

## INCREASED ENERGY YIELD OF 50% AT FLAT ROOF AND FIELD INSTALLATIONS WITH OPTIMIZED MODULE STRUCTURES

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**ABSTRACT:** We normally choose a tilt angle greater than zero for photovoltaic modules at flat roof and field installations. This increases the energy yield and decreases the losses due to module dirtying compared to horizontal systems. If we set up the modules in several rows behind each other, there will be mutual shading between the modules when the sun is low. For this reason we can only use a part of the available area at flat roof and field installations. We need a minimum distance between the module rows. In this paper we estimate the losses for different row distances and tilt angles. In addition to that we discuss how to optimize module structures to decrease the losses due to mutual shading. If we use the optimized module structures, we can minimize these losses, we can reduce the distance between module rows and we can increase the energy yield per area up to 50 %.

**Keywords:** PV Module - 1: Module Manufacturing - 2: Roofing Systems - 3

### 1. INTRODUCTION

The loss in performance at partially shaded photovoltaic modules is nearly proportional to the loss at the mostly shaded cell [1]. As a consequence the cells near the ground reduce the performance of the whole system drastically if they are shaded. The energy yield of a photovoltaic system is normally lower than we can assume from the mean solar irradiance. However, at solar thermal systems the loss is directly proportional to the mean irradiance reduction. These advantages of solar thermal systems during the shading case can be transferred to photovoltaic systems as well. We just have to optimize the module structures. By doing so, we reduce the shading losses and we can reduce the distance between the module rows.

The highest shading losses occur if a shadow covers only a part of a pv-module. If a module with crystalline solar cells is shaded at the lower bottom, this has an effect on the whole module, because in all standard modules the cells are connected in series.

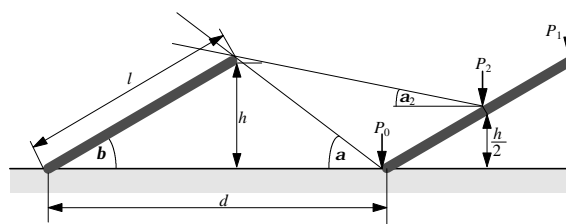
At flat roof and field installations (see Fig. 1) we have mutual shading at the lower cell rows of the modules during the morning and evening hours. Before we can discuss optimized module structures we have to show how to calculate the shading losses.



**Figure 1:** Tilted photovoltaic modules in rows behind each other at a flat roof installation

### 2. CALCULATION OF THE SHADING LOSSES

We have simulated the shading losses of standard and optimized modules with the SUNDI computer program [2]. You can download this program from our Internet server (<http://emsolar.ee.tu-berlin.de>). For the calculations we have assumed that the modules are installed in multiple long rows. Fig. 2 shows the geometry used for the calculations. We have chosen Berlin as simulation location. This means the results of the shading losses are only valid for middle-European sites. The shading losses are less important at locations that are nearer to the equator and more important near the poles.



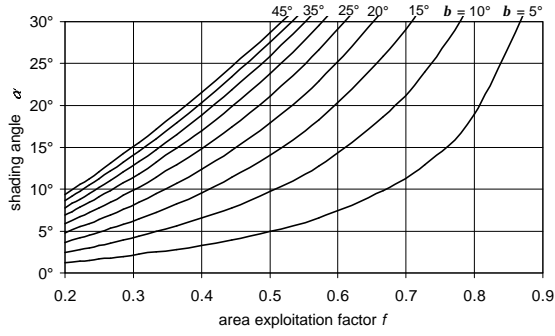
**Figure 2:** Geometry of tilted pv-rows,  $P_0$ ,  $P_1$ ,  $P_2$ : examined points

Using the distance  $d$  and the length  $l$  of the module we define an area exploitation factor  $f$ , according to [3]:

$$f = \frac{l}{d} \quad (1)$$

We choose the three points  $P_0$ ,  $P_1$  and  $P_2$  at the titled module area. The point  $P_0$  is mostly affected by the shading. The shading losses increase with the exploitation factor  $f$  and the module tilt angle  $b$  (see Fig. 3). With the area exploitation factor  $f$  and the module tilt angle  $b$  we obtain the shading angle  $a$ :

$$a = \arctan\left(\frac{f \cdot \sin b}{1 - f \cdot \cos b}\right) \quad (2)$$

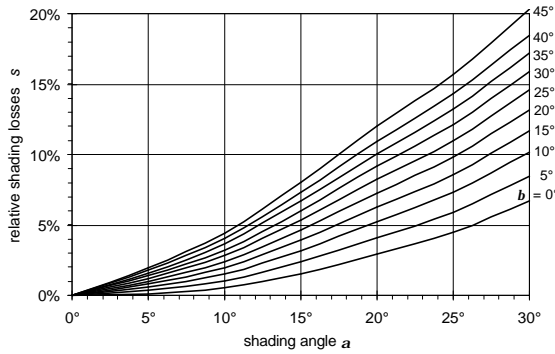


**Figure 3:** Shading angle  $\alpha$  in dependence on the area exploitation factor  $f$  and the module tilt angle  $b$

Using the annual irradiation  $H_\beta$  on a titled unshaded module and the annual irradiation  $H_{\beta,shad}$  on a titled module considering mutual shading, we define the relative shading losses  $s$ :

$$s = 1 - \frac{H_{\beta,shad}}{H_\beta} \quad (3)$$

The shading losses increase with raising shading angle. Fig. 4 shows the relative shading losses  $s$  at the point  $P_0$  for Berlin in dependence on the shading angle  $\alpha$  and the module tilt angle  $b$ .



**Figure 4:** Shading losses at standard photovoltaic systems in dependence on the shading angle  $\alpha$  and the module tilt angle  $b$  for the Berlin location

Photovoltaic systems are extremely sensitive to partial shading. For this reason we can choose the irradiation at the point  $P_0$  as reference for the whole system. Table I shows the shading angle  $\alpha$  and the resulting shading losses  $s$  for  $b = 30^\circ$  and table II the same results for  $b = 10^\circ$ . At a tilted plane we get an irradiation gain  $g$  compared to a horizontal plane due to the better orientation towards the position of the sun. We define the factor  $g$  dividing the annual irradiation  $H_\beta$  on a tilted plane by the annual irradiation  $H_h$  on a horizontal plane.

$$g = \frac{H_\beta}{H_h} \quad (4)$$

With the irradiation gain  $g$  at a tilted plane and the shading losses  $s$  we get an total correction factor  $c$  that

represents the irradiance at the point  $P_0$  compared to an unshaded horizontal plane:

$$c = (1 - s) \cdot g \quad (5)$$

**Table I:** Shading factor  $\alpha$ , shading losses  $s$ , energy gain  $g$  due to the tilt angle  $b = 30^\circ$  and total correction factor  $c$  for standard modules for different area exploitation factors  $f$  (location Berlin)

$f$	$b = 30^\circ$			
	$\alpha$	$s$	$g$	$c$
1:1.5	38.8°	0.246	1.125	0.848
1:2.0	23.8°	0.116	1.125	0.995
1:2.5	17.0°	0.074	1.125	1.042
1:3.0	13.2°	0.048	1.125	1.071
1:3.5	10.7°	0.035	1.125	1.086
1:4.0	9.1°	0.029	1.125	1.092

**Table II:** Shading factor  $\alpha$ , shading losses  $s$ , energy gain  $g$  due to the tilt angle  $b = 10^\circ$  and total correction factor  $c$  for standard modules for different area exploitation factors  $f$  (location Berlin)

$f$	$b = 10^\circ$			
	$\alpha$	$s$	$g$	$c$
1:1.5	18.6°	0.048	1.064	1.013
1:2.0	9.7°	0.015	1.064	1.048
1:2.5	6.5°	0.009	1.064	1.054
1:3.0	4.9°	0.006	1.064	1.058
1:3.5	3.9°	0.004	1.064	1.060
1:4.0	3.3°	0.004	1.064	1.060

If we choose an area exploitation factor less than 0.33 (1:3.0), we only get negligible improvements of the total correction factor  $c$ . If the area exploitation factor is greater than 0.4 (1:2.5), we can increase the irradiation by choosing a lower tilt angle  $b$ . However, if we consider 5% losses due to dirtying at the tilt angle of  $10^\circ$  compared to  $30^\circ$ , we can recommend the tilt angle of  $10^\circ$  only for area exploitation factors greater than 0.5 (1:2.0).

On the contrary, at solar thermal systems the shading losses are not so extreme as at photovoltaic systems. We can choose the mean irradiation at the module area for the considerations here. For the further calculations we examine the point  $P_0$ ,  $P_1$  and  $P_2$ . We have calculated the irradiation at the point  $P_0$ . At the point  $P_1$  there are no shading losses. At the point  $P_2$  we calculate the shading losses with the shading angle  $\alpha_2$ :

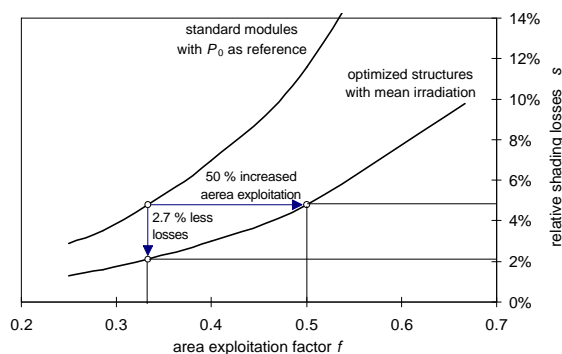
$$\alpha_2 = \arctan\left(\frac{f \cdot \sin b}{2 - f \cdot \cos b}\right) \quad (6)$$

Table III shows the mean relative shading losses  $s_{mean}$  as well as the total correction factor  $c$  of the three points  $P_0$ ,  $P_1$  and  $P_2$ . The losses decrease drastically compared to the losses at the point  $P_0$ . For area exploitation factors less than 0.5 (1:2.0) we only get very small improvements. In other words, at a tilted plane with the tilt angle  $b = 30^\circ$  we get the same irradiation if we choose  $f = 1:3.0$  for a standard system with  $P_0$  as reference or if we choose  $f = 1:2.0$  for a shading tolerant system with the mean irradiation as reference.

**Table III:** Mean shading losses  $s_{\text{mean}}$ , energy gain  $g$  due to the tilt angle  $b$  and total correction factor  $c$  for optimized modules for different area exploitation factors  $f$  (location Berlin)

$f$	$b = 30^\circ$			$b = 10^\circ$		
	$s_{\text{mean}}$	$g$	$c$	$s_{\text{mean}}$	$g$	$c$
1:1.5	0.098	1.125	1.015	0.018	1.064	1.045
1:2.0	0.048	1.125	1.071	0.006	1.064	1.058
1:2.5	0.032	1.125	1.089	0.004	1.064	1.060
1:3.0	0.021	1.125	1.101	0.003	1.064	1.061
1:3.5	0.016	1.125	1.107	0.002	1.064	1.062
1:4.0	0.013	1.125	1.110	0.002	1.064	1.062

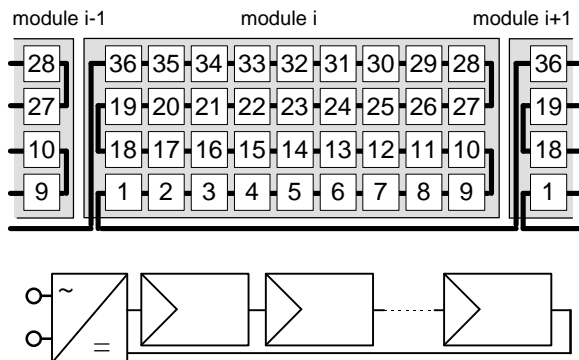
Fig. 5 summarizes the calculations. If we choose a solar thermal system or an optimized photovoltaic system with the mean irradiation as reference instead of a standard photovoltaic system with  $P_0$  as reference, we get the same shading losses as at the standard pv-systems if we increase the area exploitation factor at 50 %. The shading losses decrease if we choose the same area exploitation factor.



**Figure 5:** Relative shading losses  $s$  in dependence on the area exploitation factor  $f$  for standard modules with  $P_0$  as reference and for optimized modules with the mean irradiation.

### 3. PHOTOVOLTAIC SYSTEMS FOR FLAT ROOF OR FLIED INSTALLATIONS

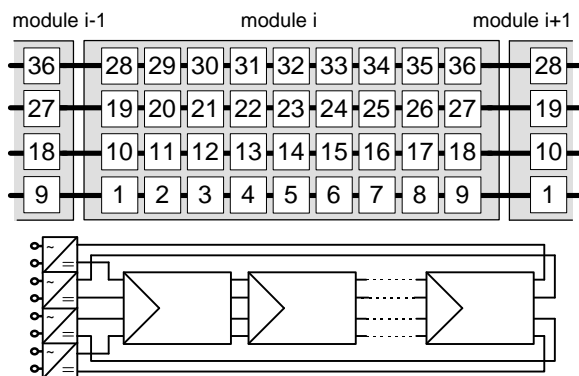
We have shown that we can increase the performance of a photovoltaic if we use optimized modules. Nevertheless, we use standard modules at most photovoltaic system today (Fig. 6). These modules were designed for battery applications in former times. For grid-connected systems we use sometimes larger modules, but the cell interconnection is similar to the standard battery modules in most cases. All cells of the standard modules are connected in series (1 up to 36). If the lower cell row (1 to 9) is covered by shading this has an effect on the whole module. Normally we use a centralized inverter for the standard modules (Fig. 6). We can also use string inverters or module inverters, but this does not improve the behavior during mutual shading.



**Figure 6:** Standard modules with a system inverter

The best system with regard to mutual shading, however, is a large cell with a cell inverter [4]. This is possible with large thin film modules that consists of only one cell, but we have increased inverter losses due to the large voltage difference between the DC and the AC voltage level. If we can solve the technical problems, this system will be without competition.

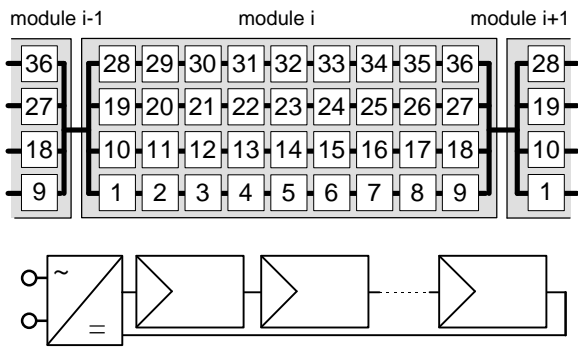
Meanwhile there are other promising solutions that will work with a high efficiency even today. Fig. 7 shows modules with uncoupled cell rows. Every cell row has a separate inverter. This does not mean that we need more inverters in this system. We can connect all cell rows at the same vertical position of the modules that are placed behind each other. However, in this solution bypass diodes are not easy to integrate.



**Figure 7:** Uncoupled cell rows with separate row inverters

Fig. 8 shows a module with parallel connected cell rows. In this solution the risk of cell-damaging due to shading is less important than for the previous system. We can avoid to use bypass diodes. If we want to increase the cell security, it easier to integrate bypass diodes.

The losses in the shading case are a little bit higher than at the system described above, but it is much more shading tolerant than a standard system. We can use the same inverter concepts as for standard systems. We only have to consider that if we have parallel cell rows, the module current will be higher than at standard modules.



**Figure 8:** Modules with parallel connected cell rows

#### 4. CONCLUSIONS

We have calculated the shading losses for standard and optimized photovoltaic modules. The standard modules were designed for battery systems. However, they are used for grid-connected systems as well. At pv-systems for flat roof or field installations the losses due to mutual shading are very high if the module rows are placed near each other. By this reason we only use one third of the available area for setting up modules at middle-European sites.

We have discussed some optimized module and inverter structures for flat roof and field installations. With these module structures only the energy of the part that is covered by the shadow will be lost. We just have to change the cell interconnections to increase the energy yield. If we use the optimized modules, we can decrease the distance between the rows by 50 % and we still get the same energy gain compared to standard modules. This means that we can increase the energy yield at the same area by 50 %.

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