

**OPTIMIZATION OF ROW-ARRANGEMENT IN PV SYSTEMS, SHADING LOSS EVALUATIONS ACCORDING TO MODULE POSITIONING AND CONNEXIONS**

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**ABSTRACT:** We present an analysis of the mutual shading effects in PV power plants in rows arrangement (sheds). We identify the main parameters involved in the optimization, mainly the plane tilt and shading Limit angle, and their implication on the plant yield and occupation ratio (or Ground Covering Ratio GCR). We performed a deep analysis of the shading effects of different components (Beam, Diffuse, Albedo and mismatch Electrical effects) over one whole year and observe that the Diffuse and Albedo losses are dominating. The beam loss is very small, and the electrical effects are important essentially with one only string in the width of the rows. This analysis is based on yearly simulations of PVsyst, in Geneva and Sevilla.

Keywords : Shading - Optimization - Modelling - Simulation

1. INTRODUCTION

The row (sheds) arrangement optimization of a PV system is often an open question for practitioners, which is not directly answered by usual PV simulation software. This is an important challenge as this concerns most of the big power plants as well as big rooftop installations.

The difficulty is that this is a multi-criteria problem, which involves several parameters like the optimum energy yield, the power installable on a given area, the weight and cost of the supports, the availability and cost of the area, the technology and arrangement of the modules (mechanical and electrical), as well as some operating conditions like soiling or snow. All these parameters have some influence on two distinct indicators, the foreseen investment and the energy cost, and finally the global profitability of the system.

Many row-like systems are based on an erroneous assumption, that the modules should have a tilt corresponding to the optimal orientation for a collector plane (usually around 30° south in medium-latitude sites). However when taking the mutual shadings into account - and even more with their electrical effects - the optimum tilt for a maximum energy yield is significantly lower than this value. Moreover this optimum is strongly dependent on the azimuthal orientation of the array.

Now the electrical effect of the mutual shadings is dependent on the module arrangement (portrait or landscape), the sub-module distribution (disposition of the set of cells protected by one by-pass diode), the technology (thin-film modules with strip-like cells), the connexion of modules as strings in the row and the number of strings in parallel. This study only concerns Si-crystalline modules (i.e. with PV cells).

Several studies about shadings effects have been published (cf for example Karateppe [2], Spertino [5]), but usually giving results for some types of days, and a restricted set of configuration examples. We have published a previous paper (Mermoud [3]) about the electrical effects of mismatch due to shades.

This study is based on full detailed simulations over one year in realistic climates (Geneva and Sevilla). The main finding is that the shading loss is dominated by the losses of diffuse irradiance and albedo, and the impact of module strings arrangements is studied.

2. – BASIC DEFINITIONS FOR ROWS LAYOUT

Row (sheds) arrangements are characterised by 3 parameters: the row active width **W**, the plane tilt **β** and the pitch **P** between rows. From these parameters we can deduce the Limit angle **LimAngle**, which is the sun's height for which the preceding row begins to produce shades on the next one.

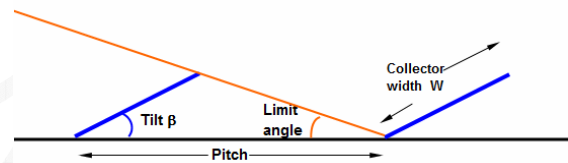


Fig 1. - Basic representation of a row arrangement.

$$\text{LimAngle} = \text{ArcTan} (W \cdot \cos \beta / (P - \sin \beta))$$

The LimAngle is an important parameter of the sizing.

We can also define the Occupation Ratio **OR** which is the area of PV modules installable on a given ground area. Many people also use the Ground Covering Ratio **GCR** which is just its inverse:

$$\text{GCR} = P / W \quad \text{OR} = W / P$$

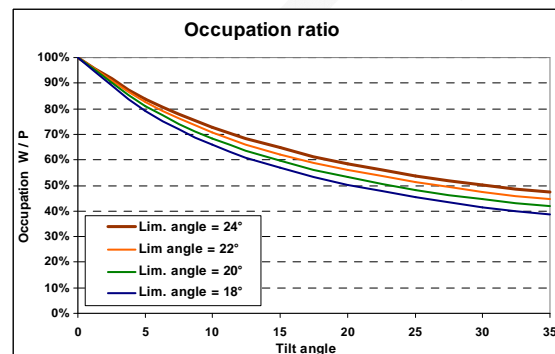


Fig 2. - OR as function of plane tilt

We can observe on fig. 2 that the occupation ratio (or GCR) is essentially determined by the plane tilt, and is very weakly dependent on the limit angle.

### 3. – YIELD OPTIMIZATIONS

Optimization of row arrangement is only pertinent when considering full detailed simulations over one year in realistic climates, using the best models and taking most of the possible perturbations into account. For this we use the simulations of the PVsyst software [ref 6], for the climate of Geneva in Switzerland (middle Europe), and we will also give some equivalent results for a sunny place (Sevilla in Spain).

If we fix a given Limit Angle, we can perform full simulations (over one year) and report the results according to the plane tilt, by respect to the horizontal case.

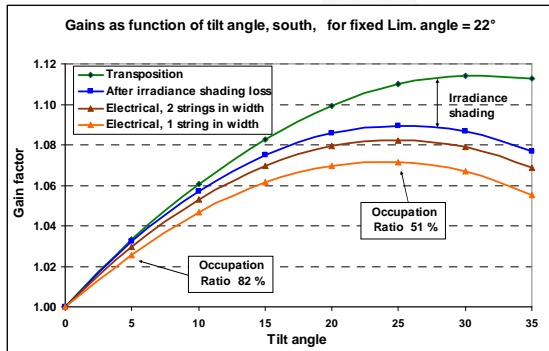


Fig 3. – System gain as function of the plane tilt

The higher curve represents the yield of a plane *without shadings* (for example the first row), which is the optimal tilt for this location and climate.

The second curve is the yield when taking the mutual shading losses into account (irradiance deficit only, named "linear shadings" in PVsyst).

The third one represents the real yield of a system with electrical mismatch losses, where there are 2 different strings in the width of the row, or the last one the same with one only string in width.

We can observe that the **optimum tilt** of the final system is **significantly below** the usual optimal tilt for this site (about 24° against 32°). Then, many power plants have been constructed with the optimal orientation without shadings...

Another observation is that the gain (by respect to an horizontal plane) is lowered by the shadings, passing from 11.5% for the pure transposition to around 7 to 8%, depending on the string connexions.

Finally, increasing the plane tilt strongly degrades the GCR: a tilt of 25° requires an horizontal area about twice the collector area, when with a tilt of 5° it is only 20% more.

This is valid for a south orientation. Now the performances are strongly degraded when the system orientation cannot be chosen facing south. The figure 4 shows that for south-west azimuth (45°), the energy gain (by respect to horizontal) of such configurations becomes almost negligible.

We also notice that in these conditions the optimal tilt drops below 18-20°.

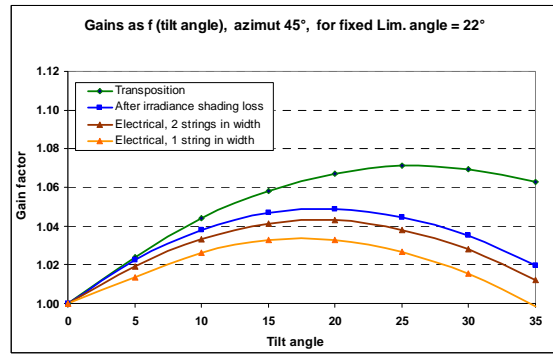


Fig 4. – System optimization with not-south orientation

### 4. – LOW TILT OPTION

The rows arrangement appears to have many inconveniences, for moderate gains by respect to horizontal systems.

Therefore we may wonder whether inclining the modules by more than 2° to 5° is really worth while. In this respect, other considerations should be taken into account:

- The energy gain at 5° is already 2.5%, so that we loose about 5% of annual yield by respect to the optimum.
- But this allows to install a collector area of 80% of the available area instead of 50%. The question arises when the investment may be increased, and will increase the profitability of the system even with slightly reduced specific yield.
- High tilts usually involve more complex and heavy supports (wind sensitivity), which may be a problem on some roofs. Some very simple low-tilt supports are now available on the market. This may also provide a cost reduction.

But:

- Low tilts will reduce the cleaning action of the rain, and may lead to dust and mosses accumulation along the frame if any. For such situations it is advised to use frameless modules (more fragile !).
- The air circulation is not so favourable, and may induce additional efficiency loss due to module's temperature.

### 5. - SHADING LOSS ON BEAM COMPONENT

In spite of a commonly admitted thought, with rows arrangement the effect of shadings on the beam component (i.e. the visible shades on the system) are not very important.

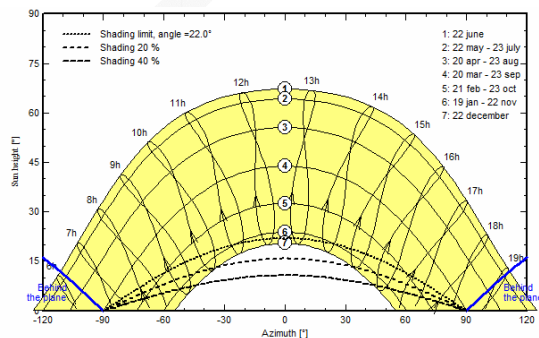


Fig 5. – Mutual shadings for a row arrangement

They occur only in winter months when the sun is low on the horizon. We will see later on (fig 8) that their

contribution is less than 0.3-0.5 %.

6. – SHADING LOSS ON DIFFUSE COMPONENT

In a rows arrangement, the main contribution of the shading loss is the attenuation of the diffuse part of the incident irradiance.

In PVsyst, the diffuse factor is evaluated using the hypothesis that the diffuse is isotropic. That is, we suppose a same irradiance density coming from any direction of the heavens vault. This is a reasonable hypothesis for our shading evaluations.

With this hypothesis, we may calculate the total diffuse irradiance on the PV plane by performing an hemispherical integral of the diffuse flux, over all heaven's directions "seen" by the plane, i.e. the orange slice limited by the horizon and the collector plane.

Now if we define a shading factor SF - for a given sun's position - as the shaded area ratio by respect to the sensitive area - we can calculate the same hemispherical integral and multiply the irradiance by the shading factor SF. This will result in a global shading factor to be applied to the diffuse component. As the sun's position is not involved in this calculation, this is a constant factor over the whole year, and even valid for any site !

Fig 5 shows the shading factor corresponding to a big plant (under "unlimited sheds" hypothesis, i.e. the plant's borders are neglected), calculated for different Limit angles and tilts. This calculation has been done for 10 sheds, with the first shed not shaded.

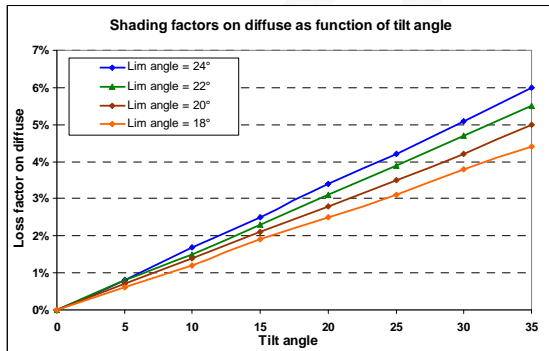


Fig 6. – Shading factor on diffuse

The diffuse component represents about 50% of the yearly available incident energy in middle Europe climates, and still more that 30% in very sunny situations (35% in Sevilla).

As the calculations of fig 5 are "universal", you can estimate the diffuse loss at any place by simply applying the above coefficients to the total amount of diffuse of the meteo data. For example, in Geneva climate (50% diffuse) and optimal tilt of 25°, the diffuse loss on global will be 1.5 to 2.1 % depending on limit angle.

6. – SHADING LOSS ON ALBEDO COMPONENT

The albedo component is null for an horizontal plane, and increases when the tilt increases, proportionally to  $(1 - \cos \beta)/2$  (i.e. 0.067 for 30° and max. 0.5 for a façade). But only the first row "sees" the ground in front of the plant. Therefore the shading factor on the albedo part is  $(n-1)/n$ , where n is the number of sheds: i.e. the albedo contribution is quite negligible in big power plants.

The figure 6 shows the share of the Albedo, Diffuse and Global annual irradiations on a "free" plane as a function of the tilt.

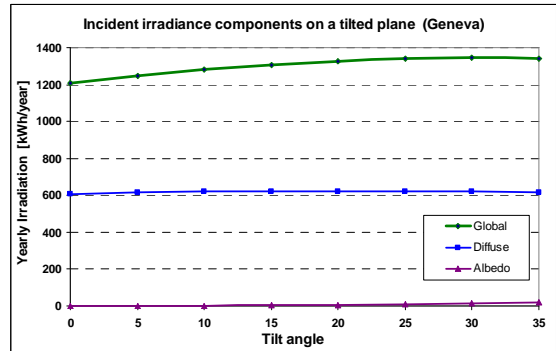


Fig 7. – Irradiance components f(plane tilt)

7. – SHADING LOSS CONTRIBUTIONS SHARES

It is interesting to analyse the different contributions to the shading loss. As shown on figure 7:

- The albedo represents a very little part of the available irradiance, but as it is completely lost, this significantly contributes to the total losses.
- The diffuse contribution has been evaluated previously, and represents about half the losses. It is active permanently, during the whole year.
- The loss on the beam component is attributed to the irradiance deficit due to the "visible" shades produced on the collectors. These occur only in the morning and evening during winter days, and often with not much beam. It represents a surprisingly little contribution of less than 10%.
- The blue line corresponds to the irradiance deficit on the collectors (which is named "Linear Shadings" in PVsyst), before taking the electrical losses into account.
- Finally the electrical losses – due to the mismatch on the I/V curves of the modules – don't represent a major contribution. The module disposition optimizations will only affect this part of the shadings.

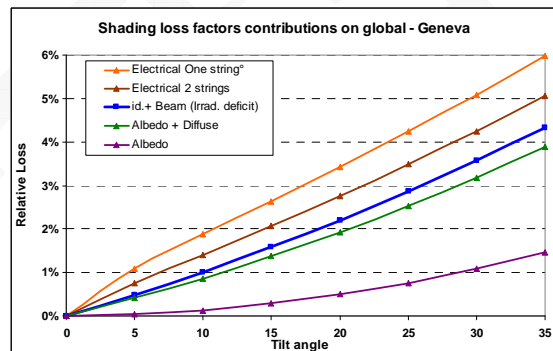


Fig 8 : The different contributions to the shading loss

8. – ELECTRICAL EFFECTS

The preceding calculations have been done using the "unlimited sheds" part of PVsyst, which uses the hypothesis that when the bottom cell is shaded, the whole string doesn't produce any electricity more.

That is, if you have one string in the width of the row, the system doesn't produce anything more except for the diffuse part. If you have 2 strings in the width, the production is limited to the second string until it is attained by the shade.

Let us define a "sub-module" as the set of cells protected by one by-pass diode.

It is a common belief that as there are -say - 3 by-pass diodes in a module, the loss will be limited to 1/3 when the lower sub-module (landscape) is shaded.

This is only (partially) true when you have *one only string* connected to the MPPT. And in this case you will have complementary losses when the string's voltage will go down to the minimum voltage of the MPPT.

When you have 2 strings or more connected in parallel on the MPPT, the production is completely lost as soon as 1/3 of sub-modules are shaded, which is always the case in rows arrangement (see fig 9, from ref [3]).

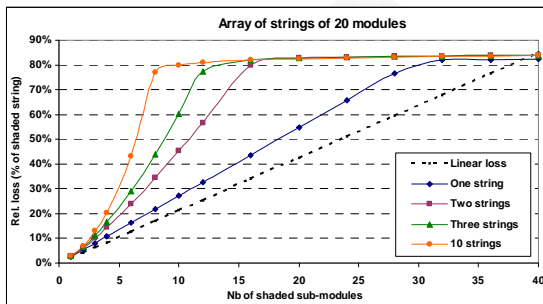


Fig 9. Relative loss, function of shaded sub-modules number.

Therefore the relevant parameter when designing a row system is the *full width of one string* within the row. With big inverters, the loss will be equivalent for one module in portrait, or 2 modules in landscape but belonging to the same string.

9. – ELECTRICAL DETAILED CALCULATIONS

The above conclusions are specific to the Rows arrangement, i.e. where full rows of cells are shaded at a time

In the general case of shadings of near objects:

- The *relative* contribution of the diffuse part is usually much lower, the albedo is not fully occulted,
- The losses on beam component may be significant,
- The simplified calculation of PVsyst "according to module strings" (ref [6]) gives an upper limit to the electrical effect, but no real value.
- The real electrical behaviour has to be evaluated by defining the position of each module of the system, and their detailed string connexion.

This last point is now implemented in the new version 6 of PVsyst, in the "Module Layout" part. The PV modules are positioned on the areas defined in the 3D editor, and each of them should be attributed to a string and an inverter MPPT input.

Then, at each hour step the simulation evaluates the number of cells shaded in each sub-module, and computes the full I/V curve at the input of each inverter.

This process involves the computation of the I/V curve of one sub-module with and without shaded cells (according to the "one-diode" model (Beckman [1] and Mermoud [4])). It performs the addition of sub-module's voltages in each string, and the addition of the currents of each string at the input of each inverter.

Finally the electrical contribution is accounted as an "Electrical Shading Loss" in the array losses, independently of the irradiance losses.

Therefore in PVsyst V6, we have now 3 ways of computing the mutual shadings of row arrangements, each with its own hypothesis:

- The "unlimited sheds" option uses the hypothesis that the rows are of infinite length; the shading calculation is analytical and straightforward, taking the cell and string width into account for the electrical losses.
- The 3D shadings with "module strings" option, i.e. each string is represented by a rectangle, and becomes electrically inactive when a part of the rectangle is shaded.
- The new calculation with module layout, evaluating the electrical behaviour of each array at the input of each inverter.

Let us consider as an example rows with 4 modules (landscape) in the width, and strings of 8 modules in series.



Fig 10. - Some string configurations in a row

For the case A, when the bottom cell is shaded a third of the sub-modules are affected. From fig 9, we can see that with 2 strings or more in parallel the loss is complete. Therefore these 3 calculations should be equivalent.

In the case B, only a sixth of the sub-modules are shaded. The fig. 9 shows that the loss is dependent on the number of strings in parallel. This can only be taken into account by the detailed electrical computation. The other calculations will give correct results for big inverters with many strings.

The case C is analogous to case B, with a higher tolerance to the number of modules in parallel.

Finally with the case D, when putting the modules in portrait all sub-modules will be shaded at a time, and the result should be equivalent to the "2 strings in width" case without by-pass diode recovery.

The table gives the results of the simulations for 3 strings on each inverter input.

Calculation mode:	Electrical loss		Total Loss
	Strings	Mod.Layout	
Case A	0.43%	0.37%	3.77%
Case B	0.92%	0.48%	3.88%
Case C	1.5%	0.57%	3.97%
Case D	0,92%	0.82%	4.22%

Table 1. - Results for then different cases. The irradiance shading loss is 3.4% in all cases.

It should be emphasized that the electrical contribution is low by respect to the total shading losses. Therefore little errors on this evaluation are not critical.

#### 10. – BEHAVIOURS IN SUNNY CLIMATES

We can wonder how these losses evolve with the climate. We have performed the same analysis in Sevilla.

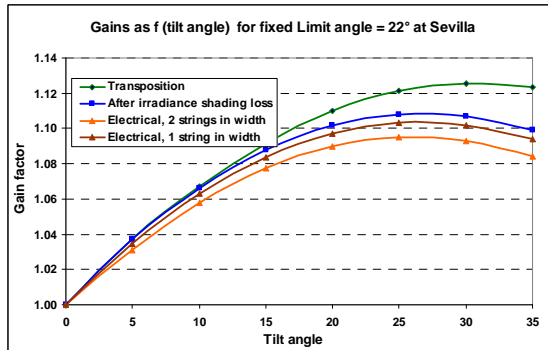


Fig 11. – Optimizations for Sevilla in Spain

We can observe :

- The optimum tilt is 30°, the same as in Geneva,
- The losses are lower, essentially due to the diffuse (same factor applied on 35% diffuse instead of 50%),
- The beam loss factor is identical, but the electrical parts are higher than in Geneva (more beam in winter?),
- Therefore the optimal tilt is higher as in Geneva, around 26°.

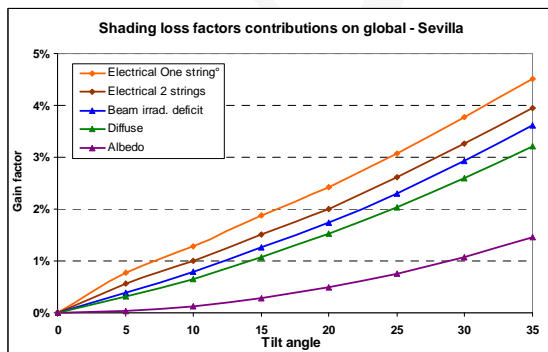


Fig 12. – The different contributions of the shading loss at Sevilla.

#### 11. - CONCLUSIONS

We have analysed the different contributions of the shading losses for PV power plants in row (sheds) arrangement.

The main observation is that - according to our hypothesis of isotropic diffuse - the losses are dominated by the diffuse and albedo contributions.

The loss on the beam component is very small (less than 9% of the total losses), and the electrical mismatch losses represent a third of the total when there is one only string in width, 18% with 2 strings and 9% with 4 strings in the width of the row.

We also confirm that in rows arrangements, when the bottom cells of a string are shaded, the whole string is affected by this shade. With several strings in parallel, it loses the full part corresponding to the incident beam. That is, the by-pass diodes are never operating for the recovery of energy.

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