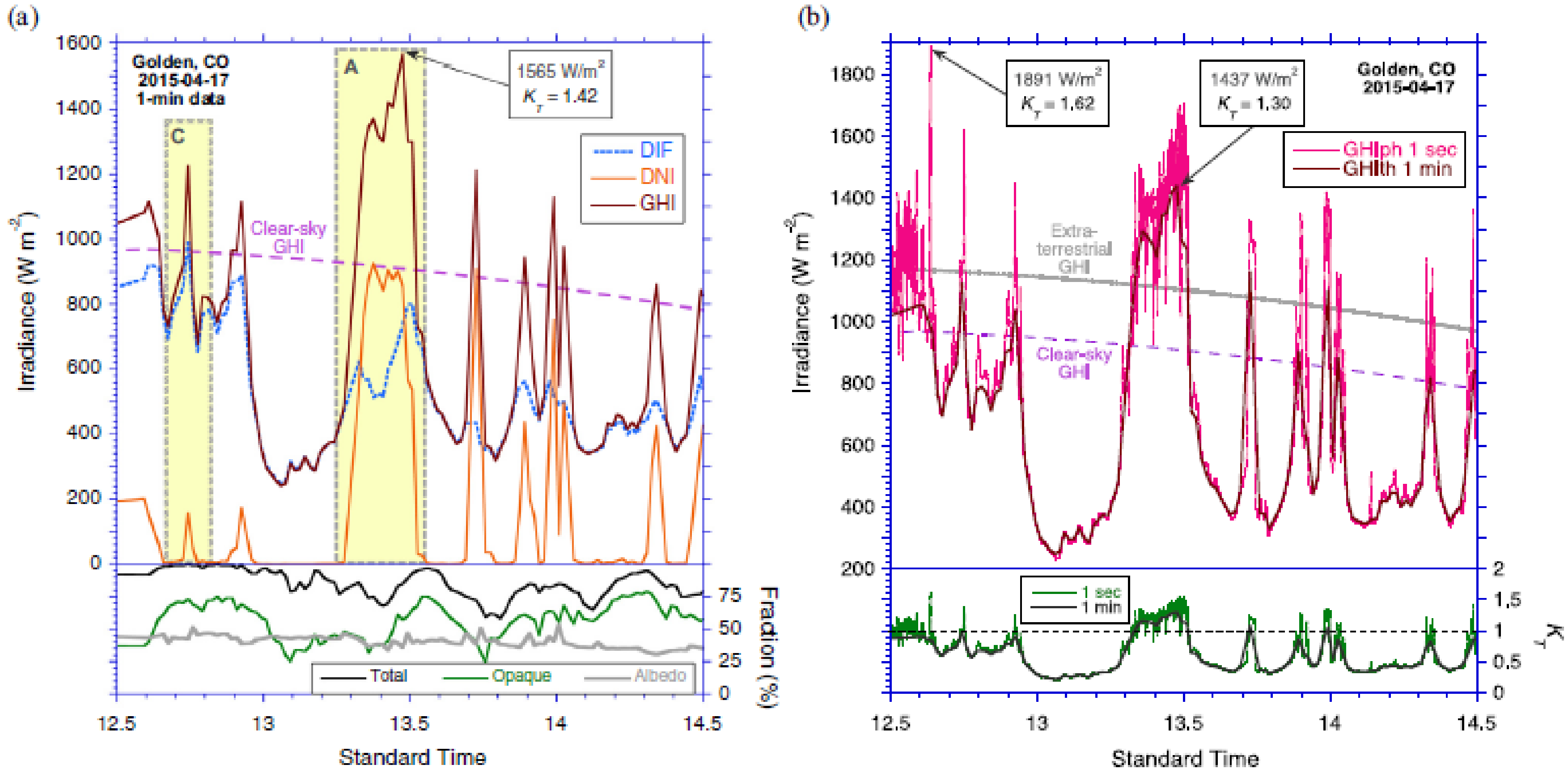


Fig 5.6: Cloud enhancement episodes during a spring day.

6. Strings design

To design the strings is important to know the characteristics of both, photovoltaic module and inverter. In the section “Appendix”, the datasheet of both of them can be found. As a summary, the main parameters are the following, with a short description to understand each of them:

- P_{dc}: Peak power that the photovoltaic module can provide under “Standard Testing Conditions” (STC; Irradiance 1000 W/m^2, Cell temperature 25 ºC, Spectra at AM1.5).
- U_{oc}: Open Circuit Voltage.
- I_{sc}: Short Circuit Voltage.
- V_{mp}: Maximum Power Voltage.
- I_{mp}: Maximum Power Current.
- TC of V_{oc}: Temperature coefficient of V_{oc}.
- $P_{dc,\ max}$: Maximum input Power that admits the inverter.
- U_{max}: Maximum Voltage that admits the inverter.
- $I_{max/String}$: Maximum Current that admits the inverter per String.
- U_{mpp}: Maximum power point voltage. Within this voltage range the efficiency of the inverter will be the maximum, around a 97%.
- $I_{mpp/String}$: Maximum power point current per string.

- Longi LR6-72PE-370M
  - P_{dc} = 370 W
  - U_{oc} = 48,3 V
  - I_{sc} = 9,84 A
  - V_{mp} = 39,4 V
  - I_{mp} = 9,39 A
  - TC of V_{oc} = -0.286%/Cº

- STP Core 1
  - $P_{dc,\ max}$ = 75,000 W
  - U_{max} = 1000 V
  - $I_{max/String}$ = 30 A
  - U_{mpp} =500-800 V
  - $I_{mpp/String}$ = 20 A

6.1. Strings sizing

After checking the main characteristics of both components is time to start with the calculations to design the strings and decide how short or long should they be. Another important fact of the photovoltaic modules is the influence of the cell temperature on the voltage. The values previously shown have been tested for a cell temperature of 25 Cº. In order to assure the proper function of the strings, the maximum and minimum ambient temperatures must be considered.

Between 2014 and 2019 it can be checked a maximum temperature of 36.6 Cº and a minimum temperature of -13.1 Cº (data obtained from a weather station in Pirmasens) (WetterKonto). Moreover, the Normal Operating Cell Temperature is 45 Cº for this solar module with an environmental temperature of 20 Cº and an irradiance of 800 W/m^2. With these values, the new voltage parameters can be calculated with the next formula:

$$T_{cell,max} = T_{enviroment} + \frac{I}{I_{NOCT}} * (T_{NOCT} - T_{enviroment,NOCT})$$

$$T_{cell,max} = 36.6\ C^o + \frac{1000\ W/m^2}{800\ W/m^2} * (45\ C^o - 20\ C^o) = 67.85\ C^o$$

$$T_{cell,min} = -13.1\ C^o + \frac{1000\ W/m^2}{800\ W/m^2} * (45\ C^o - 20\ C^o) = 18.15\ C^o$$

$$V_{mp,min} = V_{mp} + \left(T_{cell,max} - T_{cell,STC}\right) * TC$$
$$= 39.4\ V + \frac{100 - (67.85\ C^o - 25\ C^o) * (-0.286\%/C^o)}{100} = 34.57\ V$$

$$V_{mp,max} = V_{mp} + \left(T_{cell,max} - T_{cell,STC}\right) * TC$$
$$= 39.4\ V + \frac{100 - (18.15\ C^o - 25\ C^o) * (-0.286\%/C^o)}{100} = 40.38\ V$$

$$V_{oc,max} = V_{mp} + \left(T_{cell,max} - T_{cell,STC}\right) * TC$$
$$= 48.3\ V + \frac{100 - (18.15\ C^o - 25\ C^o) * (-0.286\%/C^o)}{100} = 49.28\ V$$

$$Total\ amount\ of\ modules\ that\ can\ be\ connected\ to\ the\ inverter: {}^{75,000}/_{370} = 202\ modules$$

$$Minimum\ module\ number\ per\ string: {}^{500}/_{34.57} = 14.46 \rightarrow 15\ modules\ (518.55\ V)$$

$$Maximum\ module\ number\ per\ string: {}^{800}/_{40.38} = 19.81 \rightarrow 20\ modules\ (807.6\ V)$$

Now is time to check that the open circuit voltage in the worst case will never surpass the maximum voltage that admits the inverter:

$$Maximum\ module\ number\ per\ string\colon\ {}^{1000}/_{49.28} = 20.29\ \rightarrow 20\ modules\ (985.6\ V)$$

This means, that the strings should be composed of at least 15 modules and a maximum of 20 (to avoid endangering the security of the inverter). Another essential factor to take into account is that as larger the strings are, the lesser cables between the generator and the inverter will be required. Furthermore, the flowing current through the strings will be the same even if there are 15 or 20 modules, so increasing the length of the string will make higher the peak power without increasing the Joule losses.

6.2. Cable and wire sizing

In the case of series connection of the PV solar panels (a typical situation), the inverters should be mounted as close to the injection to the grid as possible because the Joule losses caused by the current are on the AC side higher as on the DC side.

The direct current generated from the PV solar panels should reach as far as possible without losses to the inverter. How thick the cable cross-section of the DC main cable should be to keep the loss down at a reasonable level, will be explained in the following paragraph.

One designs the DC main cable so that its loss is smaller than 1% of the PV generator peak output. Each cable has an ohmic resistance. The voltage drop at this resistance is according to Ohm's law:

$$U = R * I$$

The resistance R of the cable depends on three parameters:

a) The cable length: the longer the cable, the more the resistance is.
b) The cable cross-section area: the larger this area, the smaller the resistance is.
c) The material used and its specific resistance, generally speaking, copper or Aluminum.The conductivity of the two substances is:

Copper: σ >= 58*106 S/m (Siemens pro m) = 58 m/(Ω·mm²)

Aluminum: σ >= 36.59*106 S/m =36.59 m/(Ω·mm²)

Both values are calculated at 300 K (ca. 27°C). At higher temperatures, the resistance of the material increases and the conductivity decreases.

The formula to obtain the resitance value of the cable is:

$$R = \frac{L}{A * \sigma};$$

Where:

- L: cable lenght (m) - A: cross-section area (mm^2) - σ: conductivity ($m/(\Omega \cdot mm^2)$)

Moreover, the cables will need to fulfill the requirements of the German norms, which in this case is “DIN VDE 0298-4”. In this document is explained how big the maximum allowed current is of each cable size and for each distribution plan (where the cables are lying). There are multiple factors that affect to this current such as ambient temperature, number of wires per cable, cable type… also the resistance against short overcurrents. Normally the DC cables will be made of aluminum (cheaper costs per meter) and they will have a cross-section between 4 and 10 mm^2.

7. Costs for other system components (BOS)

The main objective of this Master Thesis is to optimize the energy production by adding extra modules to the current photovoltaic power plant without exceeding the accorded power with the grid operator. However, a first economical approach of the expansion would be of interest. With this purpose, cable and structural part will not be investigated in the market, but an approximation of the cost will be required for the economic feasibility of the project.

The Balance of System (BOS) costs encompass all components of a photovoltaic system other than the photovoltaic panels and inverter. This includes wiring, switches, mounting system, civil work and all the necessary to get ready the photovoltaic power plant.

The benchmark shown in the section 2.2 by "The National Renewable Energy Laboratory" (NREL) from the United States shows a general overview of the current market and tendency. Despite being a reliable institute, the information used for its elaboration is the market from the United States, so it is important to understand that the market from Germany may be different. The Fraunhofer ISE (Institut für Solare Energiesysteme) also makes benchmark analysis for the german market.

The following figure exposes the BOS costs for a PV ground-mounted system in Germany on 2015. The actual costs for 2019 will be considered the same, because the technology around BOS did not change too much as it can be appreciated in the Fig 2.2.

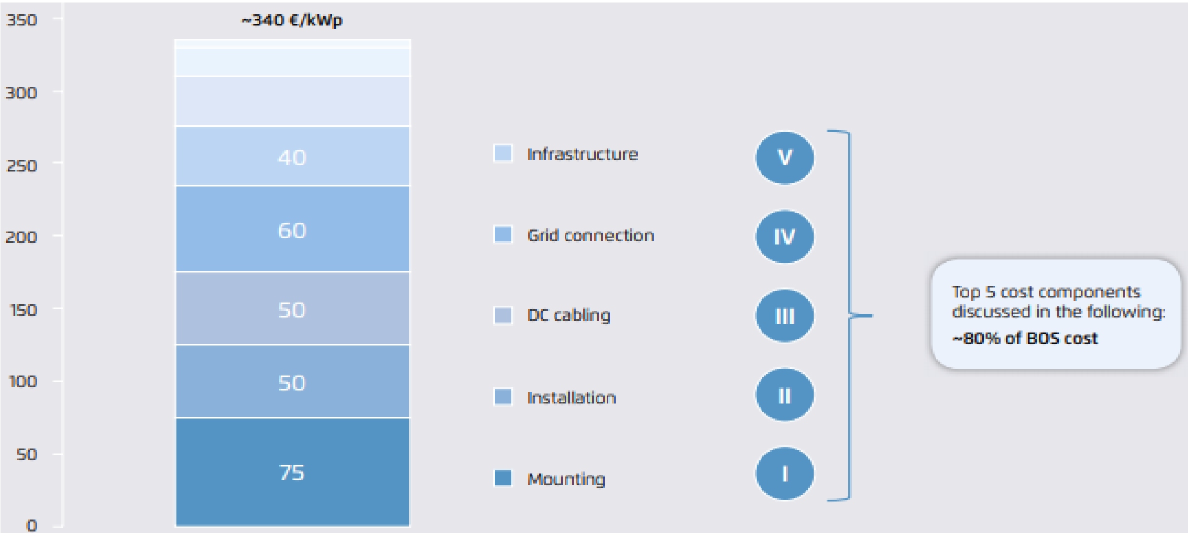


Fig 7.1: Overview of Balance of System cost for ground-mounted PV systems (example from Germany) (N. Mayer, Philipps, Saad, Schlegl, & Senkpiel, 2015).

8. Trafo station

The installation is composed by three different transformation stations situated in three distinct places. All of them are exactly the same brand and type to avoid problems. The main purpose is to increase the voltage from the 400 V of the low voltage grid to the 20,000 V of the medium voltage grid. The PV generator has an installed peak power of 3,128.92 kW (DC) whereas the inverter capacity is just 2,965 kW (AC). It is therefore that this power is distributed between the three transformers of 1,000 kVA each. Here are the main characteristics of all of them:

- Voltage: 20,000 V/400 V
- Current: 28,9 A/1443 A
- Frequency: 50 Hz
- Connection type: Dyn 5

Fig 8.1: Label of the Transformers

However the power coming from the inverters is not equally distributed between the transformers. Furthermore, the first transformer has connected more than 1 MW to its terminals, here is the power distribution coming from the inverters:

- Transformer 1: 5 distribution lines; 73 inverters; 1,025 kW (AC).
- Transformer 2: 8 distribution lines; 72 inverters; 987 kW (AC).
- Transformer 1: 7 distribution lines; 71 inverters; 953 kW (AC).

The purpose of this study is to increase the total power of the installation without surpassing the 3 MW. This would mean to increment the injected electricity without the need of acquiring new transformers, which are quite expensive. Having a look on the connected inverter power to the stations 2 and 3, and adding them more power as in the 1st one:

$$Transformer\ 2{:}\ 1{,}025 - 987 = 38\ kW$$

$$Transformer\ 3{:}\ 1{,}025 - 953 = 72\ kW$$

Which means that taking into account the power of the transformers, another 110 kW could be added on them. However, it is important to consider that most of the time they will work under these conditions, and just some times per year (when the sun is shining and the irradiance is perpendicular to the modules) they could reach this working point.

As the main objective of this Master Thesis is not analyzing the behavior of the transformers no more investigations will be required.

10. Study of viability

A short study of viability is interesting to understand how profitable could be the addition of extra power on the surface of the bunkers. With that purpose, the total budget and the cash flows for a lifetime of 25 years are obtained. Inverter, module and BOS costs have already been established and the gardening costs have been approximated considering a full day by two workers per bunker, the salary was taken as 20€/hour. The company is already in possession of the required machinery. As said in the economical approach of the section 5.3, 1010 modules and 5 inverters will be installed. Moreover, the installation, structure and civil work expenses were taken from the "Fraunhofer Institute". With all this, the investment to be made is:

	Prices	Total costs
Inverter	3.629,29 €	18.146,45 €
Module	114,67 €	115.816,70 €
BOS costs	0,34 €/W_{dc}	127.058,00 €
Gardening		2.000,00 €
	Total investment	261.021,15 €

Table 10.1: Calculation of the total costs of the installation.

Many considerations have been done such as:

- The sold energy has been obtained considering the total produced energy by the photovoltaic modules, a 98% of inverter efficiency and 1,33% of loses in the cables. The last value is an approximation obtained from the previous project of the existing installation.
- The operation and maintenance costs (O&M) will be considered as 1% of the total investment. "Die jährlichen Betriebskosten eines PV-Kraftwerks liegen mit ca. 1% der Investitionskosten vergleichsweise niedrig, auch die Finanzierungskosten sind aufgrund des aktuell niedrigen Zinsniveaus günstig." (Fraunhofer ISE, 2019).
- Three different scenarios have been obtained. The scenario A considers the same electricity price as the current panels, 0.2207 €/kWh. Scenario B takes a value of the last licensing round of the Federal Network Agency on the bid date February 1, 2018, where it was set the lowest mean value of 0.0433 €/kWh. Finally the last Scenario C was taken from the Fig. 10.1 with an approximated price of 0.07 €/kWh (Fraunhofer ISE, 2019).

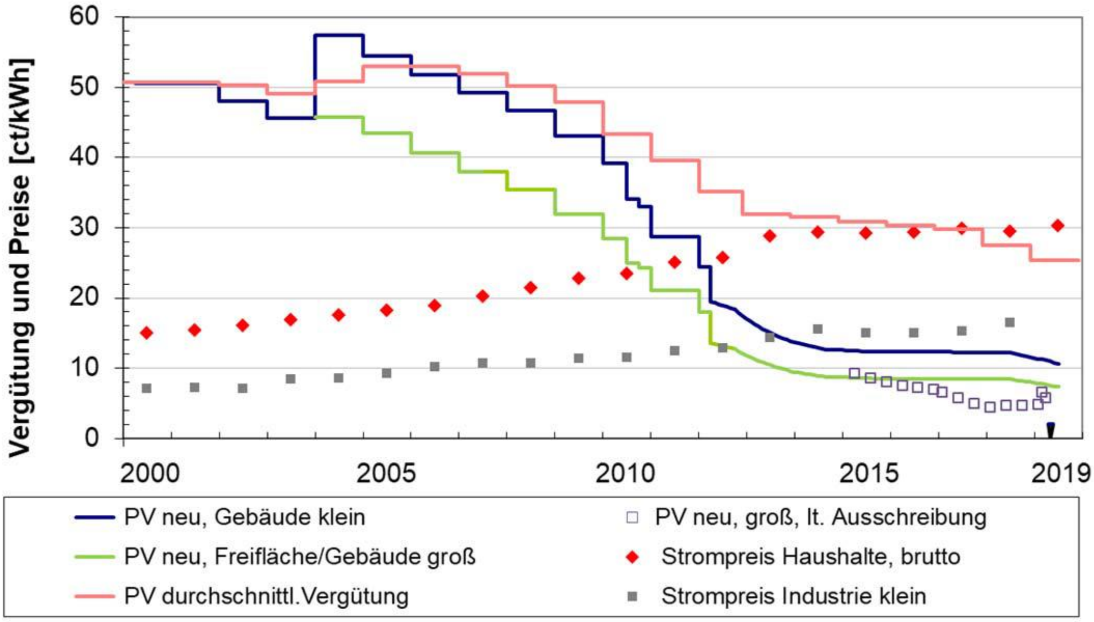


Fig 10.1: Feed-in tariff for PV power as a function of commissioning date (Fraunhofer ISE, 2019).

To consider if the project is profitable or not different indicators will be used. Using a static method where the value of the money does not change such as the “Payback” or dynamic methods like “Net present value” (NPV) and “Internal rate of return” (IRR). The first one shows the time it takes to recover the capital invested in the project. The second the difference between the present value of cash inflows and the present value of cash outflows over a period of time. The third one is a discount rate that makes the net present value (NPV) of all cash flows from a particular project equal to zero. IRR calculations rely on the same formula as NPV does.

	Scenario A	Scenario B	Scenario C
Payback	4,33	No Payback	15,61
NPV	5.527.350,07 €	-2.657.748,10 €	-1.425.830,84 €
IRR	22%	-	-6%

Table 10.2: Investment selection methods.

As observed in the Table 10.2 just one of the scenario seems attractive. Scenarios B and C make no sense from the economical point of view. This means that just maintaining the electricity prices would make this project interesting to carry on.

Year	Produced energy	Sold energy	O&M	Income A	Income B	Income C	Amortization	Cash flows A	Cash flows B	Cash flows C
1	299863,55	289957,85	2.610,21 €	63.993,70 €	12.555,18 €	20.297,05 €	10.440,85 €	- 199.637,66 €	-251.076,19 €	-243.334,31 €
2	293866,28	284158,70	2.610,21 €	62.713,82 €	12.304,07 €	19.891,11 €	10.440,85 €	- 139.534,05 €	-241.382,33 €	-226.053,41 €
3	292250,01	282595,82	2.610,21 €	62.368,90 €	12.236,40 €	19.781,71 €	10.440,85 €	- 79.775,36 €	-231.756,14 €	-208.881,92 €
4	290642,64	281041,55	2.610,21 €	62.025,87 €	12.169,10 €	19.672,91 €	10.440,85 €	- 20.359,71 €	-222.197,25 €	-191.819,22 €
5	289044,10	279495,82	2.610,21 €	61.684,73 €	12.102,17 €	19.564,71 €	10.440,85 €	38.714,81 €	-212.705,29 €	-174.864,73 €
6	287454,36	277958,59	2.610,21 €	61.345,46 €	12.035,61 €	19.457,10 €	10.440,85 €	97.450,06 €	-203.279,90 €	-158.017,84 €
7	285873,36	276429,82	2.610,21 €	61.008,06 €	11.969,41 €	19.350,09 €	10.440,85 €	155.847,91 €	-193.920,70 €	-141.277,96 €
8	284301,06	274909,45	2.610,21 €	60.672,52 €	11.903,58 €	19.243,66 €	10.440,85 €	213.910,21 €	-184.627,33 €	-124.644,51 €
9	282737,40	273397,45	2.610,21 €	60.338,82 €	11.838,11 €	19.137,82 €	10.440,85 €	271.638,82 €	-175.399,43 €	-108.116,90 €
10	281182,34	271893,77	2.610,21 €	60.006,95 €	11.773,00 €	19.032,56 €	10.440,85 €	329.035,56 €	-166.236,64 €	- 91.694,55 €
11	279635,84	270398,35	2.610,21 €	59.676,92 €	11.708,25 €	18.927,88 €	10.440,85 €	386.102,27 €	-157.138,61 €	- 75.376,87 €
12	278097,84	268911,16	2.610,21 €	59.348,69 €	11.643,85 €	18.823,78 €	10.440,85 €	442.840,75 €	-148.104,97 €	- 59.163,30 €
13	276568,31	267432,15	2.610,21 €	59.022,28 €	11.579,81 €	18.720,25 €	10.440,85 €	499.252,81 €	-139.135,36 €	- 43.053,27 €
14	275047,18	265961,27	2.610,21 €	58.697,65 €	11.516,12 €	18.617,29 €	10.440,85 €	555.340,25 €	-130.229,45 €	- 27.046,19 €
15	273534,42	264498,49	2.610,21 €	58.374,82 €	11.452,78 €	18.514,89 €	10.440,85 €	611.104,86 €	-121.386,88 €	- 11.141,51 €
16	272029,98	263043,74	2.610,21 €	58.053,75 €	11.389,79 €	18.413,06 €	10.440,85 €	666.548,40 €	-112.607,30 €	4.661,34 €
17	270533,82	261597,00	2.610,21 €	57.734,46 €	11.327,15 €	18.311,79 €	10.440,85 €	721.672,65 €	-103.890,36 €	20.362,92 €
18	269045,88	260158,22	2.610,21 €	57.416,92 €	11.264,85 €	18.211,08 €	10.440,85 €	776.479,36 €	- 95.235,72 €	35.963,79 €
19	267566,13	258727,35	2.610,21 €	57.101,13 €	11.202,89 €	18.110,91 €	10.440,85 €	830.970,27 €	- 86.643,04 €	51.464,49 €
20	266094,51	257304,35	2.610,21 €	56.787,07 €	11.141,28 €	18.011,30 €	10.440,85 €	885.147,13 €	- 78.111,97 €	66.865,58 €
21	264631,00	255889,17	2.610,21 €	56.474,74 €	11.080,00 €	17.912,24 €	10.440,85 €	939.011,66 €	- 69.642,18 €	82.167,61 €
22	263175,52	254481,78	2.610,21 €	56.164,13 €	11.019,06 €	17.813,72 €	10.440,85 €	992.565,58 €	- 61.233,33 €	97.371,13 €
23	261728,06	253082,13	2.610,21 €	55.855,23 €	10.958,46 €	17.715,75 €	10.440,85 €	1.045.810,59 €	- 52.885,09 €	112.476,67 €
24	260288,55	251690,18	2.610,21 €	55.548,02 €	10.898,18 €	17.618,31 €	10.440,85 €	1.098.748,40 €	- 44.597,11 €	127.484,77 €
25	258856,97	250305,89	2.610,21 €	55.242,51 €	10.838,24 €	17.521,41 €	10.440,85 €	1.151.380,70 €	- 36.369,08 €	142.395,97 €

Fig 10.2: Cash flows for the three scenarios.

11. Conclusions

Several results along the study were obtained about how the tilting and the orientation influence the energy production.

South facing modules have the most productive generation per module. This production increases till they reach the optimum tilting of around 35º and has the peak power during midday, when the Sun reaches the maximum height. However, the optimum tilting differs for different orientations. For North facing modules for example, the lower the tilting the higher the production will be, because increasing the tilting means giving their back to the Sun.

Southeast orientation could generate more electricity than Southwest modules with same deviation from the Sun. Sun irradiance along the day can increase the cell temperature, decreasing the efficiency for Southwest modules, on the other hand, Southeast panels will be cooler at the beginning of the day making them more productive. Moreover, clouds appear with higher probability in the afternoon than the morning, reducing the total energy that reaches the photovoltaic panels, harming in a bigger quantity the Southwest orientations. This can also explain how slightly Northeast configurations can generate more energy than a purely West orientation.

Subsidies on renewable energies where necessary at the beginning to guarantee the profits of the installing companies in order to expand and develop this sector. Nowadays, the strong price reduction has allowed them to compete against other production sources. However, they will depend strongly on the electricity prices and the equipment costs.

A further analysis in the BOS costs could expose a better economical approach than the realized in this paper. They consist on half of the costs of the project and they depend on the installation type. Moreover, offers or agreements could be reached with the provider in order to reduce the initial investment.

Finally, the electricity prices have also an important role on the feasibility of the project, and these should be agreed with the grid operator.

12. References

Energy Informative. (2014). Abgerufen am 01. October 2019 von Energy Informative: https://energyinformative.org/lifespan-solar-panels/

PV magazine. (2. May 2019). Abgerufen am 5. September 2019 von PV magazine: https://www.pv-magazine.com/2019/05/02/huawei-remained-worlds-largest-inverter-provider-in-2018/?utm_source=Bibblio&utm_campaign=Internal

Bastasch, M. (08. December 2014). *Daily caller*. Abgerufen am 05. 09 2019 von Daily caller: https://dailycaller.com/2014/12/08/112-solar-companies-have-closed-their-doors-in-5-years/

ENTSO_E. (2013). Network Code on Operational Security.

Fraunhofer ISE. (2019). *Aktuelle Fakten zur Photovoltaik in Deutschland.* Freiburg.

Fu, R., Feldman, D., & Margolis, R. (2018). *U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018.* National Renewable Energy Laboratory.

Ireland, B. (1. April 2009). *Electrical Construction & Maintenance Magazine*. Abgerufen am 5. September 2019 von EC&M: https://www.ecmweb.com/ops-amp-maintenance/module-behavior

N. Mayer, J., Philipps, S., Saad, N., Schlegl, T., & Senkpiel, C. (2015). *Current and Future Cost of Photovoltaics.* Freiburg: Fraunhofer ISE.

National Aeronautics and Space Administration (NASA). (09. April 2018). Abgerufen am 16. October 2019 von https://www.giss.nasa.gov/research/briefs/rossow_01/distrib.html#targetText=Above%20the%20oceans%20at%20low,with%20distance%20from%20the%20equator.

Renew Wisconsin. (kein Datum). Abgerufen am 09. October 2019 von https://www.renewwisconsin.org/solarfarms/

Svarc, J. (12. June 2019). *Clean Energy Reviews*. Abgerufen am 8. September 2019 von Clean Energy Reviews: https://www.cleanenergyreviews.info/blog/best-grid-connect-solar-inverters-sma-fronius-solaredge-abb

Tröster, E., & Schmidt, J. D. (kein Datum). *Evaluating the Impact pf PV Module Orientation on Grid Operation.* Darmstadt, Germany: Energynautics.

WetterKonto. (kein Datum). Abgerufen am 15. September 2019 von WetterKonto: https://www.wetterkontor.de/de/wetter/deutschland/rueckblick.asp?id=K925

Wikipedia. (kein Datum). Abgerufen am 14. October 2019 von Wikipedia: https://en.wikipedia.org/wiki/Sunlight

Yang, T. (8. August 2019). *Bloomberg*. Abgerufen am 5. September 2019 von Bloomberg: https://www.bloomberg.com/press-releases/2019-08-08/longi-reaches-record-bankability-rating-in-latest-bloomberg-nef-results

List of figures

List of tables

List of abbreviations

NREL	National Renewable Energy Laboratory
DC	Direct Current
AC	Alternate Current
BNEF	Bloomberg New Energy Finances
MTFF	Mean Time to First Failure
STC	Standard Testing Conditions
NOCT	Nominal operating cell temperature
OC	Open Circuit
SC	Short Circuit
MP	Maximum Power
MPP	Maximum Power Point
CE	Cloud Enhancement
AE	Albedo Enhancement
DIF	Diffuse horizontal irradiance
DNI	Direct normal irradiance
ISE	Institut für Solare Energiesysteme
BOS	Balance of System
NPV	Net present value
IRR	Internal rate of return

I. Annexes

A) Orientation and Tilting Analysis

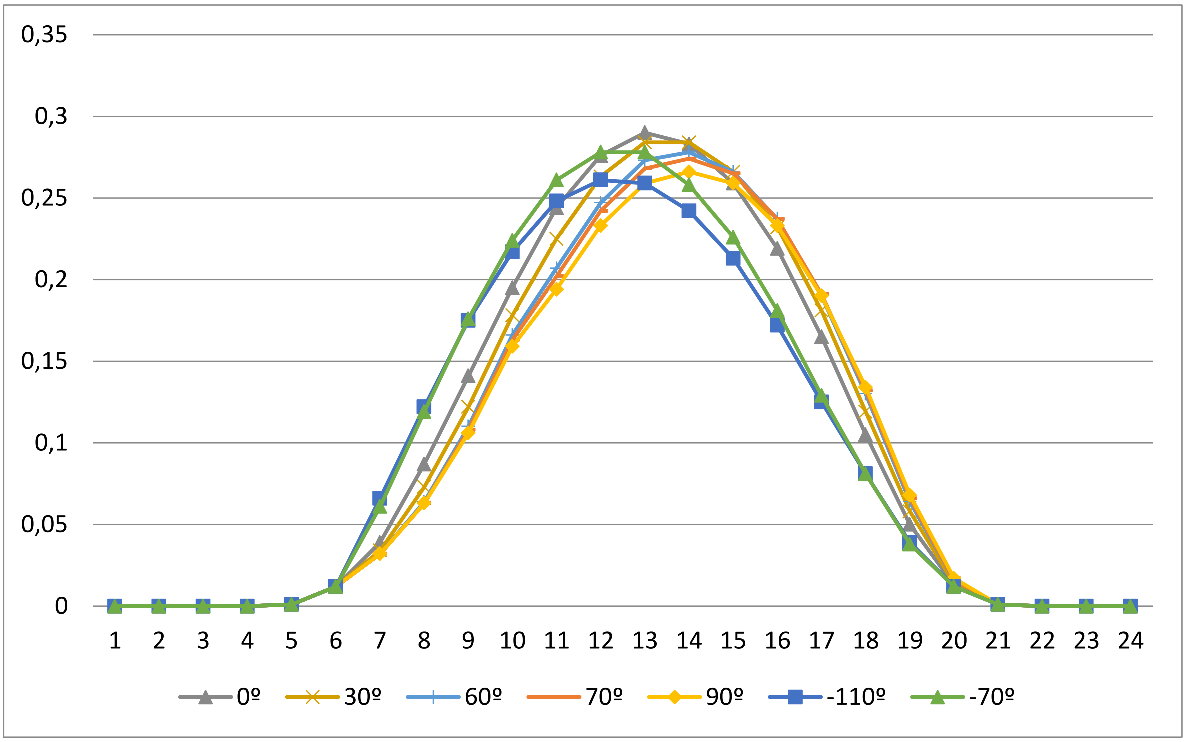


Fig I.1: Power per module (kWh) for different orientations and 15º tilting.

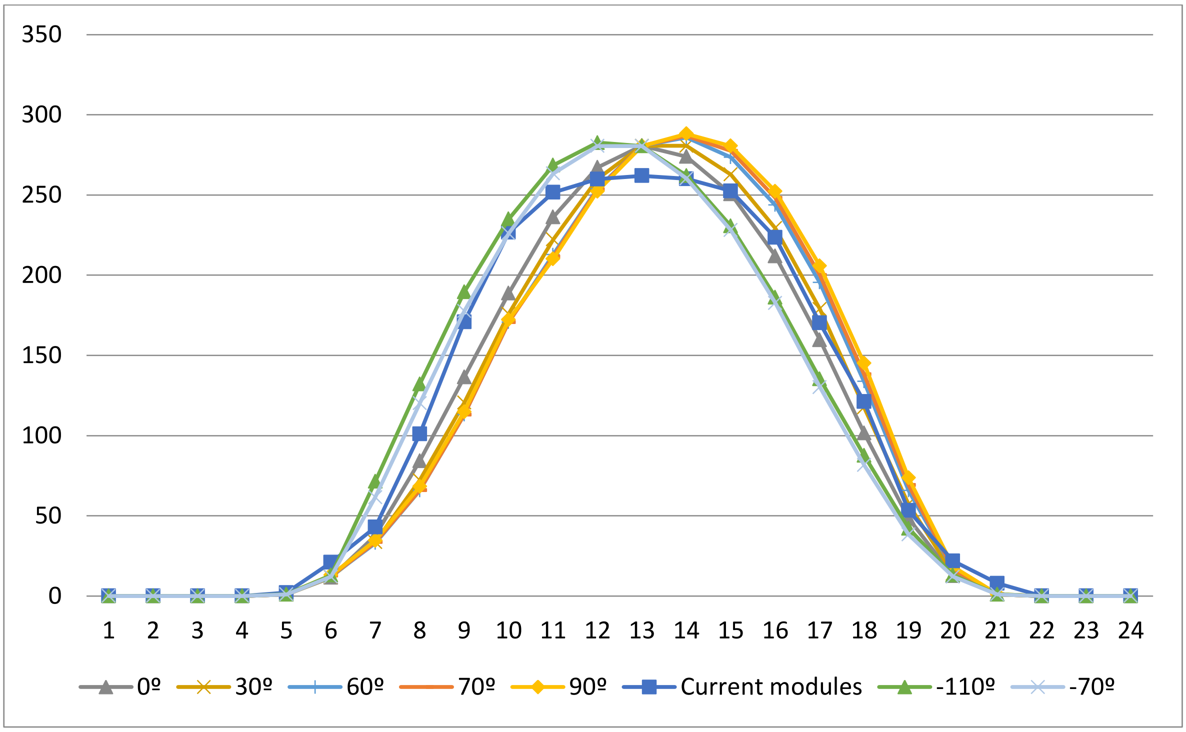


Fig I.2: Maximum added power possibility (kWh) for different orientations and 15º tilting.

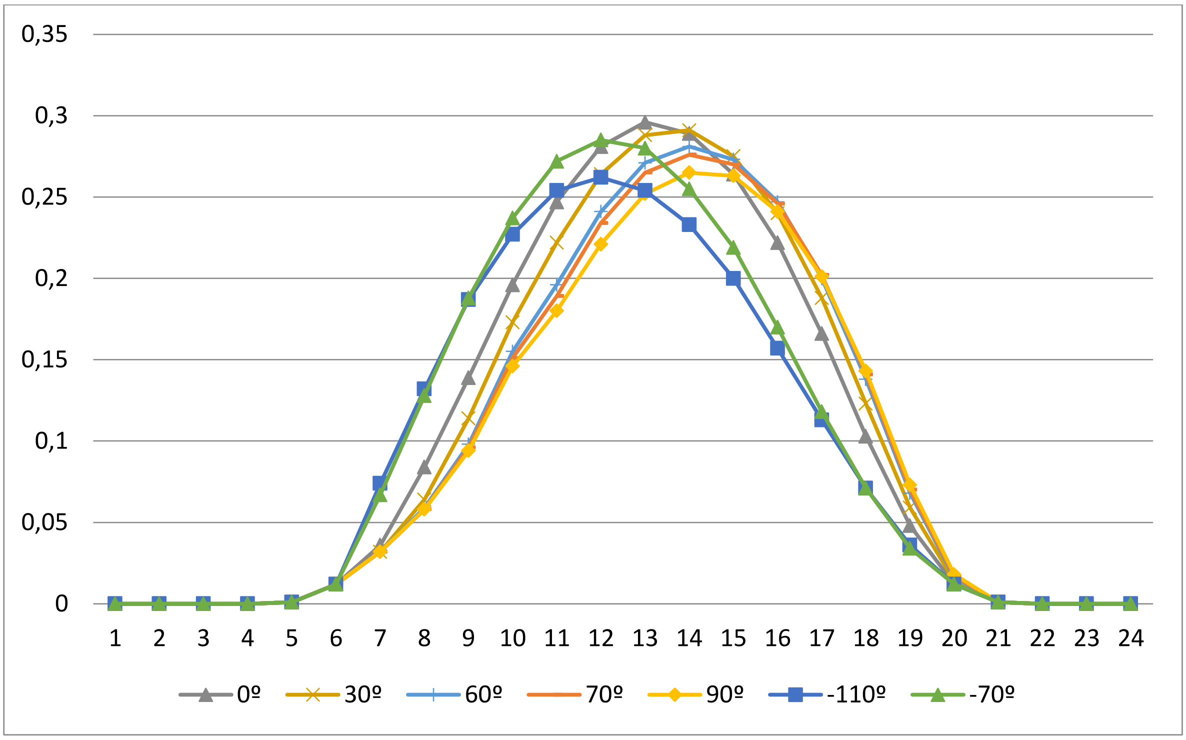


Fig I.3: Power per module (kWh) for different orientations and 20º tilting.

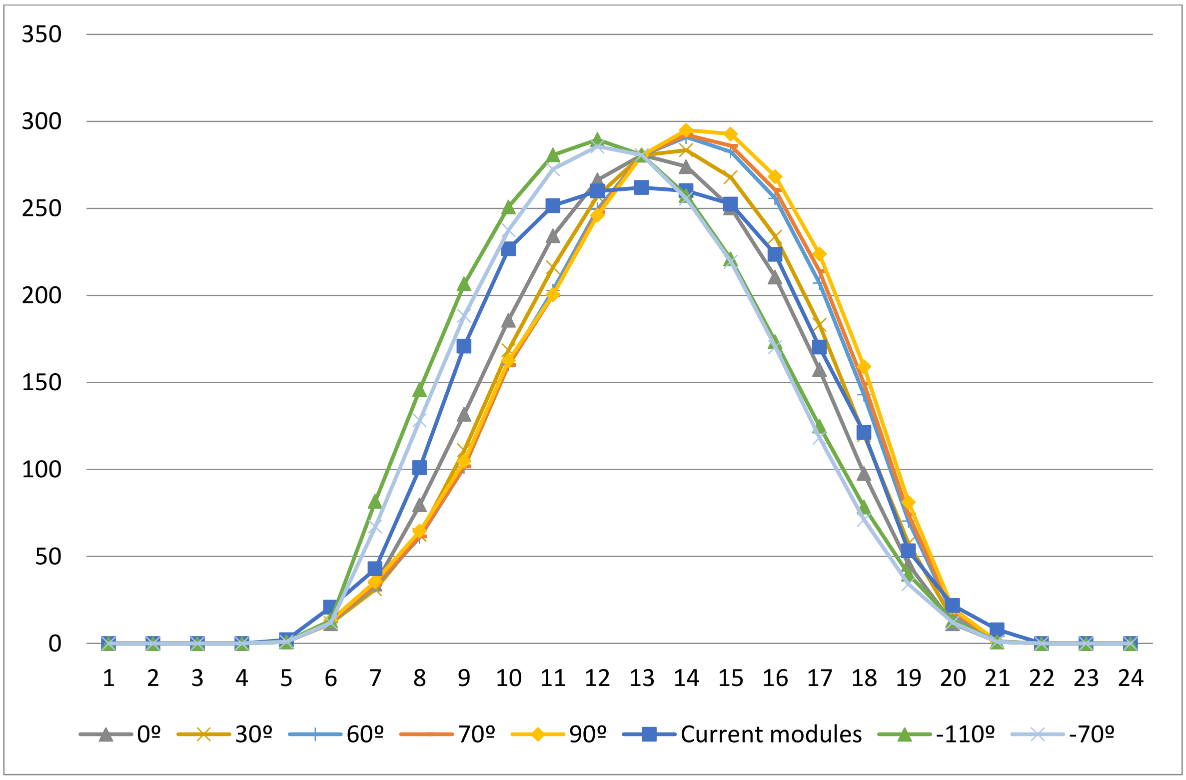


Fig I.4: Maximum added power possibility (kWh) for different orientations and 20º tilting.

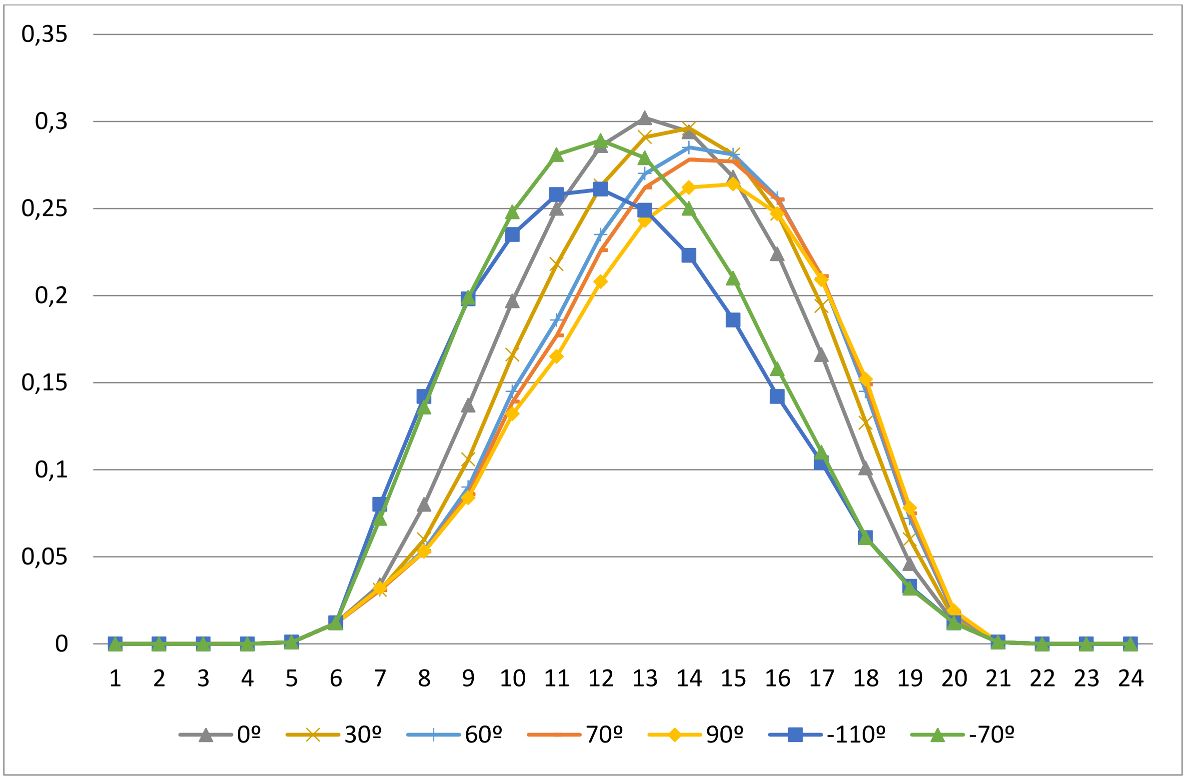


Fig I.5: Power per module (kWh) for different orientations and 25º tilting.

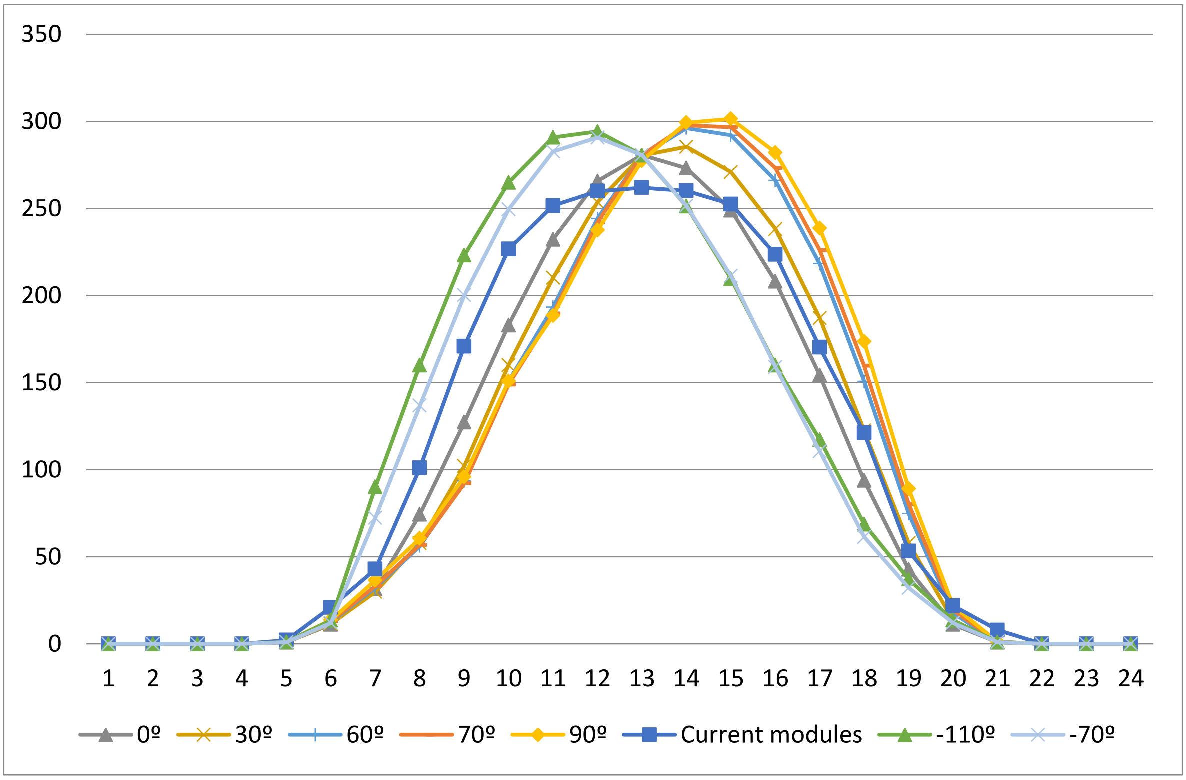


Fig I.6: Maximum added power possibility (kWh) for different orientations and 25º tilting.

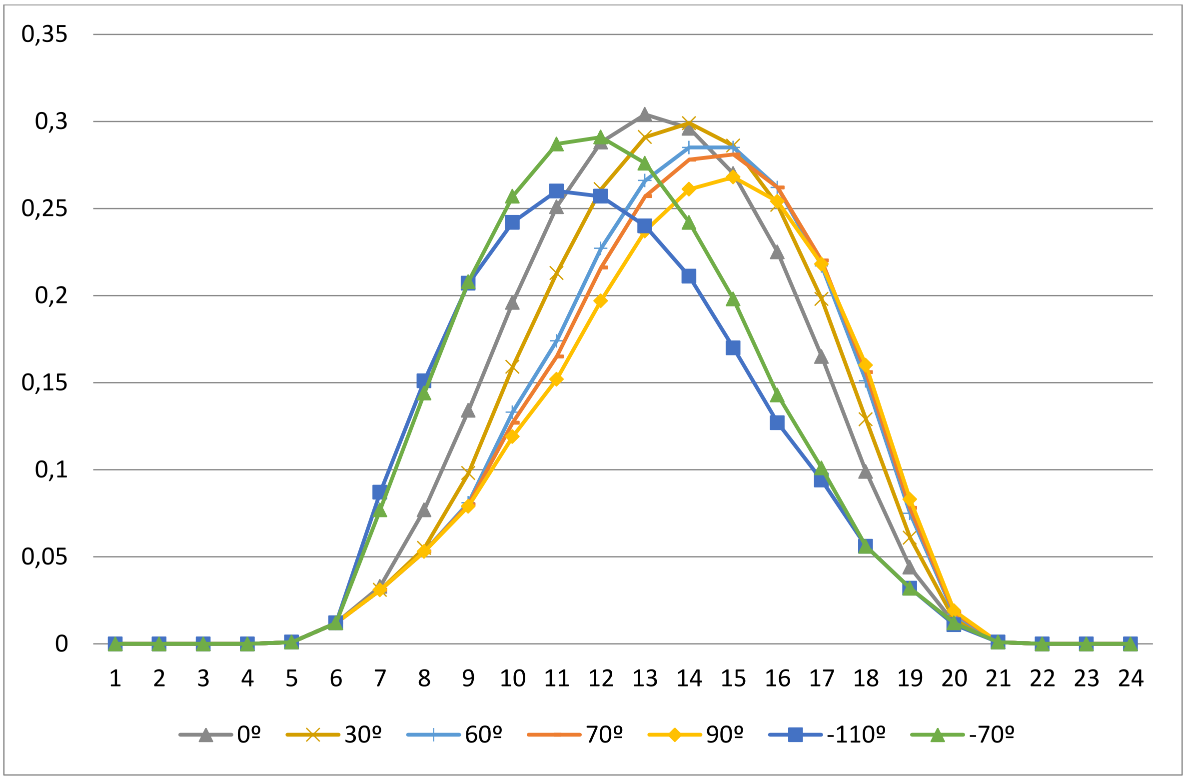


Fig I.7: Power per module (kWh) for different orientations and 30º tilting.

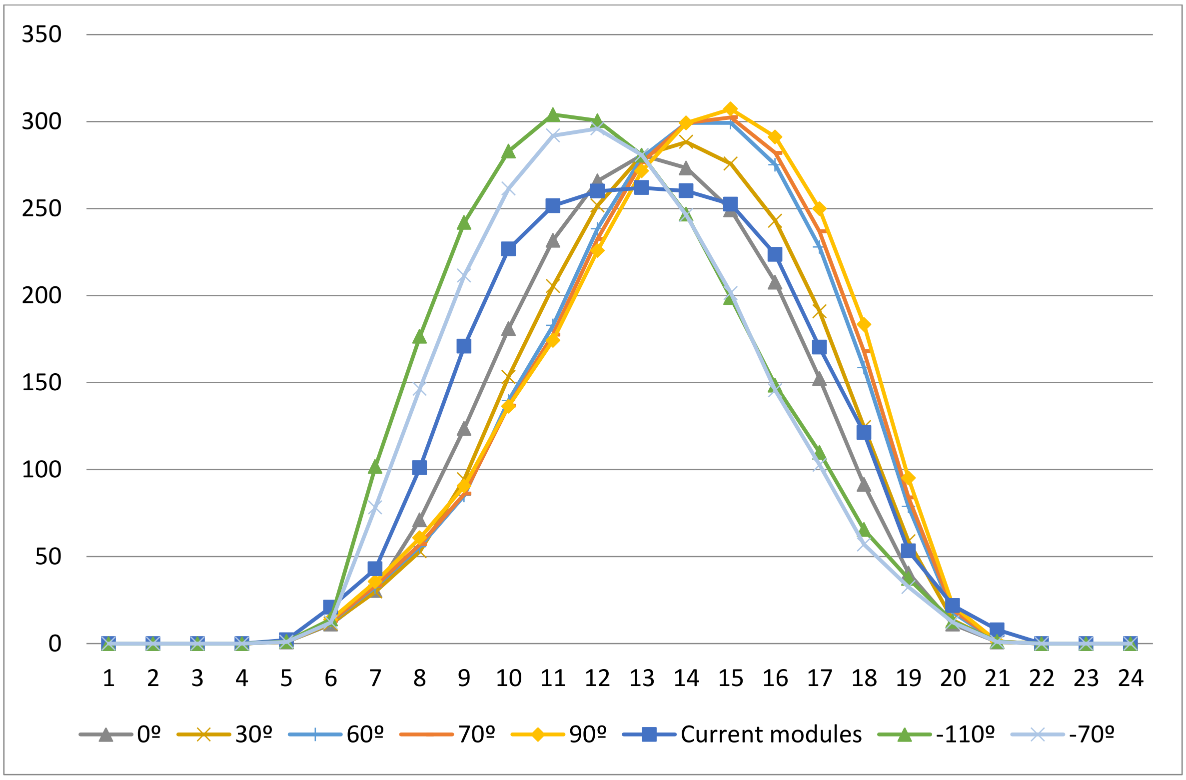
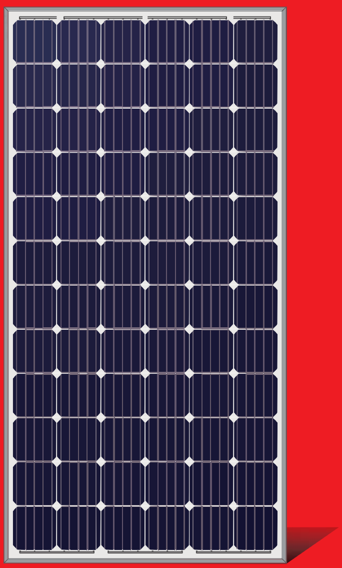


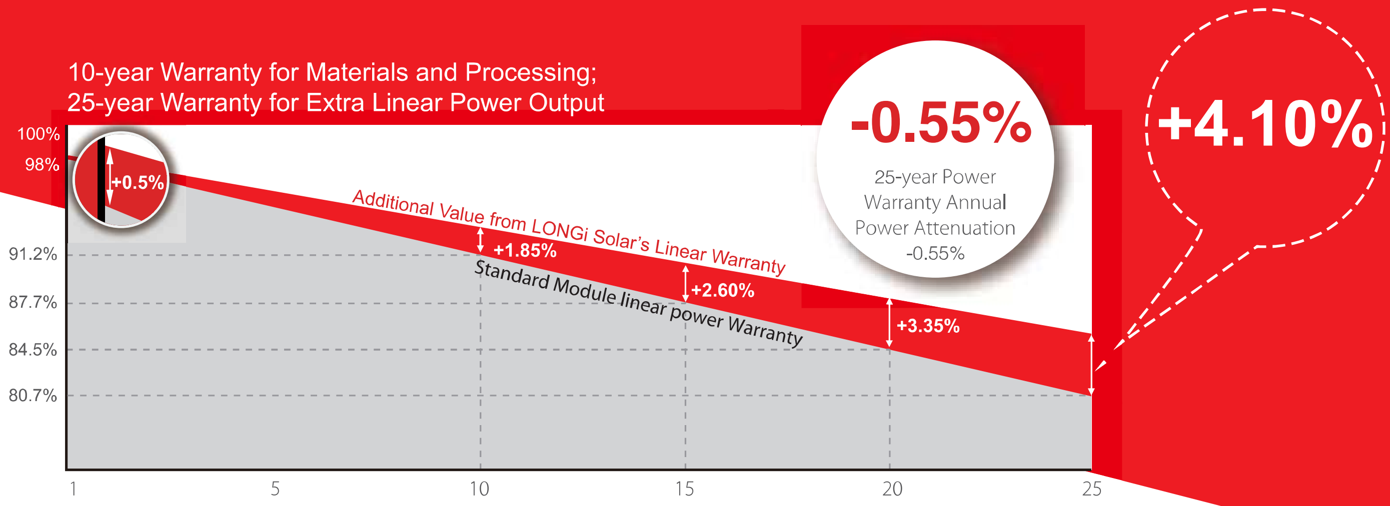
Fig I.8: Maximum added power possibility (kWh) for different orientations and 30º tilting.

LR6-72PE

360~380M

Hi-MO1 High Efficiency Low LID Mono PERC Technology





Complete System and Product Certifications

IEC 61215, IEC61730, UL1703

ISO 9001:2008: ISO Quality Management System

ISO 14001: 2004: ISO Environment Management System

TS62941: Guideline for module design qualification and type approval

OHSAS 18001: 2007 Occupational Health and Safety

* Specifications subject to technical changes and tests. LONGi Solar reserves the right of interpretation.

Positive power tolerance (0 ~ +5W) guaranteed

High module conversion efficiency (up to 19.6%)

Slower power degradation enabled by Low LID Mono PERC technology: first year <2%, 0.55% year 2-25

Better energy yield with excellent low irradiance performance and temperature coefficient

Solid PID resistance ensured by solar cell process optimization and careful module BOM selection

Adaptable to harsh environment: passed rigorous salt mist and ammonia tests

LONGi Solar

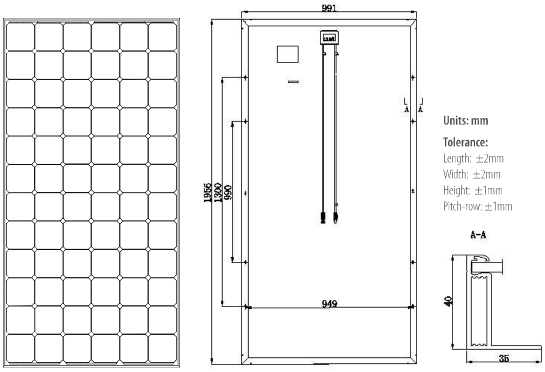
Room 201, Building 8, Sandhill Plaza, Lane 2290, Zuchongzhi Road, Pudong District, Shanghai, 201203
Tel: + 86-21-61047332 Fax: +86-21-61047377 E-mail: module@longi-silicon.com
Facebook: www.facebook.com/LONGi Solar

Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi Solar have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

20180701

LR6-72PE **360~380M**

Design（mm）



Mechanical Parameters

Cell Orientation: 72（6×12）

Junction Box: IP67, three diodes

Output Cable: 4mm², 1200mm in length

Connector: MC4 or MC4 comparable

Weight: 22.5kg

Dimension: 1956×991×40mm

Packaging: 26pcs per pallet

Operating Parameters

Operational Temperature: -40℃ ~ +85℃

Power Output Tolerance: 0 ~ +5 W

Maximum System Voltage: DC1000V (IEC&UL)

Maximum Series Fuse Rating: 20A

Nominal Operating Cell Temperature: 45±2℃

Application Class: Class A

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR6-72PE-360M		LR6-72PE-365M		LR6-72PE-370M		LR6-72PE-375M		LR6-72PE-380M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	360	266.7	365	270.4	370	274.1	375	277.8	380	281.5
Open Circuit Voltage (Voc/V)	47.9	44.7	48.0	44.8	48.3	45.1	48.5	45.3	48.7	45.5
Short Circuit Current (Isc/A)	9.70	7.82	9.74	7.85	9.84	7.93	9.90	7.98	9.99	8.05
Voltage at Maximum Power (Vmp/V)	39.2	36.2	39.3	36.3	39.4	36.4	39.6	36.6	39.8	36.8
Current at Maximum Power (Imp/A)	9.18	7.36	9.29	7.45	9.39	7.53	9.47	7.59	9.55	7.66
Module Efficiency(%)	18.6		18.8		19.1		19.3		19.6	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25℃, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20℃, Spectra at AM1.5, Wind at 1m/S

Temperature Ratings（STC）

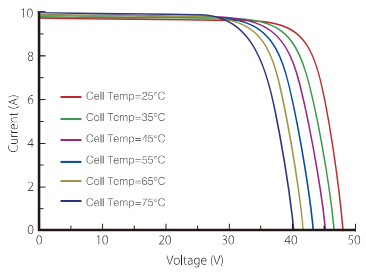
Temperature Coefficient of Isc	+0.057%/℃
Temperature Coefficient of Voc	-0.286%/℃
Temperature Coefficient of Pmax	-0.370%/℃

Mechanical Loading

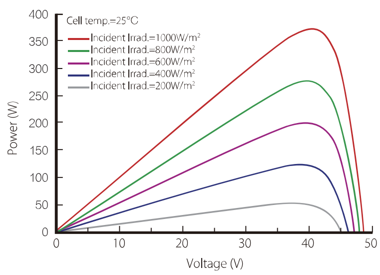
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hailstone Test	25mm Hailstone at the speed of 23m/s

I-V Curve

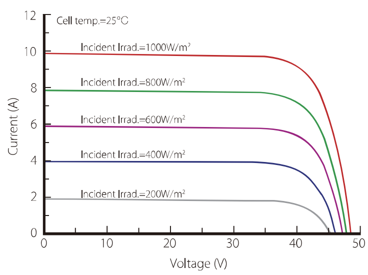
Current-Voltage Curve (LR6-72PE-370M)



Power-Voltage Curve (LR6-72PE-370M)



Current-Voltage Curve (LR6-72PE-370M)



LONGi Solar

Room 201, Building 8, Sandhill Plaza, Lane 2290, Zuchongzhi Road, Pudong District, Shanghai, 201203
Tel: + 86-21-61047332 Fax: +86-21-61047377 E-mail: module@longi-silicon.com
Facebook: www.facebook.com/LONGi Solar

Note: Due to continuous technical innovation, R&D and improvement, technical data above mentioned may be of modification accordingly. LONGi Solar have the sole right to make such modification at anytime without further notice; Demanding party shall request for the latest datasheet for such as contract need, and make it a consisting and binding part of lawful documentation duly signed by both parties.

SUNNY TRIPOWER CORE1
STP 50-40

Kostengünstig

- Standgerät mit geringstem Montageaufwand
- Keine DC-Sicherungen erforderlich
- Integrierter DC-Trennschalter

Konsequent integriert

- Integrierter WiFi-Zugang mit jedem mobilen Gerät
- 12 direkte String-Eingänge reduzieren Arbeits- und Materialaufwand
- AC-/DC-Überspannungsschutz (optional)

Kürzeste Installationszeit

- Schneller Netzanschluss durch einfache Wechselrichter-Konfiguration und –Inbetriebnahme
- Optimal zugängliche Anschlussbereiche

Maximale Erträge

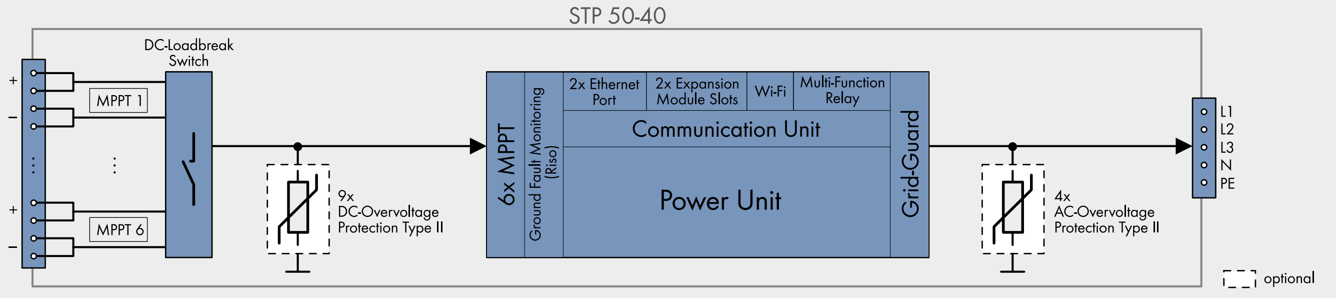
- Bis zu 150 % Überdimensionierung des PV Generators
- 6 unabhängige MPP-Tracker sichern optimale Energieerzeugung - auch bei Verschattung

SUNNY TRIPOWER CORE1

Stands on its own

Der Sunny Tripower CORE1 ist der weltweit erste frei stehende String-Wechselrichter für dezentrale Aufdach- und Freiflächenanlagen sowie überdachte Parkplätze. Der CORE1 ist die 3. Generation der erfolgreichen Sunny Tripower Produktlinie und revolutioniert mit seinem innovativen Konzept die Welt der gewerblichen Wechselrichter. Maßgabe der SMA Ingenieure war es ein einzigartiges Design und eine innovative Installationsmethode zu verbinden, um damit die Installationsgeschwindigkeit deutlich zu erhöhen und für alle Zielgruppen einen optimalen Return on Investment zu erzielen.
Von der Auslieferung über die Installation bis hin zum Betrieb ermöglicht der Sunny Tripower CORE1 umfassende Kosteneinsparungen bei Logistik, Arbeitsaufwand, Material und Service. Gewerbliche PV-Installationen sind ab jetzt schneller und einfacher zu realisieren als je zuvor.

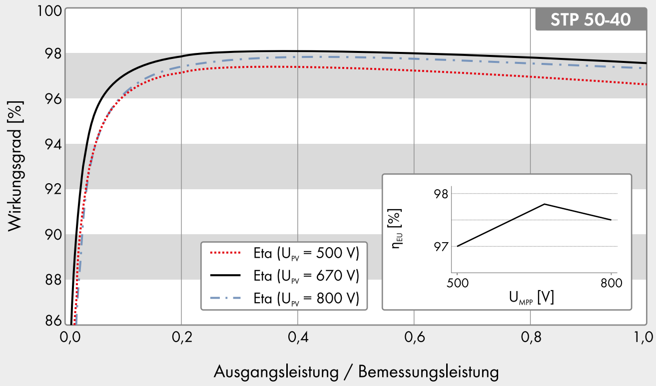
BLOCKSCHALTBILD



Technische Daten	Sunny Tripower CORE1
Eingang (DC)	
Max. PV Generatorleistung	75000 Wp STC
Max. Eingangsspannung	1000 V
MPP-Spannungsbereich / Bemessungseingangsspannung	500 V bis 800 V / 670 V
Min. Eingangsspannung / Start-Eingangsspannung	150 V / 188 V
Max. Eingangsstrom / per MPPT	120 A / 20 A
Max. Kurzschlussstrom per MPPT / per String-Eingang	30A / 30A
Anzahl der unabhängigen MPPT-Eingänge / Strings pro MPPT-Eingang	6 / 2
Ausgang (AC)	
Bemessungsleistung (bei 230 V, 50 Hz)	50000 W
Max. AC-Scheinleistung	50000 VA
AC-Nennspannung	220 V / 380 V 230 V / 400 V 240 V / 415 V
AC-Spannungsbereich	202 V bis 305 V
AC-Netzfrequenz / Bereich	50 Hz / 44 Hz bis 55 Hz 60 Hz / 54 Hz bis 65 Hz
Bemessungsnetzfrequenz / Bemessungsnetzspannung	50 Hz / 230 V
Max. Ausgangsstrom / Bemessungsausgangsstrom	72,5 A / 72,5 A
Einspeisephasen / AC-Anschluss	3 / 3-(N)-PE
Leistungsfaktor bei Bemessungsleistung / Verschiebungsfaktor einstellbar	1 / 0 übererregt bis 0 untererregt
THD	< 3 %
Schutzeinrichtungen	
Eingangsseitige Freischaltstelle	●
Erdschlussüberwachung / Netzüberwachung	● / ●
DC-Verpolungsschutz / AC-Kurzschlussfestigkeit / Galvanisch getrennt	● / ● / –
Allstromsensitive Fehlerstromüberwachungseinheit	●
Schutzklasse (nach IEC 62109-1) / Überspannungskategorie (nach IEC 62109-1)	I / AC: III; DC: II
AC-/DC-Überspannungsableiter (Typ II)	○ / ○

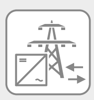
Technische Daten	Sunny Tripower CORE1
Wirkungsgrad	
Max. Wirkungsgrad / Europ. Wirkungsgrad	98,1 % / 97,8 %
Allgemeine Daten	
Maße (B / H / T)	621 mm / 733 mm / 569 mm (24.4 in / 28.8 in / 22.4 in)
Gewicht	84 kg (185 lb)
Betriebstemperaturbereich	-25 °C bis +60 °C (-13 °F bis +140 °F)
Geräuschemission (typisch)	< 65 dB(A)
Eigenverbrauch (Nacht)	4,8 W
Topologie / Kühlprinzip	Transformatorlos / OptiCool
Schutzart (nach IEC 60529)	IP65
Klimaklasse (nach IEC 60721-3-4)	4K4H
Zulässiger Maximalwert für die relative Feuchte (nicht kondensierend)	100 %
Ausstattung / Funktion / Zubehör	
DC-Anschluss / AC-Anschluss	SUNCLIX / Schraubklemme
Aufstellfüße	●
LED-Anzeige (Status / Fehler / Kommunikation)	●
Schnittstelle: Ethernet / WLAN / RS485	● (2 Eingänge) / ● / ○
Datenschnittstelle: SMA Modbus / SunSpec Modbus / Speedwire, Webconnect	● / ● / ●
Multifunktionsrelais / Steckplätze für Erweiterungsmodule	● / ● (2 Eingänge)
OptiTrac Global Peak / Integrated Plant Control / Q on Demand 24/7	● / ● / ●
Off-Grid fähig / SMA Fuel Save Controller kompatibel	● / ●
Garantie: 5 / 10 / 15 / 20 Jahre	● / ○ / ○ / ○
Zertifikate und Zulassungen (weitere auf Anfrage) * Gilt nicht für alle nationalen Anhänge der EN 50438	ANRE 30, AS 4777, BDEW 2008, C10/11:2012, CE, CEI 0-16, CEI 0-21, EN 50438:2013*, G59/3, IEC 60068-2-x, IEC 61727, IEC 62109-1/2, IEC 62116, MEA 2016, NBR 16149, NEN EN 50438, NRS 097-2-1, PEA 2016, PPC, RD 1699/413, RD 661/2007, Res. n°7:2013, SI4777, TOR D4, TR 3.2.2, UTE C15-712-1, VDE 0126-1-1, VDE-ARN 4105, VFR 2014, P.O.12.3, NTCO-NTCyS, GC 8.9H, PR20, DEWA
● Serienausstattung ○ Optional – Nicht verfügbar Angaben bei Nennbedingungen - Stand 07/2017	
Typenbezeichnung	STP 50-40

Wirkungsgradkurve

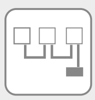


Zubehör

SMA
Sensor Module
MD.SEN-40



SMA IO-Module
MD.IO-40



SMA
RS485 Module
MD.485-40

Antenna
Extension Kit
EXTANT-40

AC Surge Protection Module Kit
AC_SPD_Kit1-10
DC Surge Protection Module Kit
DC_SPD_Kit4-10

www.SMA.de **SMA Solar Technology**

STP50-40-DDE1728-V20 SMA und Sunny Tripower sind eingetragene Warenzeichen der SMA Solar Technology AG. SUNCLIX ist eine eingetragene Marke der PHOENIX CONTACT GmbH & Co. KG. Gedruckt auf FSC-Papier.
Änderungen von Produkten und Services, auch aufgrund länderspezifischer Voraussetzungen, sowie Abweichungen von technischen Daten bleiben vorbehalten. SMA übernimmt keine Haftung für Irrtümer oder Druckfehler. Für die neuesten Informationen wenden Sie sich bitte an www.SMA-Solar.com