COMPARISON OF PARTIAL SHADING LOSSES IN FREE FIELD PV-PLANTS WITH DIFFERENT ARRAY CONFIGURATIONS

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ABSTRACT: A common problem when planning large free field PV-plants is optimizing the ground occupation ratio while maintaining low shading losses. Due to the complexity of this task, several PV-plants have been built using various configurations. In order to compare the shading losses of different PV technologies and array designs, empirical performance data of five free field PV-plants operating in Germany was analyzed. The data collected comprised 140 winter days from October 2011 until March 2012. The relative shading losses were estimated by comparing the energy output of selected arrays in the front rows (shading-free) against that of shaded arrays in the back rows of the same plant. The results showed that landscape mounting with mc-Si PV-modules yielded significantly better results than portrait one. With CIGS modules, making cross-table strings using the lower modules was not beneficial as expected and had more losses than a one-string-per-table layout. Parallel substrings with CdTe showed relatively low losses. Among the two CdTe products analyzed, none showed a significantly better performance.
Keywords: Shading losses, PV-array configurations, Grid connected PV-plants

1 INTRODUCTION

Near shadings can be one of the main causes for losses in PV-systems. They can in some cases account for up to 10% of the yearly potential [1]. Even with an optimal orientation and inclination of the modules, shading losses cannot be avoided completely in many cases. For free-field PV-plants, the main source of shading comes from the light obstructions caused by front rows onto the rows behind. This type of construction dependent shading can be reduced with an appropriate design of the layout [2].

The present study focused on comparing empirical energy output data of commercially operating free-field PV-plants in Germany. The data collected comprised 140 winter days from October 2011 until March 2012. The selected PV-plants had an installed peak power ranging from 2,38 to 19,48 MWp. In all of the studied PV-plants the terrain is flat with no more than 2° inclination and the racks with the modules are facing south with a tilt of 25°. Due to the different locations and various occupation ratios, the distance between the rows and thus the limiting angles varied among the plants.

1.1 Aims

The objectives of this work were to asses and compare the performance of several PV-arrays configurations installed in commercial free-field PV-plants. It represents an attempt to quantify the shading losses in a real practical case.

Due to the limitations of the project, no differentiation was made between diffuse or beam shading components. However, it was decided to use data from the winter months to emphasize the effects of direct beam shading. The use of central inverters made it not possible to measure the “electrical” MPP mismatch losses of the individual strings as suggested in [3].

2 SHADING LOSSES ON PV-PLANTS

The main source of shading for free-field PV-plants comes from the light obstructions caused by front rows onto the rows behind. This type of construction dependent shading can be reduced with an appropriate design of the layout [2].

The amount of shading a PV-array will receive is determined by several factors. These include: the tilt angle (β) of the rack; the solar Zenith angle (θ_z) depending on the location, the racks’ width (b), and the distance between the rows (d) (see Figure 1) [4].

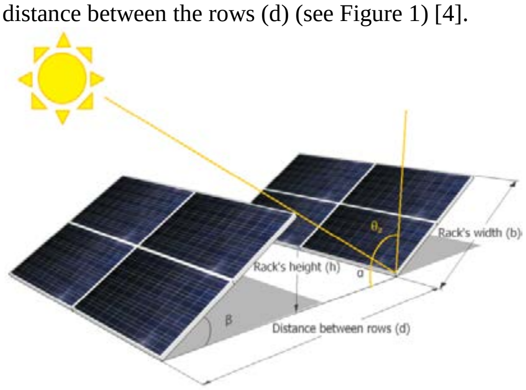

Figure 1: Distance between rows to avoid shadings from front racks

For better results, it is often recommended that the modules remain shade-free at least at noon of the shortest day of the year which corresponds to the Winter solstice, normally on December 21st [4]. To accomplish this, an optimal “no shading distance” can be calculated using Eqn. 1 if a flat terrain is assumed:

$$d = \mathrm{b} \cdot \frac{\sin(90 - \beta + \theta_{Z;\,21^{st}\,Dec,12:00pm})}{\cos(\theta_{Z;\,21^{st}\,Dec,12:00pm})} \qquad \text{Eqn. 1}$$

During planning and construction, the distance between rows is not only decided by the shading angle. Other factor such as land costs; area exploitation factor (f); wind and snow loads; soiling and self-cleaning effect; and material costs play an important role in the design of the layout [5]. Equation 2 can be used to calculate the degree of land utilization as a ratio between the racks’ width (b) and the distance between the rows (d).

$$f = \frac{\mathrm{b}}{d} \qquad \text{Eqn. 2}$$

Once the location of the PV-plant is known, the shading angle for different rack tilts and row distances can be calculated and optimized depending on the other factors such as land costs [6].

3 METHODOLOGY

Five commercially operating free-field PV-plants with different array configurations were selected for comparison (see Table I). The data was collected in 15 minutes intervals throughout the whole period of the study. The electrical (DC) values were measured at the combiner boxes to avoid inverter losses. At each PV-plant, all the selected strings were assumed to be operating under the same conditions (ambient and electrical).

It was assumed as well that all the modules in one PV-plant perform equally at diffuse light and despite that the front rows “see” more of the sky as the back rows, this difference was neglected. Thus when the sun is behind the array or just below the horizon, the PV-modules would be receiving only diffuse light and there should be no difference between back and front rows at these moments. These cases that, under these assumptions don’t affect, can be filtered out by restricting Air Mass values larger than 39 and angles of incidence larger than 90°, since these cases would not cast a shadow and would not affect. Other systematic errors in the measuring and data acquisition equipment were assumed to equally affect both front and back rows. This way, any further difference in outputs between front and back row strings could be attributed to shading losses.

Table I: PV-Plants selected for the partial shadings study

Plant location	Capacity Installed	Modules Area	Modules Used
Bavaria	3,53 MWp	24.770 m²	mc-Si
Bavaria	2,38 MWp	16.985 m²	mc-Si
Saarland	3,35 MWp	23.694 m²	mc-Si
Vorpommern	19,48 MWp	163.916 m²	CdTe CdTe CIGS
Saxony-Anhalt	6,59 MWp	65.679 m²	CIGS

For each plant, several front and rear PV-strings were selected and analyzed. An Analysis of Variance (ANOVA) at 95% level of confidence was done between the two subgroups (front and back row strings) [7]. As they were designed with the same configuration and assumed to be operating under equal conditions, any significant deviation would mean a malfunctioning (e.g. defective module in the string) or other external factor (e.g. a tree’s shading). Thus, strings that evidenced a significant variation were filtered out. Once that statistically similar front and back strings were left, they were averaged and their energy production (E) compared. The comparisons made for this work were:

- Shading losses of arrays with mc-Si modules; comparing portrait against landscape mounting.
- Shading losses of arrays with CIGS modules; comparing arrays where each table is connected as one string against arrays with a lower cross-table-string from table to table.
- Shading losses of arrays with CdTe modules with same mounting layout but of two different electrical specifications.

These comparisons were first done internally for each PV-plant calculating the difference between the unshaded (front) rows and the shaded (back) rows as a percentage. Then, using Eqn.3, the relative losses per installed power were computed and compared to those of the other PV-plants. These shading losses are strictly valid only for that particular location but can be still be used to get an idea of relative losses an array can have. They represent the losses compared to a hypothetical ideal layout when all the arrays are in a shadings-free front row.

$$E_{losses,rel} = \frac{(E_{front} - E_{rear})}{kWp\ installed} \qquad \text{Eqn. 3}$$

First, the energy output of a single sunny day in November 2011 was analyzed to obtain an estimation of a worst case scenario: a sunny winter day with beam shadings. The relative losses (Eqn. 3) were calculated for each 15 min. interval and then added for that day. Then, using the same procedure, the relative losses for each of the 140 days were computed. In the configurations where more than one strings per table, the losses were first calculated independently for the upper and bottom strings. Then they were combined to obtain the result of whole rack. The more sunny days that the winter had, the more days with direct beam shading there would be.

4 RESULTS

4.1 Portrait mounting of mc-Si PV-modules

The mc-Si modules used in the PV-plants here studied are internally divided by three bypass diodes in three sub-strings of cells. In the case of the portrait mounting, the shadow of the front rows obstructs the light simultaneously for the three substrings. This causes the whole module to underperform and to have considerable high shading losses. It is not until the complete module is unshaded that the cells start producing energy at normal levels.

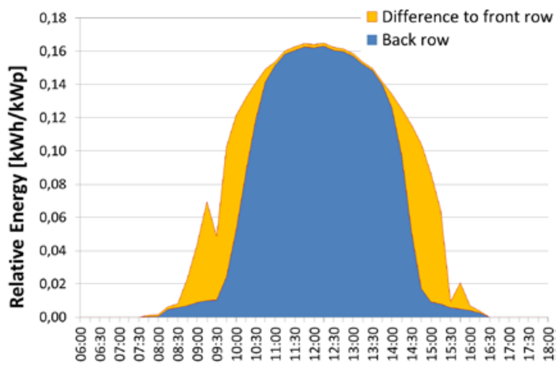

Figure 2: Shading losses for one day at *Bavaria 1*

In Figure 2 there are clear bends in the relative energy production of the back row. In the morning and afternoon, the bottom cells of all substrings in the module are shaded so the complete energy production is reduced.

Table II: Summary of results

Module type	Array type	Rack Width [m]	Rack tilt	Zenith angle	Optimal pitch [m]	Actual pitch [m]	Area exploitation	One day rel. losses		140 days rel. losses (13.Oct.11 - 01.Mar.12)	
		(b)	(β)	($\theta_{z;\ 21st\ Dec,\ noon}$)	($d_{optimal}$)	(d_{actual})	(f)	(%)	[kWh/kWp]	(%)	[kWh/kWp]
mc-Si	2 x 11 portrait	3,28	25°	71,21°	7,07	7,38	0,44	21,70%	0,74	12,40%	31,49
mc-Si	2 x 11 portrait	3,28	25°	71,47°	7,12	7,12	0,46	32,30%	1,15	14,30%	34,1
mc-Si	4 x 11 landscape (2 strings comb.)	3,97	25°	72,93°	9,08	8,32	0,48	6,90%	0,23	4,30%	9,12
	2x11 landscape (upper string)							*-0,30%*	*-0,01*	*0,30%*	*0,62*
	2x11 landscape (lower string)							*14,20%*	*0,47*	*8,30%*	*17,62*
CIGS	5 x 7 (1 string per table)	3,73	25°	75,36°	9,45	9,45	0,39	14,10%	0,42	5,60%	11,77
CIGS	5 x 8 (cross-table string combined)	3,73	25°	77,37°	10,47	8,41	0,44	23,20%	0,52	12,00%	21,22
	4x8 landscape (upper string)							*12,10%*	*0,27*	*9,00%*	*15,85*
	1x32 landscape (cross table string)							*67,30%*	*1,5*	*24,10%*	*42,68*
CdTe 1	5 x 10 (parallel strings)	3,29	25°	77,37°	9,42	7,56	0,44	12,30%	0,28	4,80%	7,75
CdTe 2	5 x 14 (parallel strings)	3,29	25°	77,37°	9,42	7,56	0,44	13,00%	0,29	5,00%	9,14

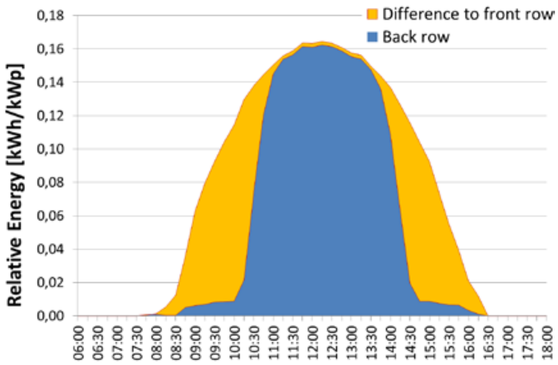

Figure 3: Shading losses for one day at *Bavaria 2*

Similar to the results in *Bavaria 1*, Figure 3 evidences high shading losses for the PV-plant *Bavaria 2* at the beginning and end of the day. In this case there is also clear bends in the relative energy production curve of the back row. These similar results in both PV-plants confirm the problematic of the portrait mounting and its inadequacy for mc-Si modules in free field plants.

4.2 Landscape mounting of mc-Si PV-modules

Installing the mc-Si modules horizontally (landscape mounting) has the advantage that the substrings can start working earlier even if part of the module is still shaded. At the end of the day, this results in higher energy production.

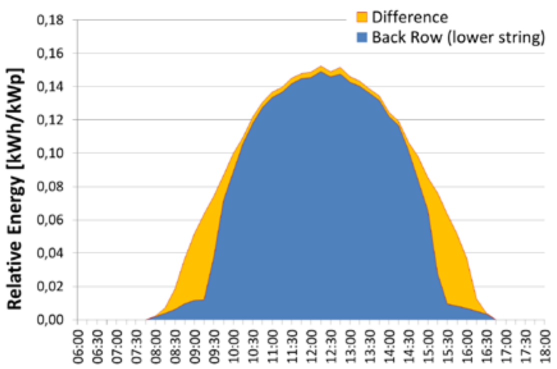

Figure 4: Shading losses of bottom string for one day at *Saarland*

After analyzing the shading losses of the lower string for one day in the landscape mounting arrangement (see Figure 4), one can also observe the bend in the curve due to the bypass diodes. Nevertheless, the bend occurs much earlier in the day as in the portrait arrangement and the change is not so abrupt. This is due to different substrings starting to generate energy one by one as they become unshaded and not all at the same time.

Despite the shadings, the lower-back rows have around two thirds of the losses of the portrait array because one of the substrings still works even when the others are not. The landscape orientation of the mc-Si modules profits from the bypass diodes decreasing its shading losses.

When combining the shading losses of the upper and lower strings as shown in Figure 5, it is possible to observe that they are considerably reduced. Since the upper-back rows are completely unshaded during the whole year, they produce as much energy as the front rows. At the end, the combined losses of the landscape array configuration during the winter (see Table 2) account for approximately one third of the total losses of the portrait arrangement in the same period.

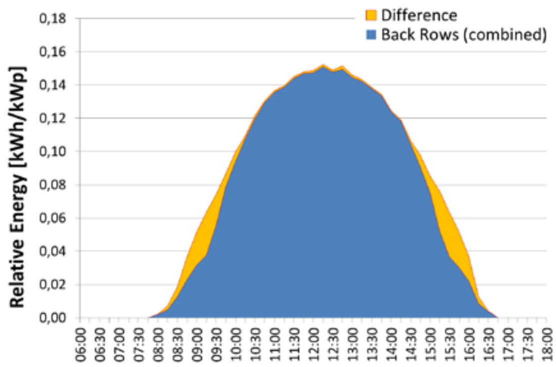

Figure 5: Shading losses of both strings combined for one day at *Saarland*

4.3 One string per table using CIGS PV-modules

The CIGS modules studied are internally connected in two parallel substrings of cells. This configuration yields a losses pattern similar to that of the mc-Si modules. The sudden bending in the curve shows when one of the substrings changes from being unshaded to shaded reducing drastically its energy production.

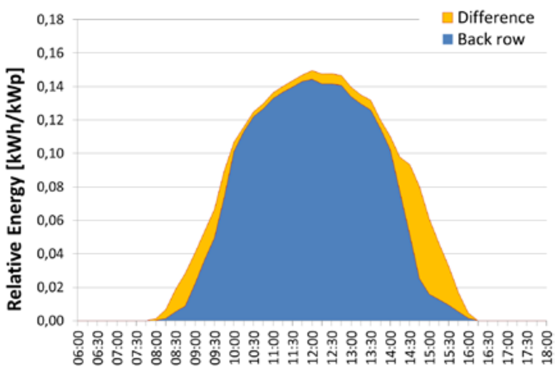

Figure 6: Shading losses for one day at *Saxony-Anhalt*

The higher losses in the afternoon could be due to a light inclination of the terrain. The same effect was observed in the energy production of several arrays located throughout the plant during the whole winter. Determining the concrete cause for this difference between morning and afternoon was outside the scope of this project.

4.3 Cross-table bottom string using CIGS PV-modules

When designing the CIGS arrays at *Vorpommern* a different solution was attempted in which the rows distance could be decreased but maintaining the shading losses low. The upper modules were connected similarly to the *"one-string per table"* configuration, while the lower modules of four adjacent tables were connected to form a cross-table string (see Figure 7).

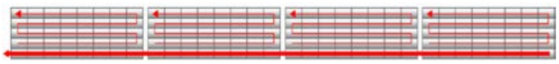

Figure 7: Bottom cross-table string configuration used in *Vorpommern*

Despite these efforts, this strategy did not bring the benefits expected. The shading on the lower string reduces considerably its output (see Figure 8). The fact that during noon the energy generated only reaches half the level of the unshaded front strings indicates that at least one substring of the modules is constantly shaded. This means that throughout the whole winter, the modules on the bottom row are only working at half or less of their capacity.

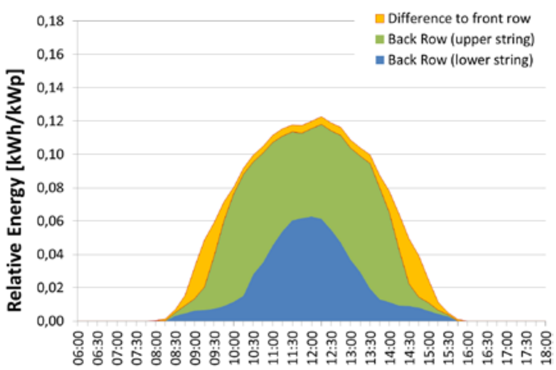

Figure 8: Shading losses of each string for one day at *Vorpommern*

The upper row has noticeably less losses but still has a lower energy output than the front strings. The bend in the curve of the upper-back row during morning and evenings evidences the existence of partial shadings (Figure 8). This could be consequence of having decreased the row distance too much. As with the case of *Saarland*, the upper string should remain shadings-free to be able to compensate for the losses of the bottom string. The losses of the upper string and the constant shading of the bottom string make the overall result worse than the alternative of *one-string per table.*

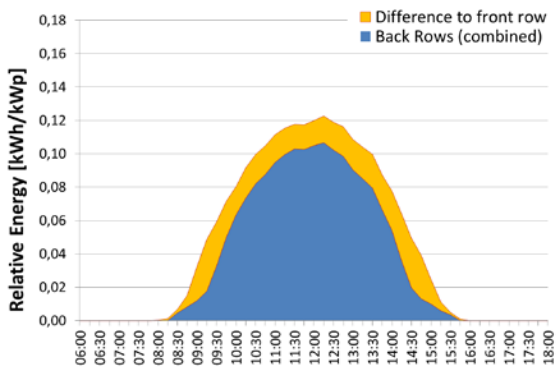

Figure 9: Shading losses of both strings combined for one day at *Vorpommern*

It is important to consider that the plant configuration plays an important role and the results have to be examined carefully. The row distance in this PV-plant is significantly shorter than the optimal and thus the lower string is constantly shaded during the short winter days. Also, due to the shorter row distance, the upper row is also partly shaded in the morning and evenings. This results in much higher losses that the upper row cannot compensate.

4.4 Parallel sub-strings using CdTe PV-modules

There was no significant difference observed for the two CdTe arrays studied. The parallel sub-strings system here used with both product generations proved to have one of the lowest relative losses. This is due to the fact that only the part or sub-string that is shaded is affected but the rest continues to generate energy normally.

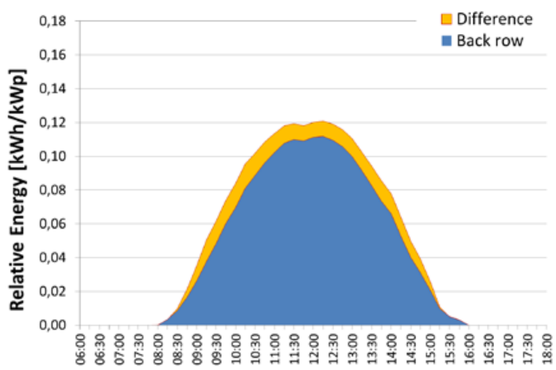

Figure 10: Shading losses for one day at *Vorpommern – CdTe 1*

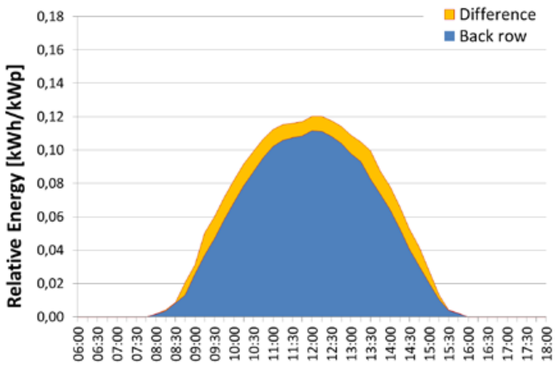

Figure 11: Shading losses for one day at *Vorpommern – CdTe 2*

5 SUMMARY

The relative energy production of front (unshaded) and back (shaded) rows of several grid connected PV-plants was compared. Since back and front rows were under the same conditions and constructed with the same configurations, it was assumed that no other source of variation existed. Thus, any difference in the output was due to the partial shadings. Data filters were used mainly for sorting out the unnecessary data points where no shadow could be projected on the modules. This corresponds to the Sun being below the horizon (AM ≤ 40) or being behind the plane of the PV-modules (Angle of Incidence ≥90°).

The landscape installation for mc-Si modules proved to be significantly better than the portrait one. This is mainly due to the use of bypass diodes in the PV-modules and the internal connection of the cells in substrings. Portrait mounting of standard mc-Si PV-modules in free-field PV-plants should be avoided due to the partial shadings coming from the front rows. In case of different internal connections, the arrangement of the cells substrings should be studied first in order to avoid having all the substrings simultaneously shaded.

A high sensibility to shading was observed at the CIGS arrays analyzed. Shortening the row distance and dividing the bottom row to form a cross-table string that concentrated all the shading losses did not bring the expected results. Since the distance was reduced considerably compared to the ideal, also the upper string was shaded during the morning and afternoon. At the end, the losses of the bottom string were too high to be compensated by the upper strings which also presented output reductions. From the results of this study, it was concluded that the *no-shading distance* should be respected and kept when using these specific modules with this particular array arrangement.

The CdTe arrays evaluated were connected in five parallel horizontal substrings. This layout used seemed to be working properly keeping the shading losses relatively low. Besides, no considerable difference in the performance under partial shadings was observed between the two product generations.

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