A TOOL TO OPTIMIZE THE LAYOUT OF GROUND-BASED PV INSTALLATIONS TAKING INTO ACCOUNT THE ECONOMIC BOUNDARY CONDITIONS

Bruno Wittmer, André Mermoud
PVsyst SA
Route du Bois de Bay 107, CH 1242 Satigny, Switzerland

ABSTRACT: Current optimization tools and methods for the layout of large PV installations aim at maximizing the yield or the performance ratio of the installation. Nevertheless, there are situations, where the economical boundary conditions, namely the investment and maintenance costs, the availability of surface and the feed-in tariff have an impact on the optimal design choices. We propose a tool which addresses this problem by finding the ground covering ratio and tilt angle that maximize the economic benefits. Furthermore for feed-in-tariffs that vary with the time of the day, the optimization also includes the azimuthal orientation of the collector plane. The method is intended to support PV installation designers in making optimal design choices from an economical point of view. The problem consists in a multivariable optimization, subject to specific boundary conditions. To solve this problem the relative energy yield of the installation has to be known as function of the design parameters. This is obtained with the help of PV simulation software. The proposed tool then offers comprehensive and synthetic views of the economical and design parameters, providing graphs that allow a quick spotting of the optimal choices. After describing the details of the tool, a few typical scenarios will be discussed as examples.

Keywords: Simulation, Economic Analysis, System Performance, Large Grid-connected PV systems, Shading

1 INTRODUCTION

In times, where the costs of solar panels are still dropping, the optimization of a PV installation goes beyond the mere maximization of energy yield. With a decrease of the module prices, other costs like surface and maintenance, play an ever more important role in the cost effectiveness of a PV installation. In order to optimize a PV system, economic figures of merit should be used, which reflect the interplay of costs and benefits properly. In this paper we present a general approach that is meant to facilitate this kind of analysis. The optimization of a PV system design with these criteria and boundary conditions is not a straightforward task. It is a multi-variable optimization with many non-intuitive correlations. Already the question about the best combination of module tilt angle and spacing between module rows has not a general answer, but needs a detailed analysis of the balance between Plane-of-Array Irradiation and shading losses, including electrical effects. If on top of this the price of modules, area and maintenance has to be considered, it is clear that a specialized and powerful tool is needed to get meaningful results.

In our systematic approach, we first define the parameters that should be optimized. They represent the degrees of freedom for the optimization and span up the ‘parameter space’. The next section discusses the variables that are useful for an optimization. We will focus mainly on economic figures, and mention only shortly other possible criteria, like environmental aspects or balancing the load to the grid. Then we will present the simulation of the PV system, which takes as input the optimization parameters, and calculates the yearly energy production. Some guidelines will be given that should be followed to achieve meaningful results. The next section shows, how the output of the simulation is visualized within the parameter space. For more than one dimensional spaces we will use contour plots in which special boundary conditions can also be displayed as curves. With these plots it is possible to identify the optimal design parameters for a given figure of merit. In the last section we will then present some examples to illustrate the analysis method. These include large installations in sheds with a single orientation, an example with self-consumption and installations with two opposite orientations on inclined or flat roofs. Many of the results in this section have general character and can be applied to a wide range of PV installations. A few results are specific to some choices made in the example and this will be mentioned and discussed.

2 PARAMETERS FOR OPTIMIZATION

The two most basic design parameters for a PV installation are the azimuth and the plane tilt of the solar panels. For this study, which focusses on optimization, we will consider installations where these parameters can be chosen within some range. Mostly these are large PV installations organized in rows, which we will also call sheds. For such installations there is a third parameter to be considered, which is the distance between rows, also called pitch.

2.1 Azimuth

The best azimuthal orientation of a solar panel is generally towards the sun position at noon (south on the northern hemisphere and north on the southern hemisphere). This will give the maximum energy yield, and in principle there is not much room for optimization. There may be however reasons to diverge from this orientation, for example to avoid a high production peak at noon, in favor of a broader energy production profile over one day. This will be discussed in the last example of section 6. Sometimes there are also technical constraints to the orientation, when a roof edge is not exactly parallel to the east-west axis, and placing the panels facing south would mean a complication in the support structures. For these cases it is good to understand the relative gain that can be achieved in optimizing the azimuth, so that increased costs can be weighed against potential production gains. Two examples in section 6 will address this question, one for an inclined roof, and one for row-based installations.

2.2 Tilt

The tilt of the solar panels is a very important optimization parameter for row-based PV systems. For a single free-standing solar panel, the tilt which maximizes the energy production depends on the latitude, which defines the solar path. There is also a significant dependence on the sharing between direct and diffuse irradiation, which is specific to the local climate. For shed-based arrangements however, the mutual shading of the rows comes into play, and the optimal tilt will be lower than for a free-standing panel. To find the tilt of maximal energy yield one needs to balance the losses of a less inclined panel against the reduction of shading between rows.

2.3 Pitch and Ground Covering Ratio

The pitch of a shed installation determines, together with the tilt, the mutual shadings between rows. The optimization of these two parameters is therefore strongly correlated. Furthermore, the pitch has a direct impact on the costs of the installation. If a given nominal power is to be installed, then the pitch will determine the surface that is needed to accommodate the solar modules, which comes with some cost. If on the other hand a fixed surface is to be equipped with a PV installation, then the pitch will determine the number of modules. This will drive the costs of the installation as well as the total energy production, and thus the expected revenues. The pitch is therefore the crucial link between the economic variables and the design parameters. Often the density of modules in a PV installation is expressed by the Ground Covering Ratio GCR, which is the total area of PV modules divided by the surface needed for their installation. In regular shed-based installations, this can be expressed by the pitch P and the row width W, as GCR =W/P. The GCR usually takes values between zero and one. In principle it could become larger than one for rows with large tilt that are very close to each other. Since this leads to unreasonable shading losses, this case will not occur in practice. An exception are installations with two opposite orientations, for which an example is also discussed in section 6.

3 Figures of Merit

There are several variables which can be maximized or minimized, to find the optimal configuration of a PV installation. The most basic one is the total energy production E_Grid, and it is in general a good idea to get an overview on how the design parameters influence this quantity. However, as stated in the introduction, this may not give the final answer to the best economic choices. To address this, we need to consider the economic variables linked to the PV installation. These could be for example:

- Levelized cost of Energy
- Internal Rate of Return
- Simple or discounted Payback Time

This list is not exhaustive, there are other variations of the above variables that can in principle be used for optimization (see for example [1]). Furthermore there can also be criteria that go beyond the economic assessment, like environmental impact (CO2 balance) or technical aspects (minimizing the impact on the Grid stability).

In order to compute the economic variables, we need to be able to calculate costs and benefits of the PV system. The costs are subdivided into 2x2 categories. They can either happen only once, for putting the installation into place, or they can be yearly costs linked to operation and maintenance. Both of these categories can be either proportional to the installed power or proportional to the required surface. We assume the revenues to be proportional to the total energy production. This leads to the following list of figures that are needed for the economical evaluation:

- Investment Costs per kWp (mainly modules, supports and inverters)
- Investment Costs per surface (buying of land, reinforcement of roof, etc.)
- Maintenance costs per kWp (replacing of modules and inverters, cleaning of modules)
- Maintenance costs per surface (lease for the area, clearing vegetation, etc.)
- Tariff for selling electricity to the Grid
- Timespan for which the economic analysis is to be performed

Additionally, many economic variables make use of the so-called discount rate d. This number is a measure of the time value of an investment, and is used for example to calculate present values of future payments. There is no general value that can be assigned to the discount rate, it has to be chosen according to specific conditions and investment strategies (see [1]). A common procedure is to take the interest rate for d.

4 Simulation

The strategy for the optimization process starts with the definition of a reference project. For this reference project many simulation will be performed, where the design variables are varied, in order to find the optimal layout. Care has to be taken, to define the reference project in a general way, so that the result can be scaled to different sizes without introducing large errors. Practically this means, that the nominal power should be rather large and that a regular shed geometry is chosen. No detailed shading scenes should be defined for the reference project, as this will not easily scale. Modules, inverters and possibly optimizers, that will be used for the installation should be known and used for the simulation.

For this study we used the software PVsyst Version 6.26, which is a powerful tool to simulate a wide range of PV installations. The PV module used for the simulation is a generic 250W poly-Si panel which follows the typical behavior of this kind of modules. The reference projects in the examples use strings of 16 modules and three strings connected to one 12 kW inverter. The inverter type was also taken as generic, which models typical inverters of this power range. The total number of strings in the reference projects was 720 and 1440. The strings are distributed over 40 sheds, each shed containing up to three rows of modules, leading to a variable shed length. The modules are all in landscape orientation to minimize the shading losses (the bypass diodes connect cells parallel to the long side of the module). The strings do not spread over several rows inside a shed, so that all modules of a string get the same amount of shading (except for the two outermost modules in a row).

In the simulation the electrical effects of the shading are taken into account. To save computing time, the simulation was not carried out in the most detailed option, where the interconnection of every module to every inverter is taken into account. Instead the ‘string’ approximation was used, where the energy production of a string becomes zero, as soon as it is partially shaded. This represents an upper limit to the electrical shading losses. The simulation includes also losses on the diffuse irradiance due to the incidence angle and ohmic losses.

The meteorological input to the simulation is data provided by the Meteonorm software version 6.1. The geographical location is Geneva, Switzerland, at 46.25° northern latitude. When performing the simulations, the so-called ‘batch mode’ was used. In this mode a file containing a list of parameter combinations is supplied to the program, which will execute a full simulation for each combination and store the results. The parameters that were varied for the examples in section 6 are tilt, pitch and azimuth. The simulation is always performed in hourly steps over a full year. The output of each individual simulation is a list of variables describing the losses and intermediate results of the simulation, as well as the final the energy production E_{grid}. For the results that will be shown, only E_{grid} has been used to compute the figures of merit for the optimization.

5 Visualization and Optimization

Once the map of energy yield is known for the different orientations and GCR values of the reference project, one can proceed to the optimization of the PV installation layout. To visualize the optimization process, the figures of merit are displayed against the design variables. The following examples are always for two parameters and the figure of merit will be color-coded in a two-dimensional contour plot. Dark red is used for the highest, dark blue for the lowest value. The optimal point can be either the maximum or the minimum of the plot, depending on the variable under consideration. If more than three parameters would need to be varied, 2D-cuts through the parameter space at the optimal point could be used. In the examples where the shed pitch is varied, the Ground Covering Ratio GCR will be used for the plots instead of the pitch, since the GCR has a more general character and can directly be compared to other PV installations.

6 EXAMPLES

6.1 Optimization of sheds with a single orientation

For the example with single orientation, we assume that there is no need to optimize the azimuth. The panels will be oriented towards sun at noon, to achieve a symmetric and maximal energy yield.

It is less evident, what the best tilt and GCR will be. The GCR will impact on the economic variables, since it will define the amount of space and number of modules that are needed for the installation, both of which are associated to a certain cost. This cost has to be put into relation to the benefits obtained from the energy production, to find the configuration that optimizes the figure of merit.

Maximizing Energy yield

The most basic variable to consider when performing an optimization of the PV installation, is the Energy injected to the grid E_{grid}, which is also referred to as energy yield. The figure 1 shows the calculated E_{grid} for the simulated GCR and Tilt and has been normalized to the maximum value. For this plot the nominal power was kept fixed. The grey line in the plot connects the optimal tilt values for each GCR value. It is intuitively clear that the optimal tilt for GCR zero is the same as for an individual unshaded PV plane. As the GCR increases, the shading losses increase as well, and the best tilt decreases, reaching zero at a GCR of 100%, which means horizontal orientation of the modules.

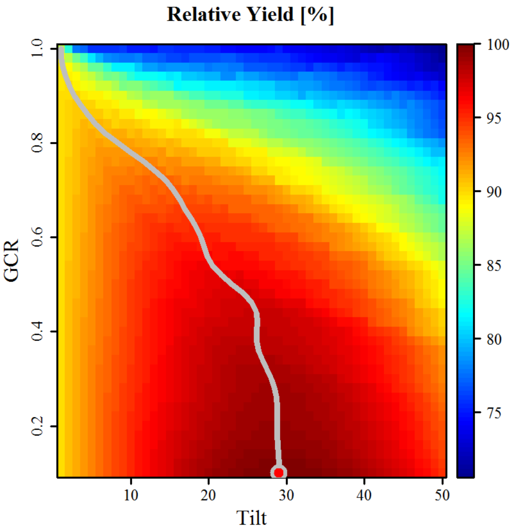

Figure 1: Relative Energy Yield for a shed installation with fixed nominal power as function of Tilt and Ground Covering Ratio

Extreme cases for fixed P_{nom} or fixed area

If only the Energy yield serves as criteria to optimize the installation, then there are two particular cases which are relevant to study. First, one might consider the case where the nominal power is given, and there is unlimited space for building the installation. This has been shown in the plot of the previous example. In this case the optimal solution is to choose the smallest GCR possible, and the best tilt will be the same as the one of a single free-standing PV plane. The second case assumes a limited amount of space for the installation, but unlimited resources to fill this space with solar panels. This case is displayed in figure 2, which was obtained multiplying the Energy yield inform the first example with 1/pitch. This

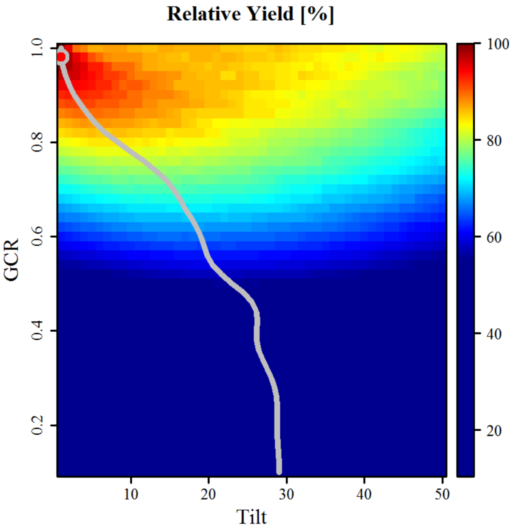

Figure 2: Relative Energy yield for a shed installation with fixed area as function of Tilt and Ground Covering Ratio

transformation will have no effect on the curve of the best tilt values. Now the optimal solution is to go to a GCR of 100% and to install the modules in horizontal position.

These two extremes are idealized cases, which will not be encountered in practice, because even with unlimited surface, it is not practical to build the sheds very far apart. On the other hand, if the surface is limited, one cannot fully cover it, because the solar modules have to be accessible for maintenance and repair. Also a horizontal mounting is not the best solution if soiling or snowfall can be an issue. Finally, adding more and more modules to a fixed surface will lead to ever smaller increases of energy yield, making it at some point uninteresting to invest in more modules for an irrelevant increase of production. In a realistic scenario, the surface and the installation have a cost that needs to be balanced with the revenues obtained from the electricity production. For these cases, the optimal solution will be located in between these two extremes.

Economic Optimization

To identify the optimal design parameters with respect to economic variables, one has to specify the parameters that define the costs and revenues of the system. The costs can be either proportional to the nominal power, or proportional to the used area. Furthermore they can be either nonrecurring, or yearly costs. The revenues are assumed to be proportional to the produced energy E_{grid}, with the feed-in-tariff as conversion factor. On top of this, the timespan for which the optimization should be performed, needs to be known. This is not necessarily the lifetime of the installation itself, it could also be for example the financial horizon of an investor. These inputs already allow a simple calculation of the financial balance, without depreciation or inflation corrections. The result in figure 3 show such a calculation, using the input parameters given in table I, which are meant to be close to realistic values. In the plots we can see, that the optimal solutions for the fixed P_{nom} and fixed area scenarios move to GCR values which are not exactly zero or one. For the fixed P_{nom} scenario this means, that an increase of the area, although increasing also E_{grid}, might not be interesting from the economic point of view, since the additional costs for the surface are not compensated by the additional revenues. For the fixed area scenario, the fact that the optimal GCR is smaller than one, means that it is not always worth adding more solar panels to the installation, because although E_{grid} will also increase, the costs of the additional panels might not get compensated by the additional revenues. It is clear, that the optimal point in these figures is not a general result, but closely linked to the specific economic parameters at the input of the calculation.

Table I: Economic input variables for the examples

	P_{nom}	Area
Investment	1500 $/kWp	8 $/m^2
Operation & Maintenance	29 $ kWp yr	0.03 $/m^{2}yr
Return	0.13 $ / kWh	
Timespan	16 years	
Discount Rate	8.7 %	

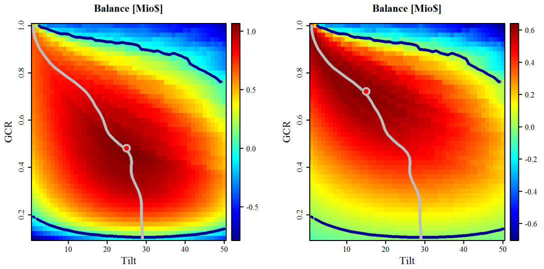

Figure 3: Financial Balance for the installations of Fig. 1 and 2. The optimal design parameters have moved away from GCR=0 and GC =1

It is interesting to note, that even the timespan that is chosen for the analysis, can have an impact on the best choice for the GCR and tilt. Figure 4 shows the results for one and the same system, where only the timespan has been varied from 12 years (top) to 18 years (bottom). The calculation was performed for the fixed area scenario. One sees, that for the shorter timespans a small GCR is preferred, whereas for 18 years, the optimal GCR is close to one. The reason for this is, that the ratio of E_{grid}/P_{nom} is always higher for smaller GCR, meaning that the same number of modules will produce more energy, if they are spaced far apart, and thus minimizing the shading losses. For a fixed area condition, this means that when a small number of modules is placed in the installation, the investment costs are recovered faster, but not much profit will be made after that. On the other hand, placing a high number of modules on the same area, will first lead to a less efficient ratio between installed power and produced energy, because the modules need to be placed at lower tilt angles to minimize the shading losses. This will increase the time needed to recover the investment, but after that point it will also lead to higher profits, which on the long term can outweigh the less efficient energy production. As a general rule of thumb, one can state that optimizing short term returns will neglect future benefits.

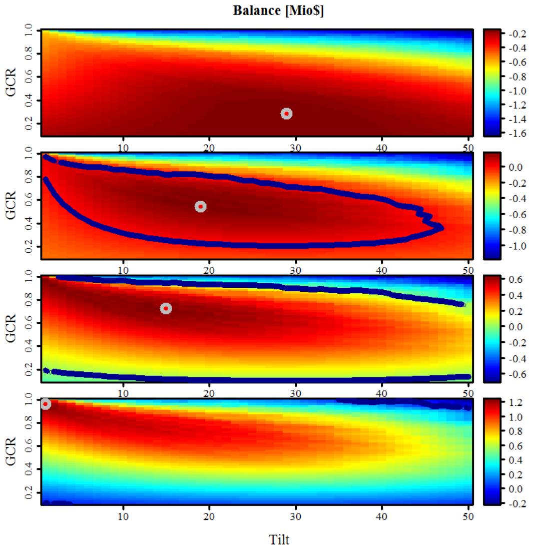

Figure 4: Financial Balance for fixed area but different timespans. The optimal design parameters are a function of the timespan.

More complex economic variables

A simple uncorrected balance like in the previous plots, can be refined by using more sophisticated economic variables. For this it is not necessary to repeat the simulations of the PV system. As long as the quantities can be expressed as functions of the nominal power, the surface and the yearly energy production, one can immediately compute the result, and plot it in the above manner. As an example, we will consider two variables that make use of the discount rate. Figure 5 show the 'Levelized Cost Of Energy' (LCOE) and the 'Discounted Payback Period' (DPB) for the example discussed above. The definitions of these variables follow the US NREL recommendations [1].

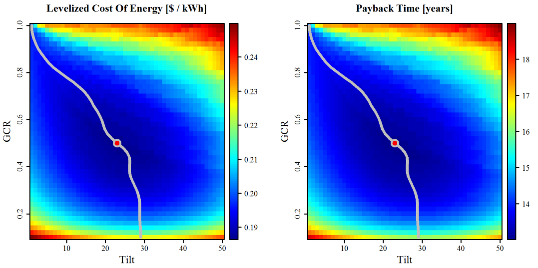

Figure 5: Levelized £Cost of Energy and Discounted Payback Time for the example in Fig. 1.

These two examples are only two out of a long list of possible choices, which includes also 'Internal Rate of Return' (IRR), 'Net Present Value' (NPV), 'Benefit-to-Cost Ratios', to mention just a few. The choice of the variable that is used for the economic optimization of the PV installation will depend on the financial strategy and objectives of the investor. In most cases it is even useful to make an analysis for more than one variable, in order to get a more complete overview of the investment.

Including net metering

A further complication arises for the case where some of the energy that is produced by a PV installation, is directly used by the owner or user. This is the case where for example factories or utilities partially cover their electricity demand with their own PV installation and sell a possible overproduction to the grid operator. This case is called 'Net Metering', and now the optimization will include the balance between the electricity that is consumed directly by the user, the electricity that is injected to the grid, and the amount of electricity that has to be bought from the grid, to fill in the periods where the PV production does not fully cover the user needs. To be able to perform this calculation, the load profile of the user needs to be known. This load profile can either be given as a daily profile that is constant over the year or, in more complex cases, include variations with the day of the week and/or seasonal variations.

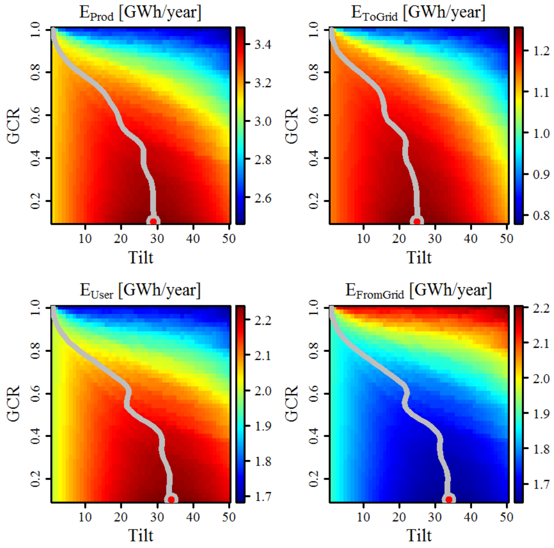

Figure 6: Produced, sold, used and bought energy for an installation with self-consumption. The optimal design will depend on the weight given to each of these components.

As a simple example, Figure 6 show the result for a calculation using a load profile that peaks at noon on working days, is zero on weekends, and that is constant over the year. We note, that the load profile is an input for the simulation, and that for this example the simulations had to be repeated in order to calculate for every hour the energy that is injected to or taken from the grid. The first plot shows the available energy E_{Prod}, which reflects the total electrical PV production of the installation. It is the same as the one in section 'Maximizing Energy yield'. E_{ToGrid} shows the production surplus that is injected into the grid. It becomes highest at rather low tilt angles, which is due to the fact, that the highest instantaneous production can be achieved in summer, where low tilt angles are more efficient. On the other hand, the energy consumed by the user E_{User}, and the energy bought from the grid $E_{FromGrid}$, get maximal for larger tilt angles. The reason for this is, that although a larger tilt angle leads to higher losses in summer, it will be more efficient for energy production in winter. Since in summer there is anyhow a surplus in energy production, the used energy will be maximized for a higher tilt angle. To get the economic optimum, one needs to specify, additionally to the tariff for the electricity injected to the grid, the price that has to be paid for a kWh of electricity supplied by the grid. The optimal solution will not be a general result, but depend on the ratio of these two numbers.

6.2 Optimization for two opposite orientations

Shed Installations

A more and more common practice in PV installations on flat roofs is to place rows of panels in two opposite directions and using a rather flat tilting angle. The idea of this layout is to maximize the GCR while minimizing the support structures and the wind loads. Since by design, the modules of one orientation never produce shades on the ones with the opposite orientation, the simulations of the two orientations can be performed independently from each other, and the results combined. In Figure 7, the top left plot shows the energy yield for a field of regular shed rows. Tilt and azimuth were varied, and the pitch was always such, that a row with same tilt would fit into the space between two sheds. The top right plot shows the same simulation, with the azimuth shifted by 180°. On the bottom we finally see the sum of both orientations. First of all we note, that the energy yield becomes independent of the azimuth, being only a function of the plane tilt. Furthermore, the best tilt is zero, meaning horizontally installed panels produce most energy. This corresponds to a GCR of 100%. This result has been obtained for a rather large installation, in order to minimize the border effects and ensure scalability. For small-sized installations, where border effects may become relevant, the individual shading conditions and space constraints have to be studied.

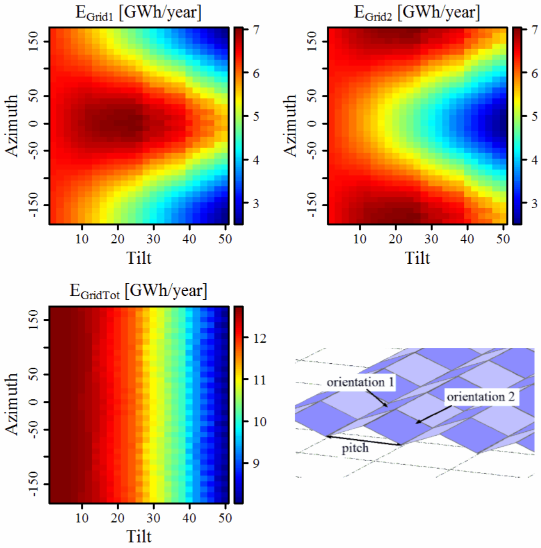

Figure 7: Energy production of a 'dome' installation. On the top the production for each of the two orientations, on the bottom the total production.

Two-Sided Roof

The parameter optimization can also be applied to inclined roof installations, where both sides of the roof are equipped with modules. In Figure 8 the top left plot, shows the side of the roof defining the azimuth. We see that the optimal orientation is towards zero azimuth. The best tilt is around 35° for this example and depends on the latitude of the installation and the sharing between direct and diffuse irradiation, which changes in general over the year. The plot on the top right shows again the energy production for the opposite direction. The bottom plot shows the result, when both sides of the roof are added up. Here too, a lower tilt will always increase the energy yield. In the extreme case of horizontal orientation, as one would expect, the azimuth has no impact on the energy production. When the tilt increases, the best azimuthal orientation is along the east-west direction. This optimum gets more and more pronounced as the roof gets steeper. The azimuthal variation is a function of the latitude and will become smaller as one moves closer to the equator.

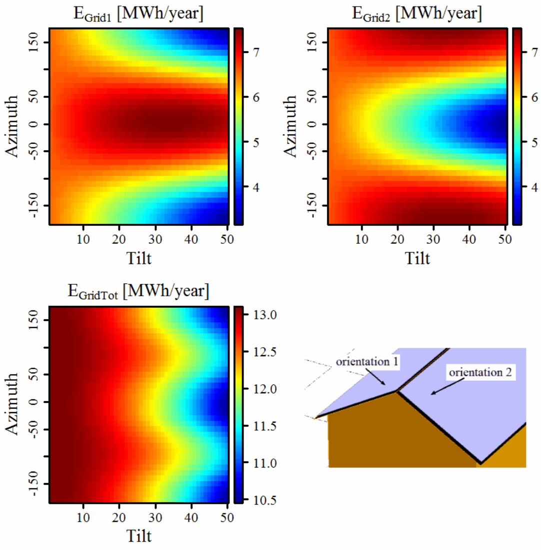

Figure 8: Energy production of a roof installation with two opposite orientations. On the top the production for each orientation, on the bottom the total production.

We conclude, that if the roof is not very steep, the orientation has little impact on the total energy yield, the losses one gets from moving away one of the sides from the optimal 0° azimuth, are mostly compensated by the increase of yield on the opposite side. Of course, such a layout only makes sense, if the space for the installation of modules is limited, since there is always a loss compared to a single-sided roof installation with the same nominal power.

7 CONCLUSIONS

In this paper we discussed a general way to optimize design parameters of PV installations. The optimization is done not by maximizing only the energy yield, but rather looking at more complex economic variables like the cash flow balance, levelized cost of energy and payback time amongst others. Starting from a reference project, a set of simulations is performed where the optimization parameters are varied over a wide range of values. From the results of the simulations, expressed in the energy production, one can compute the variables that are used for the optimization. Plotting these figures of merit in the parameter space quickly identifies the optimal design parameters.

The procedure was demonstrated in several examples, which led to non-trivial results. For example it could be seen that the optimal design parameters can depend on the timespan that is chosen for the economic analysis. Another interesting result is that in shed-installations with two opposite orientations the energy yield does not depend on the azimuthal orientation, and is maximized by a horizontal layout. The example with net metering illustrated, that also the optimal design for a given user load can quickly be identified with these tools. In general, this kind of analysis is very useful to get a quick and thorough understanding of the interplay of design variables and their impact on the figures of merit.

The studies in this paper are based on batch simulations that were performed with the software PVsyst V6.26. It is planned to include the visualization and optimization techniques that were presented here, in one of the next versions of the PVsyst software.

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