Technical and Economic Solutions for Grid-Connected Utility-Scale Solar Photovoltaic Power Plants

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Abstract

The continuous consumption of fossil fuels is leading to large amounts of greenhouse gases emissions, giving rise to unsettling phenomena responsible for harming the environment as well as world population's health. The solar energy has shown to be a successful renewable source, wherefore large investments are planned in the upcoming decades. This study aims at maximizing the energy to inject into the grid by a solar photovoltaic PV park with $24MW_p$ of installed capacity. Several successive simulations were automatically performed with the PVSyst software, so that each considered parameter could be individually analysed, allowing one to understand their influence on the variable to maximize. The best combination of module/inverter was chosen, and two different string inverters were included to evaluate their efficiency relatively to the central inverter. The fixed tilt and single-axis tracking (SAT) systems were optimized and the layout of each case scenario was undertaken, which enabled the different devices to be distributed over the available area. An economic analysis was carried out so that the most viable solution could be selected. When employing the central inverter and string inverter, the SAT system produces 15% and 14.3% more energy relatively to the fixed tilt one, respectively. Additionally, the string inverters led to 3.5% and 2.7% higher energy yields when employed in the fixed tilt and SAT system, respectively. The most economic viable solution is characterized by the employment of the SAT system together with the string inverters and module portrait configuration.

Keywords: Utility-scale solar PV park, optimization, design parameters, economic analysis

1. Introduction

Energy is crucial for a wide range of applications in agriculture, transportation, industry and household sectors. The continuous consumption of fossil fuels for power generation is leading to large amounts of greenhouse gas emissions, which consequently heavily harms the environment. Among many consequences stemming from it, the global warming and climate change have been identified as an unsettling phenomena, which requires the mankind to reverse this process at the earliest possible. In this regard, the employment of renewable energies appear to be one of the foremost efficient solutions.

In the past few years, solar energy has shown to be a promising solution, since the installation is accessible and it can be extended to any place where there exists abundant sun radiation. The reduction of the investment costs along with the diverse components' efficiency improvements will make the installed power to keep growing in the future, namely through the implementation of large-scale grid connected solar PV parks. Hence, the optimization of solar PV parks turned out to be a crucial topic to be studied since it highly influences the energy output and the project's economic viability in the long term. The solar PV park optimization is a not straight forward problem due to the existence of many variables needed to consider, which might result in controversial parameters' values.

Throughout time, several studies concerning performance assessment of solar PV parks have been carried out aiming at the attainment of greater performance values. Furthermore, research in the field of solar PV power plants optimization has been undertaken as this represents a multivariable problem involving several parameters that must be considered. The optimization domain is a crucial matter that has been gaining particular importance in the past few years, since PV technology prices have been decreasing and large-scale parks have been built, where just few improvements may lead to important yield performance differences.

A grid-connected solar PV power plant performance was assessed through PVSyst software. Performance ratio and various types of power losses data were obtained and from it, the viability of installing a 1MW solar PV power plant in four different areas was discussed. The solar modules' tilt angle was adjusted accordingly to the site latitude and both the modules and inverter assumed throughout the study were initially chosen, having been the only option considered [3].

A design simulation was carried out aiming at the performance assessment yield and loss forecasting for a 100 kW_p grid connected solar PV system [1]. Throughout the study, an equivalent mathematical model was developed and the performance parameters were obtained with the help of PVSyst design tool. Similarly, the study developed in [9] aimed at the design and simulation of a 1kW solar PV system power plant using PVSyst software. The energy generated by the system and incurred losses were computed and analyzed. As it does not represent a large-scale system, the modules tilt angle was simulated as being varied seasonally accordingly to the "optimal angle" provided by the software. As in [3], both module and inverter type were initially chosen. [2] presents a similar study to [9], evaluating the performance of a 10MW PV power plant to be installed in a given area of fifty acres, while also considering seasonal tilt angle variation.

In [4], a study of a 150MW grid-connected utility-scale solar PV plant to be installed within a 750 acres land is presented. The analysis was mainly focused in the preliminary design of the case project such as the feasibility study and PV solar design aspects, which were underpinned by an energy yield assessment simulation study performed using PVSyst software. The fixed tilt angle was also set accordingly to the site coordinates. In [11], a research study was carried out, in which several performance parameters (PR, cumulative utilization factor) and factors contributing to the performance of solar power plants (climate conditions, design parameters) are covered, which is essential in the extent that it helps when one is trying to optimize the energy generation and the PV park overall performance.

All these aforementioned articles do not focus on a detailed optimization but rather on an evaluation of the performance through the analysis of the already mentioned parameters. Next, articles related with the optimization of PV solar parks will be introduced as they cover some of the relevant topics to be addressed along this study. These studies, however, have used different approaches since some were carried out employing the PVSyst software (as in the present study) while others are underpinned by optimization algorithms.

In [6] an analysis of the mutual shading effect in rows arrangement is undertaken using PVSyst software, which plays a major role in a fixed tilt solar PV park optimization. A deep analysis of the different components' shading effects (beam, diffuse, albedo and mismatch electrical effects) was carried out and it was concluded that the diffuse and albedo losses are dominating. Additionally, it was shown that the electrical effects are essentially important with one only string in the width of rows. Furthermore, in [7], the same author introduced a tool to optimize the layout of ground-based PV solar systems considering economic boundary conditions. Besides the optimization aiming at maximizing the installation yield performance, economic boundary conditions as the investment and maintenance costs, surface availability and feed-in tariff have also a relevant impact on the design choices. As so, the optimization tool addresses the mentioned problem by finding the ground cover ratio and module tilt angle capable of optimizing the economic benefit.

A cuckoo search-based algorithm was developed [8] aiming at the sizing optimization of a 5MW large-scale grid connected photovoltaic system. Over this study, the algorithm was used to select the optimal combination of the system components (PV module and inverter) so that the performance ratio (PR) was maximized. In [10] a method through the employment of a genetic algorithm was developed for the calculation of the optimal configuration of large PV plants aiming at minimizing the levelized cost of energy (LCOE). The design optimization was carried out considering the number of components and their arrangement within the field as well as the lifetime cost and energy production. The design results allowed to conclude that the proposed optimization method leads to a reduction of the energy cost generated by the PV plant, enabling the economic benefit maximization.

Relatively to what is described in the articles, this paper approaches this multi-variable problem through a generic method to optimize the parameters deemed relevant in both fixed and single-axis tracking PV utility-scale installations. Initially, simulations were carried out aiming at finding the module/inverter combination leading to the greater energy output, so that the pair with the best performance could be selected. Different central and string inverters were included in the study so that their performance could be assessed and compared in both technical and economical terms.

This work aims at developing technical and economical solutions to optimize a utility-scale grid connected solar photovolatic park with an installed capacity of 24 MW_p and a limited land area of approximately fifty hectares. To that end, the maximization of the energy to inject into the grid will be attained through the seek of the most appropriate considered parameters' values, which will be varied through successive simulations automatically performed by the PVSyst software. Furthermore, along with the energy yield maximization, an economical study will be carried out so that the most viable solution can be chosen. The mentioned goal is planned to be achieved through the following outlined steps to be developed along the present study:

- Choice of the main equipment (solar modules and inverters);
- Study of the central and string inverter alternatives;
- System sizing;
- Fixed tilt system parameters' optimization;
- Single axis-tracking system parameters' optimization;
- Park layout;
- Economic viability maximization.

In the methodology section, the used strategy to conclude about the selection of the PV module and different inverters to employ is presented as well as the approach to optimize the fixed tilt and SAT systems. Finally, the levelized cost of energy is described, as it was the measure of comparison between the different studied alternatives. Next, in the results' section, the main study findings stemming from the performed simulations are depicted. The conclusions provide a resume of what was found along the study as well as the recommendations of what equipments and configurations should be employed to maximize the energy yield.

2. Methodology

The developed method to analyze and solve the problem at stake will be briefly structured and outlined throughout this section. Initially, the strategy path taken to conclude about the modules and inverters to employ will be shown. Afterwards, both fixed tilt and SAT systems will be considered in the extent that key parameters will be introduced, as they highly influence the variable to maximize. Finally, the method also introduces the levelized cost of energy model, which shows to be extremely useful to compare the different cases.

2.1. Equipment's' Selection Strategy

In an early stage of this study, it is prominent to decide the main devices to employ so that the simulations may be performed with a particular type of configuration, which subsequently allows other parameters of interest to be tested. Besides the type of central and string inverter, the quantity was also varied as it influences the park performance as well as the investment and maintenance costs.

2.1.1 Central Inverter

Initially, the number of sub-arrays (number of arrays in which the total PV park is divided) must be chosen, which subsequently influences the type of module and central inverter to select. The central inverter to be used hinges on the total power of each sub-array and on the deemed $P_{inv,ratio}$ interval. The central inverter minimum and maximum admissible power for each different case (where a different number of sub-arrays is considered) might be found based on the inverter maximum and minimum power ratio $P_{inv,ratio}$ respectively, given by:

$$P_{min,inverter} = \frac{P_{subarray,\text{STC}}}{P_{inv,max,ratio}} \tag{1}$$

$$P_{max,inverter} = \frac{P_{subarray,\text{STC}}}{P_{inv,min,ratio}} \tag{2}$$

where $P_{subarray,\text{STC}}$ (sub-array peak power) varies depending on the number of sub-arrays. The $P_{inv,max,ratio}$ and $P_{inv,min,ratio}$ refer to the considered inverter maximum and minimum $P_{inv,ratio}$, respectively. If $P_{inv,ratio}$ is higher than the chosen $P_{inv,max,ratio}$ value for the project, the system is undersized since the inverter AC power would decrease, which in turn could lead to a premature power clipping. On the other hand, if $P_{inv,ratio}$ is lower than the chosen $P_{inv,min,ratio}$ value, the system would be oversized. As so, an interval between $P_{inv,min,ratio}$ and $P_{inv,max,ratio}$ is required for the inverter power intervals to be found, which in this study was decided to be within 1.1 and 1.3, respectively [5]. Once the number of sub-arrays to test is known and the $P_{inv,ratio}$ interval range is decided, the initial available central inverters can be selected.

Once the PV modules and available central inverters are selected, the goal is to carry out several simulations in which all these two types of devices are combined with each other, aiming at drawing conclusions regarding the performance of each combination. Thereby, for each case where a different number of sub-arrays is considered, all modules will be matched with all available inverters (already selected based on the inverter power ratio) under the same conditions.

2.1.2 String Inverter

As the power of a string inverter is much lower in comparison to a central inverter, the solar park does not need to be splited in several high power sub-arrays. In contrast, each string inverter is connected to a few strings over all the PV park, which will also result in a a larger number of inverters. In this case, simulations are to be performed for every combination of module and string inverter.

Furthermore, each of these combinations is simulated taking into account a different number of inverters (always complying with the $P_{inv,ratio}$ interval) to perceive the energy yield output difference, being useful to conclude if the initial investment is worth the additional produced energy.

2.2. Fixed Tilt Definitions

Along this section, the undertaken stages related to the fixed tilt system analysis will be described. The sheds arrangement are mainly characterized by the collector width (W), pitch (P) and tilt angle (β), being this nomenclature presented in the figure 1.

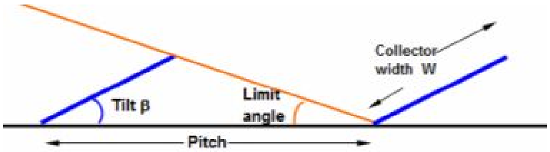

Figure 1: Sheds scheme [6]

The shading limit angle (θ) is the angle from which shadow starts to be produced on the next shed (figure 1). There is no optimum value for this angle but often one considers the worst case scenario (December 22^{nd}) for mutual shadings to be minimized. For a given shading limit angle, the pitch is computed through the equation 3 so that no shadings are produced on the solar panel plane [6]. The variables P, W, β and θ represent the pitch , width, plane tilt and shading limit angle, respectively.

$$P = W\left(cos(\beta) + \frac{sin(\beta)}{tan(\theta)}\right) \tag{3}$$

The ground cover ratio (GCR) is one of the foremost parameters to regard while designing a PV park, being given by the ratio of the modules sensitive area to the ground total area occupied by the PV park (equation 4).

$$GCR = \frac{A_{modules}}{A_{ground}} \tag{4}$$

As the ground area to be used must not be surpassed, the GCR to obtain must not be lower than the value stemming from the equation 4, if the available area is to be totally occupied. However, the ”real” ground cover ratio may also be presented through the ratio of the width to the pitch (equation 5), being the one used in the design of PV parks, as it is based on the shed parameters and not on the initial available area.

$$GCR = \frac{Width}{Pitch} \tag{5}$$

2.2.1 Portrait vs Landscape

At first, the solar panels' disposition was studied taking into account two different possible solar panels' arrangement: portrait and landscape. It is important to highlight that shading is a factor to consider when optimizing a PV array, as the beam component has influence in the electrical shading part of the system. Hence, several simulations were performed varying the plane tilt angle for these two different arrangements, allowing one to conclude about the shading impact on each case individually.

2.2.2 Plane Tilt, Pitch and Azimuth

When employing a fixed tilt system, the annual energy yield and performance ratio strongly depend on both pitch and plane tilt as they influence both incident irradiation and shading in the collector plane. An initial sensibility analysis was carried out to perceive the influence of the tilt angle and pitch on the grid energy and performance ratio, which allowed one to conclude that the tilt angle that leads to the maximum energy yield is often not equal to the site latitude (as assumed in several studies) but lower than this value, due to the mutual shading effect. The figure 2 includes a chart that proves what was mentioned above, where the angle that would lead to a maximum energy yield is 34° whereas a plane tilt of 29° would lead to a maximum value of energy injected in the grid. The nominal energy curve presented in the graphic depicts the energy that would be produced if the solar panel works at its nominal efficiency (STC). This figure presents the results in per unit scale. Regarding the performance ratio, one can see that the maximum value is given for the minimum tilt angle, which supports that the optimal system hinges on what is to be maximized. For this specific case, when there is an increase of the tilt angle, the global incident irradiation will increase significantly. However, the mutual shadings will also increase, which in turn will lead to a decrease of the grid energy and, consequently, a degrading of the performance ratio.

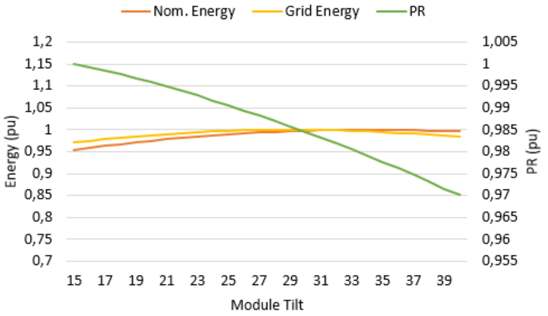

Figure 2: Energy Yield/PR vs Tilt Angle

Relatively to the azimuth angle, in the northern hemisphere, it is common for the plane to face south (0° azimuth angle) to receive the maximum amount of irradiation. The azimuth angle is an important parameter to take into account in both fixed tilt and SAT systems. Simulations varying the azimuth angle were carried out to show and prove the best orientation the solar panels should face.

2.3. Single-Axis Tracking Definitions

2.3.1 Backtracking vs No Backtracking

When using single-axis trackers, near shadings have always to be considered when employing or not the backtracking strategy. In the former case (with backtracking), instead of tracking the sun so that the solar modules are always perpendicular to the beam irradiance (without backtracking), these will adopt a lower angle (in the morning and evening) to avoid beam mutual shadings, which also makes the incidence angle to increase. Thus, when making use of this strategy, the shading electrical loss effects are reduced but the losses stemming from mis-orientation increase. The factor that might lead one to adopt the backtracking strategy is the lower electrical shading effects, since when a part of a string gets shaded, the full production from that string is affected. Simulations considering both strategies were performed under the same conditions to draw results regarding the best one to employ.

2.3.2 Pitch

As in the fixed tilt configuration, the distance between trackers (pitch) highly influences the energy yield. After a certain pitch, the energy yield does not vary significantly and the ground cover ratio may be obtained as in the fixed tilt configuration through the equation 5. As so, if the width and pitch are known, the ”real” ground cover ratio might be found as well as the required initial available area (equation 4).

2.4. Economic Viability

Besides the technical optimization through the equipments' choice and parameters' variation, the economic viability analysis of each different studied case should be carried out as well. As so, conclusions should be drawn from an economic analysis, where all different cases are compared based on their annual energy yield, investment and maintenance costs. To that end, the levelized cost of energy (LCOE) may be computed for every single case. The LCOE (€/MWh) is the cost per unit of electricity produced during a given time period (hour, day, month, year or solar PV park lifetime):

$$LCOE = \frac{C_T}{E_a} = \frac{C_F + C_V}{E_a} \tag{6}$$

where C_T is the total annual cost (€) given by the sum of the current annual fixed cost (C_F) and annual variable cost (C_V). In a solar PV power plant, as there are no fuels involved, there is no variable cost. The fixed cost C_F (€/MW) include both the initial investment I_0 (€) and the fixed $O\&M$ costs over the power plant lifetime. The former one can be written in function of a constant annual payment over the project's lifetime (A_T):

$$I_0 = A_T \sum_{j=1}^{n} \frac{1}{(1+r)^j} = A_T \frac{(1+r)^n - 1}{r(1+r)^n} \tag{7}$$

In the previous equation (7), r and n are the minimum expected rate of return and the project's lifetime to be considered, respectively. Summing both the annuity payment (which can be easily written in function of the investment based on the equation 7) and the fixed $O\&M$ (which is assumed to be proportional to the investment per unit of power by a factor β), one can obtain the fixed annual generation cost per installed unit of power:

$$C_F = \left(\frac{r(1+r)^n}{(1+r)^n - 1} + \beta \right) I_0 \tag{8}$$

3. Results & discussion

3.1. PV Module and Inverter Selection

Initially, the PV modules and inverters must be chosen so that other parameters can be analyzed with a particular configuration. Hence, the choice regarding the number of sub-arrays as well as the results obtained from the simulations in which every combination of module/inverter was tested is presented throughout this section. Several central inverters and two string inverters provided by Huawei were considered.

3.1.1 Central Inverter

This sub-section presents the obtained results relatively to the number of sub-arrays as well as the choice of the central inverter and PV module to employ. Relevant initial system data is depicted in table 1, where it is shown the considered $P_{inv,ratio}$ interval, accordingly to what was specified in section 2.

Total Installed DC Capacity (kW_p)	24 000
Max. Power Grid Connection (kW)	20 000
$P_{inv,max,ratio}$	1.3
$P_{inv,min,ratio}$	1.1
Total Available Ground Area (m^2)	478 800

Table 1: General System Data

The obtained inverter power intervals (table 2) allowed one to select the central inverters that could possibly suit each different case (from 5 to 8 sub-arrays). Based on these power intervals calculated for all the different cases, the available central inverters were selected. After the selection of the central inverters for each case, several simulations were carried out to match all possible module/inverter combinations, being the results leading to a higher energy yield presented in table 3.

As one may conclude from the same table, the 370W module (Hanwha Qcells) combined with the central inverters SG3000HV and SG2500HV manufactured by SunGrow make up the best case scenarios for 7 and 8 sub-arrays, respectively. When employing seven inverters, the energy per sub-array will be higher due to the greater inverter AC nominal power. However, the total annual produced energy is similar in both cases. Following the reasoning related with the redundancy factor and since the maximum power to inject in the grid must not surpass 20MW, the combination leading to a greater grid energy (SunGrow SG2500HV) corresponding to the case of 8 sub-arrays was selected to proceed with, being used hereafter in the next simulations.

3.1.2 String Inverter

The strategy followed to select the string inverter to be used was slightly different from the one used for the central inverter. Although there is no need to divide the park according to the number of inverters, one amongst the eight aforementioned sub-arrays was also used to perform the simulations with the string inverters. As the total capacity to be installed is the priority, the simulations were undertaken considering a maximum power of $3000kW_p$ and the same $P_{inv,ratio}$ interval (table 1).

These simulations were carried out considering a configuration of 29 modules in series and 280 strings in parallel, whose best results are depicted in the table 4. As one may notice, a decrease in the number of inverters causes a decrease in the AC output power, which in turn is associated with a higher $P_{inv,ratio}$. The choice between the number of inverters hinges on a trade-off between the energy produced and the price of each inverter. From the table 4, one may conclude that in both cases an increase in the number of inverters leads to a higher energy yield. However, the energy yield difference between using 22 or 26 SUN2000-105KTL inverters is only 0.04%, which is not enough to offset the initial investment of four string inverters. As so, the simulations carried out henceforth considered 22 inverters of this type, which results in 176 string inverters to be used in the entire PV park (8 sub-arrays). Since the energy yield difference between using both SUN2000-185KTL string inverters makes up only 0.012%, 14 string inverters of this type will be considered.

3.2. Fixed Tilt Energy Maximization

The portrait and landscape dispositions (figure 3) used in the following simulations were considered to have two modules vertically oriented and four modules horizontally oriented along the shed's width, respectively. The graphic 3 depicts the electrical loss due to shadings, having been obtained through the variation of the tilt angle. When the tilt angle increases, more shadings will be produced in the collector plane, causing an increase in the electrical losses as well (figure 3). On this basis, landscape configuration will be employed henceforth to analyze the other different parameters while seeking the maximization of the energy yield.

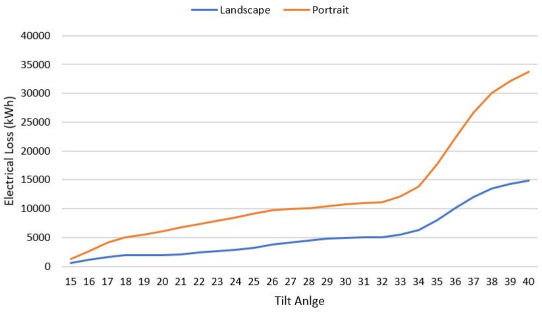

Figure 3: Electrical Loss (Portrait vs Landscape)

However, different string cables' length are required depending on whether the panels are disposed in portrait or landscape. Thus, no conclusions can be drawn from this analysis regarding the most economical viable configuration to employ, as different dispositions lead to different energy values but also to different initial investments. Along this section, even though the goal is to maximize the energy yield, an economical analysis will also be carried out, which will consider both portrait/landscape configurations.

Through the pitch and tilt angle, one must ensure that the shadings stemming from adjacent rows are minimized as much as possible. Based on the site solar chart, a limit angle of 18° was set for no shadings to be produced between 9h and 16h on the December 22^{nd}, approximately. If the shading limit angle is to be kept constant, the pitch and tilt angle are dependent on each other. As so, a tilt angle increase will be followed by a pitch increase (figure 4) for the shading limit angle to remain constant. As pictured in figure 4, there exists a maximum of produced energy corresponding to a specific pitch and tilt angle. Below and above 30°, the beam and diffuse irradiance hitting the solar modules decrease, leading to the shape of the blue curve. The exact values leading to the maximum energy yield are given by a tilt angle of 30° and a pitch of 9.65m,

Nº Sub-Arrays	5	6	7	8
Installed DC Capacity (kW_p)	4800	4000	3429	3000
Inverter Min. Power (kW)	3692	3077	2637	2308
Inverter Max. Power (kW)	4363	3636	3117	2727
Sub-Array Max. Area (m^2)	95760	79800	68400	59850

Table 2: Data for a different number of sub-arrays

Nº Sub-Arrays	Module	Inverter	E_{grid}/SA (kWh)	E_{tot} (kWh)
7	Hanwha Qcells 365W	SunGrow SG3000HV	5,362,425	37,536,975
	Hanwha Qcells 370W	SMA Central 2750	5,399,701	37,797,907
	Hanwha Qcells 370W	SunGrow SG3000HV	5,441,810	**38,092,670**
8	Hanwha Qcells 370W	SMA Central 2750	4,730,099	37,840,792
	Hanwha Qcells 370W	SMA Central 2500	4,739,968	37,919,744
	Hanwha Qcells 370W	SunGrow SG2500HV	4,760,757	**38,086,056**

Table 3: Best module/central inverter combinations (7 and 8 sub-arrays)

Module	Inverter	Nº of Inverters	E_{grid} (kWh)	AC Power (kW)	$P_{inv,ratio}$
Hanwha Qcells 370W	SUN2000-105KTL	26	5,010,423	2730	1.10
		25	5,010,356	2625	1.14
		24	5,010,244	2520	1.19
		23	5,009,724	2415	1.24
		22	5,008,389	2310	1.3
Hanwha Qcells 370W	SUN2000-185KTL	15	5,002,248	2625	1.14
		14	5,001,644	2450	1.23

Table 4: Module/String inverter combinations

which results in a GCR of 41.45%.

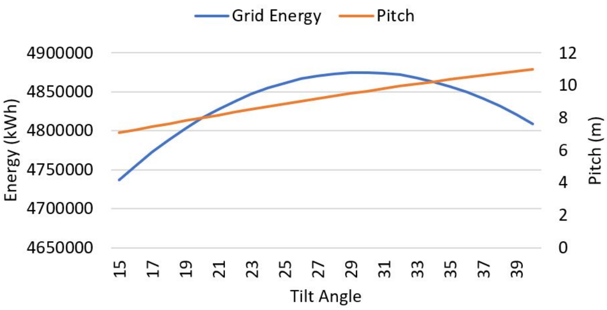

Figure 4: Grid Energy and Pitch Variation

Simulations for all possible combinations of pitch and tilt angle (within a specific interval range) were carried out to conclude about their influence on the final output. The chart presented in the figure 5 depicts the result stemming from a set of simulations in which both parameters pitch and tilt were varied from 6m to 12m and from 15º to 40º, respectively. Besides the result of energy yield for every single combination of both parameters, it also shows the "combination path" (green line) that leads to the maximum energy yield. As it can be seen, both pitch and tilt angle start to increase initially for the energy yield to be maximized. However, the tilt angle tends to become steady after the pitch has reached a certain value, after which the grid energy does not vary significantly as well.

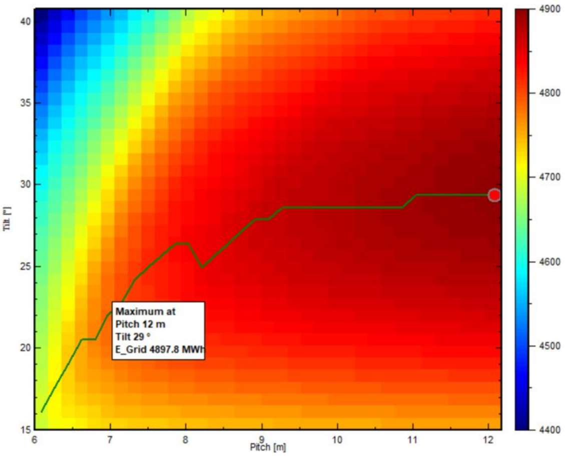

Figure 5: Pitch/Tilt Variation

In figure 6, the grid energy output as well as its percentage difference variation along the pitch are presented for a fixed tilt angle of 30^{o} (corresponding to the optimal value according to the previous obtained result). After a pitch of approximately 9m has been attained, the percentage difference variation stays below 0.13%, which is already considered negligible.

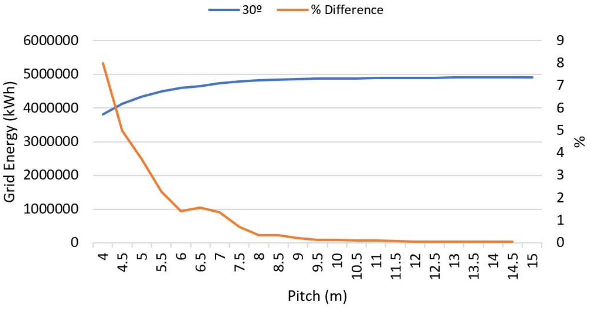

Figure 6: Grid energy difference with pitch variation for 30^{o} tilt angle

Lastly, the azimuth angle was varied from -15^{o} to 15^{o} to perceive the direction the solar modules should face for the energy yield to be maximized. The maximum values of produced energy were obtained for an angle of approximately 30^{o} and for an azimuth angle of zero degrees (southern orientation).

3.3. Single-Axis Tracking System

Initially, simulations were carried out considering a single-axis tracking system with and without the employment of the backtracking strategy. Hence, the influence of this strategy was assessed, being the grid energy output and shading losses arising from each case presented in figure 7, which vary depending on the pitch between rows. As one may notice, the backtracking strategy (orange) shows to be more advantageous in relation to the case in which it is not employed (blue), leading to slightly greater values of grid energy yield output.

The shading losses per unit area associated with each one of these cases are included in the same graph, being the scale presented on the right side of the figure. A smaller value of pitch, together with the non-implementation of the backtracking strategy (grey) leads to greater shading losses' values, stemming mainly from the the lack of incident beam component on the collector plane (visible shades). On the other hand, when the backtracking strategy is employed, there are no beam shading losses, since the collector plane constantly modifies the angle depending on the sun height. In this latter case, the shading losses (yellow) arise mainly due to the diffuse and albedo component, which do not vary significantly along the pitch.

For the pitch between rows to be set, the grid energy percentual difference variation was also obtained along the pitch (considering an interval ranging from 5.5m to 16m). For a pitch between 9.5m and 10m, a difference of 0.7% was obtained for the value of grid energy percentual difference. As so, the same pitch as the one used for the fixed tilt system was considered.

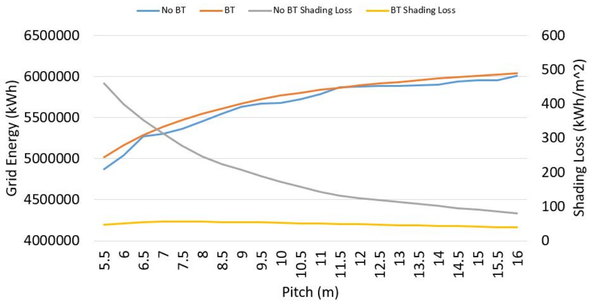

Figure 7: Backtracking vs No Backtracking

3.4. Systems' Performance Comparison

Along the previous sections both fixed tilt and SAT systems' performances were improved in the extent that relevant parameters were varied aiming at maximizing the energy yield. Additionally, both these systems were simulated with the already mentioned central and string inverters to conclude about their effect in the final output.

The single-axis tracking system proves to clearly generate a greater amount of energy in comparison with the fixed tilt system. More specifically, when employing the central and string inverter, the single-axis tracking system produces 15% and 14.3% more energy than the fixed tilt one, respectively. Furthermore, the string inverters led to 3.5% and 2.7% higher energy yields when employed in the fixed tilt and single-axis tracking system, respectively. The higher energy yield difference obtained in the fixed tilt system (3.5%) compared to the single-axis tracking one might be explained due to the beam shading, which is responsible for the strings' mismatch connected to the same MPPT. As a string inverter possesses many more available MPPT inputs than a central inverter, the beam shading (and consequently the mismatch) is better circumvented.

3.5. Economic Viability

The PV park layout was undertaken (AutoCAD) to dispose the different equipments over the given available area. Thus, for every situation, the different cables were sized and their length was found, having been useful for a subsequent price estimate. Data related to the system components' costs (table 6), cables' price estimate (table 8) and each system's maintenance costs (table 9) are presented in appendix A. Hence, all costs together with the obtained energy along the project's lifetime were useful to carry out an economic viability study, enabling one to predict how successful the project would be in the long run. The levelized cost of energy for both studied systems was calculated while employing the three different types of inverters and both modules dispositions.

		LCOE (€/MWh)	
		Landscape	Portrait
FT	Central	35.06	35.07
	String 185	34.55	34.57
	String 105	34.56	34.58
SAT	Central	32.38	32.29
	String 185	32.28	**32.23**
	String 105	32.29	32.24

Table 5: Levelized Cost of Energy

As reflected in table 5, the single-axis tracking system LCOE shows to be significantly lower relatively to the fixed tilted one regardless of the configuration type (portrait/landscape). Thus, even though the tracking system is more expensive than the fixed tilt one, the energy produced is significantly higher to offset the initial investment. Based on both current MIBEL (Iberian Electricity Market) average market price (50€/MWh) and on the data from table 5, it is clear the competitiveness of this type of technology.

From the same table, one can perceive that in the fixed tilt system the landscape configuration leads to slightly better results. As so, in this case, the higher energy produced is sufficient to compensate the greater cables' initial investment. On the other hand, the portrait configuration has shown to be slightly cheaper in the case of the single-axis tracking system. The difference between these two systems might be justified due to the near shadings, which hinge on both solar panels' configuration and tracking system. In addition, for both type of systems, the string inverters have proved to perform slightly better, leading to lower values of LCOE. More specifically, the SUN2000-185KTL string inverter has proved to achieve the lowest values, being 1.4% and 0.24% lower than when using the central inverter for fixed tilt and single-axis tracking system, respectively. Hence, one might conclude that the string inverter stands out relatively to the central inverter mainly when used in the fixed tilt system.

Through the obtained results, one can conclude that the most suitable solution is the single-axis tracking system rather than the fixed tilted one. Furthermore, it should be employed 176 SUN2000-185KTL string inverters in total, enabling the connection of 8 sub-arrays composed of 280 strings of 29 modules (Hanwha QCells 370W) each. Additionally, the system should use the backtracking strategy as well as the modules disposed in portrait configuration.

4. Conclusions

The main goal of this paper was to maximize the energy output stemming from a $24MW_p$ grid connected solar PV park, having PVSyst software been chosen as the decision support tool software. PVSyst was a crucial tool as it allowed one to run successive simulations for each considered parameter, enabling them to be individually varied. Hence, through an automatic trial-error method, one could perform a sensibility analysis and perceive the influence of each parameter on the energy yield maximization. Additionally, an economical analysis was carried out so that each case scenario viability could be evaluated in a long term period. Initially, all available PV modules were combined with each central inverter so that the most suitable combination module/inverter could be selected based on the energy output. Moreover, two different string inverters (manufactured by Huawei) were also included in the study to assess their possible advantage relatively to the central inverter.

After the modules and inverters have been chosen, two different types of system (fixed tilt and SAT) were considered and significant parameters were varied to perceive how differently each one of them influences the energy output. Regarding the fixed tilt system, the module configuration (portrait/landscape) was analyzed, which allowed one to conclude that, due to the module electric circuit, the landscape configuration leads to slightly greater energy yields on account of near shadings. Concerning the single-axis tracking system, the backtracking strategy was assessed and concluded to be slightly advantageous. The grid energy was obtained for the project's lifetime and it was concluded that, when employing the central inverter and string inverter, the single-axis tracking system produces 15% and 14.3% more energy relatively to the fixed tilt one, respectively. Furthermore, the string inverters led to 3.5% and 2.7% higher energy yields when employed in the fixed tilt and single-axis tracking system, respectively.

The PV park layout was carried out in two different phases. At first, the devices' distribution and connections were undertaken based on the respective modules and inverters' data sheets, which was crucial to properly decide regarding the required equipments' quantity. Secondly, the different equipments were disposed over the available area (AutoCAD), allowing the different cables' lengths to be estimated for each different case scenario. Finally, the cables' sizing was undertaken as well as their prices' estimates, having been prominent for a subsequent economic analysis. The

LCOE was obtained for twelve different cases in which, for both fixed tilt and SAT, all inverters and portrait/landscape configuration were considered.

Throughout this study,a generic method was developed to solve the problem related with the optimization of a utility-scale solar PV park. Specifically, this method was applied in a specific solar park case study, contributing for its performance improvement as well as the choice of the most suitable devices and parameters to employ. Based on the obtained results and among the wide range of possibilities through which this study has came across, one may conclude that the most viable solution is the one employing a single-axis tracking system together with backtracking strategy as well as with the modules disposed in portrait configuration. A comparison between the considered central/string inverters together with an economic analysis has shown that the string inverter (SUN2000-185KTL) is the best alternative to employ as it does not just provide a better price per unit of energy as well as it allows to be easily replaced whenever it is needed.

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A. Appendix (Costs)

	%	€/W_p	Price (€)
PV Modules	51	0.306	7,354,771
Support Structures	7	0.042	1,009,478
Accessories	16	0.096	2,307,379
Central Inverters	9	0.054	1,297,901
Elect. and Mech. Installation	15	0.090	2,163,168
Project and Commissioning	1	0.006	144,211
SCADA	1	0.006	144,211

Table 6: Fixed Tilt components' cost (central inverter and portrait configuration)

	Quantity	Unit Price	Price (€)
SUN2000-105KTL	176	4000	704,000
AC Combiner	88	250	22,000
STS-2500	8	78,000	624,000
SmartACU2000B-D-PID/PLC	8	3000	24,000
One time discount	1	320,000	320,000
Total Cost (SUN2000-105KTL)			1,694,000
Total Cost (SUN2000-185KTL)	112	14437.5	1,617,000

Table 7: SUN2000-105KTL components' costs and both string inverters' total cost

Inverter	Disposition	Price (€)
Central	Landscape	134,600
	Portrait	122,504
String 105	Landscape	262,790
	Portrait	250,694
String 185	Landscape	307,251
	Portrait	295,155

Table 8: Cables' total costs

System	Inverter	€/$W_p(Annual)$	Price (€)/Year
Fixed	Central	0.007	168,246
	String	0.00652	156,637
Single-Axis	Central	0.00714	171,611
	String	0.00665	159,770

Table 9: Fixed Tilt and Single-Axis System Operation and Maintenance Costs