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HOT-SPOT ENDURANCE TEST
MODIFICATIONS FOR BIFACIAL PHOTOVOLTAIC MODULES

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ABSTRACT: This paper aims at identifying suitable procedures for hot-spot endurance tests on bifacial PV modules. Drawing on the relevant background, i.e., normative requirements and available studies, it considers existing theoretical models and procedures for their application on bifacial modules. The resulting assumptions are subjected to experimental tests on four modules and in three approaches varying in their irradiance of module sides as well as location and degree of cell shading. In a second cycle, the first two approaches were repeated with extreme variations in irradiance level foreseen by the standard IEC 61215-2:2016. As it turns out, worst-case hot-spot temperatures appear in all three approaches, indicating a necessity for comprehensive testing. However, worst-case hot-spot temperatures are highly sensitive to irradiance intensity in general to an extent that may affect their passing or failing a hot-spot test, even if the test is done within the specified range of 900 to1100 W/m². It is therefore advised to reconsider the currently permitted leeway in equipment precision for both bifacial and conventional monofacial modules.

1 MOTIVATION AND BACKGROUND

Bifacial solar modules can operate at higher currents compared to conventional modules as they use irradiance from both their front and rear sides. However, the electrical point of operation of single modules or cells can vary in a wider range, as more factors influence the overall irradiance. Thus, bifaciality presents particular challenges of its own not only for the system layout but also with regard to reliability. This paper addresses the behavior of bifacial PV modules under inhomogeneous illumination, especially under partial shading. The results and findings are based on a series of shading experiments on several commercially available bifacial modules. The major aims of this study are to

- contribute to the adaptation of important testing standards (IEC 61215-2:2016 and IEC 61730-2:2016) for bifacial modules
- enhance the general understanding of the behavior of bifacial modules under inhomogeneous front or rear side illumination.

2 THEORY

2.1 Focus of hot-spot testing acc. to IEC 61215-2:2016

Almost every PV module type commercially available on the world market has been tested according to the hot-spot endurance test described in the above-mentioned quality standard.

The purpose of the hot-spot test acc. to IEC 61215 is to “determine the ability of a module to withstand hot-spot heating effects, e.g. solder melting or deterioration of the encapsulation. While absolute temperature and relative power loss are no criteria of this test, the most severe hot-spot conditions are utilized to ensure safety of the design.” [1] In fact, the idea of the IEC hot-spot test is to check whether the module suffers substantial damage under <u>worst-case</u> shading and operation conditions. While the exact temperature of the hot spot is irrelevant, the electrical safety must not be negatively affected.

Experience in hot-spot testing at Fraunhofer ISE showed that critical damages that may result in the module failing the standard requirements are caused by temperatures between 160 °C and 200 °C for typical glass/backsheet PV modules. The exact value is of course strongly depending on the specific materials used.

To obtain the worst-case hot-spot condition, the standard requires operating the module in short circuit at 1000 ±100 W/m² while particular ambient conditions (T_{amb}, wind) assure that the module temperature (T_{mod}) is kept stable at 50 °C ± 10 K [1]. The shading situation leading to the highest temperature is determined and maintained for one hour.

As the amount of dissipated energy grows approximately linearly with the increase in irradiance (see Figure 1), it is important to point out that the permitted ranges for irradiance (±100 W/m²) and module temperature (±10 K) can lead to significant variation in hot-spot temperatures even within the allowed limits for the equipment.

Side note: In real PV module operation such worst-case operation conditions are quite rare, while minor temperature differences between 15 and 25 K relative to the average module temperature are much more common. These situations do normally not lead to fatal module defects, but even minor over-temperatures can be relevant with regard to long-term stability due to the influence of temperature on chemical degradation [2]. Therefore, in practice it is desirable to avoid local overheating.

2.2 Development of local overheating

Hot spots occur if for any reason the short-circuit current of a cell is reduced to a level below the string operation current. This may happen due to shading or as a consequence of cell defects, such as deactivating cell cracks. In this situation, the cell with the reduced short-circuit current operates in reverse bias and dissipates energy in form of heat.

The amount of dissipated energy depends on the reverse characteristic of the shaded cell, the overall irradiance on the module, and the point of operation of the unshaded cells. Figure 1 shows the simplified I-V curve of a cell string of 20 cells with one cell shaded to receive reduced irradiance relative to the other cells (50 and 80 %), and with the shaded cell assumed to have high (upper graphs) and low (bottom graphs) shunt resistance, respectively. The model illustrates that the amount of dissipated energy strongly depends on the reverse characteristic of the shaded cell as well as the current of the shaded and unshaded cells. Furthermore, it can be seen that the likelihood that the shaded cell is pushed into reverse bias is much lower when an external load is connected, which reduces the current.

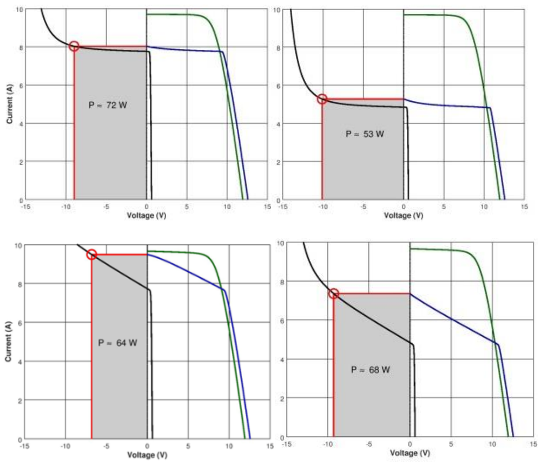


Figure 1: Simplified I-V curve of a cell string of 20 cells with one cell shaded to 80 % (left) and 50 % (right) irradiance compared to the others, with the shaded cell assumed to have high (top) or low (bottom) shunt resistance. Legend: **Green**: unshaded cells; **Black**: shaded cell; **Blue**: resulting curve; **Gray** area: dissipated energy

In addition to the above-mentioned factors, which influence the dissipated energy, local shunts play an essential role for the actual temperature of a hot spot. According to testing experience of the TestLab PV Modules at Fraunhofer ISE, the most critical hot spots typically occur on cells which have areas with relatively low shunt resistances. In these cases, the highest temperatures are not necessarily measured under the shading condition with the highest total amount of dissipated energy, but in conditions where the dissipated energy is most concentrated on a small spot of the shaded cell.

2.3 Considerations for bifacial modules

For bifacial modules, the first question is if and how the additional light from the rear can be factored in to an adapted test procedure. Following the purpose of the current standard, to obtain the worst-case condition the first consideration concerns the irradiance reaching the module.

For instance, it could be assumed that 20 or 30 % of the front irradiance reaches the module's rear side due to a reflecting environment. Typically, the values may be a lot lower in practice. However, in case of an extremely reflecting environment even higher reflection rates may be possible. Adding 20 % to 1100 W/m² (max. allowed irradiance for testing monofacial modules) would result in a total irradiance of 1320 W/m² for a bifacial test. Assuming 30 %, the irradiance would rise to 1430 W/m², respectively.

The second consideration refers to size and position of the shaded area. As shown in Figure 1, both the overall irradiance and the difference in irradiance between shaded and unshaded cells substantially affect the dissipated energy. However, in terms of the resulting hot-spot temperature the size of area dissipating this energy matters strongly, which is exemplarily illustrated in Figure 2 for a bifacial cell shaded either 100 % from the rear side or 20 % from front side. In case of 100 % rear side shading, the whole cell heats up, in case of 20 % front side shading mainly the unshaded area (80 %) heats up. Respectively different temperature values are expected in both cases.

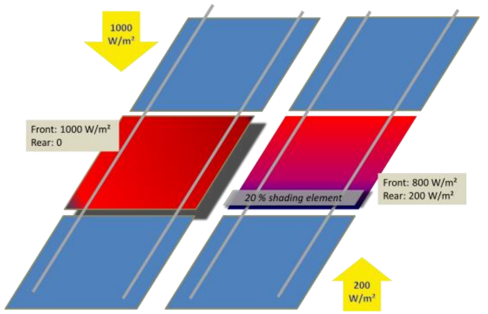


Figure 2: Schematic representation of a shaded bifacial cell. Left string: the rear side of a cell is fully shaded; right string: the front side is 20 % shaded. Assuming a bifacial factor of 1, the amount of dissipated energy is similar in both cases.

Last but not least, it has to be considered if and how design elements, e.g., junction boxes or frames, which may continuously affect the overall irradiance reaching the cells, should be taken into account.

3 EXPERIMENTAL PART

3.1 Testing environment

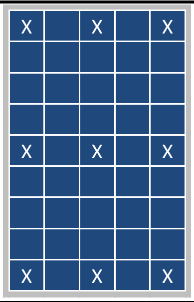
To analyze the influence of shading on bifacial modules, four samples have been exposed to artificial sunlight in a combined climate chamber and steady state solar simulator (Figure 3). The device guarantees comparable conditions in terms of temperature and illumination throughout the experiments. Furthermore, the intensity of the irradiance can be varied between 80 and 100 % by dimming the lamps.

Figure 3: Test setup with mounted module

The modules are mounted in the center of the chamber. By mounting highly reflective cloth on the chamber's rear side, floor, and ceiling, the light passing the module laterally, at the top and the bottom is reflected to the rear side of the module, allowing partial rear-side illumination between 17 and 20 % for full size modules. Table I shows the distribution of rear side illumination over a PV module.

Table I: Irradiance measured on nine positions of the module surface (front and rear sides) after being mounted in the climate chamber

Measurement position	Irradiance [W/m²]	
	front	rear
Top left	1074	200
Top middle	1113	187
Top right	1076	181
Center left	1118	230
Center middle	1113	199
Center right	1109	198
Bottom left	1169	197
Bottom middle	1118	199
Bottom right	1171	200



Thin cardboard pieces (thickness 2 mm) were used as shading elements. The same material was used to shade the entire rear side of the module in approach 1.

3.2 Results

Four bifacial PV modules of two different manufacturers were used for the experiments. All modules consist of a 60-cell design of similar size. The following table shows an overview of the samples and their ID.

Table II: Test modules and their characteristics for monofacial front and rear side irradiance

ID	Type	P_{max} [W] front/rear	I_{sc} [A] front/rear	Bifaciality I_{sc}/P_{max}	Remark
M01	A	266/159	9.12/5.28	0.58/0.60	mono
M02	B	268/207	9.07/7.17	0.79/0.78	poly
M03	C	242/186	8.72/6.57	0.75/0.76	mono
M04	D	266/159	9.12/5.28	0.58/0.60	mono

Experiment I – Three approaches to illumination and shading

The four modules were exposed to controlled irradiance and temperature conditions by means of a solar simulator integrated in a climate chamber. Due to modified reflective properties of the inside of the climate chamber they could be illuminated from both sides as shown in Table I. A hot-spot test similar to IEC 61215-2:2016 was conducted under three different shading conditions and irradiance settings. In the following, they are referred to as "approaches" (see Table III).

Table III: Three different irradiance / shading combinations applied on bifacial modules in the conducted hot-spot endurance test

Approach	Irradiance on front side	Irradiance on rear side	Shading of individual cells
1	100%	0%	on front side
2	100%	~20%	on front side
3	100%	~20%	on rear side

In a first step the cells with the lowest shunt resistances were determined by fully shading the cells one by one and measuring the I-V characteristics of the module. The shape of the curve indicates low or high shunt resistance. (Cells with local shunts are able to carry higher current in a fully shaded situation).

As it turned out, none of the modules and cells under review exhibited low shunt resistances. This fact is relevant to the interpretation of the following results.

The following graphic (Figure 4) exemplarily shows the selection of cells of one of the tested modules (M02). As can be seen, none of the shaded cells carry a high current in shaded condition, i.e., none of the shaded cells has low shunt resistance.

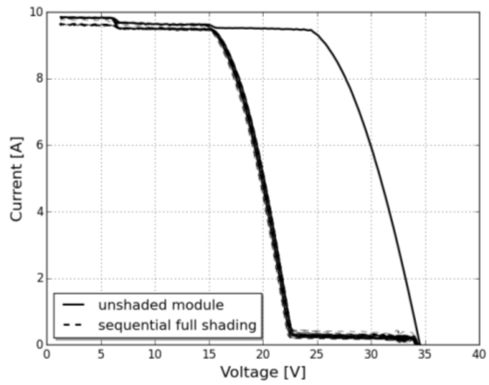


Figure 4: Exemplary I-V curves of a module with fully shaded cells and none of the cells indicating low shunt resistance.

In a second step, the worst-case shading situation was identified for three cells per module. This was done by varying the degree of shading while the module was short-circuited. The maximum temperature was measured with an IR camera.

The following graphics (Figure 5 to Figure 7) show the maximum temperatures vs. the respective degree of shading of the tested cells and modules for each of the testing approaches. Figure 5 represents approach 1, Figure 6 approach 2, and Figure 7 approach 3, respectively. As no low-shunt resistance cells could be detected on any of the modules, the findings correspond to theoretical assumptions that in case of high-shunt resistance cells the worst-case shading situations appear at lower degrees of shading (< 40 % in approach 1; < 60 % in approach 2). In approach 3, an energetically similar situation results from a higher degree of rear side shading.

Table IV shows the highest measured hot-spot temperatures for each module and approach. Unexpectedly, for M01 the highest overall temperature was measured in approach 1 (without rear side illumination). Also, for M02 and M04 the temperature was higher in approach 1 than in approach 2 (with rear side illumination). However, for these modules the highest temperature was measured in approach 3 in which the cell was shaded on the rear side.

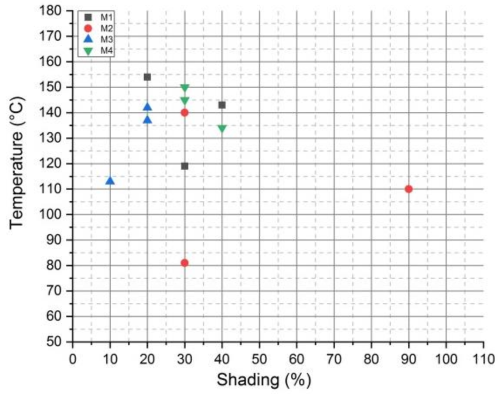


Figure 5: Approach 1 – three cells per module shaded on the front side. For high-shunt resistance cells, the highest temperatures are typically measured at shading levels < 40 %.

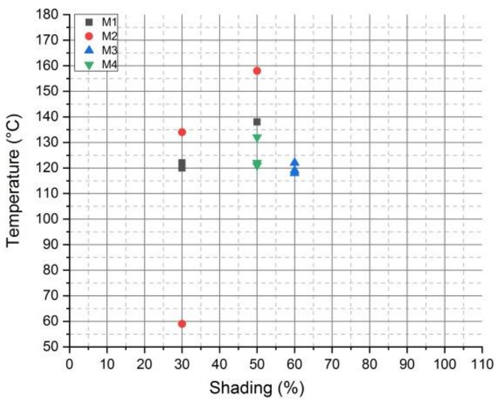


Figure 6: Approach 2 – three cells per module shaded on the front side. For high-shunt resistance cells, the highest temperatures are typically measured at shading levels < 60 %.

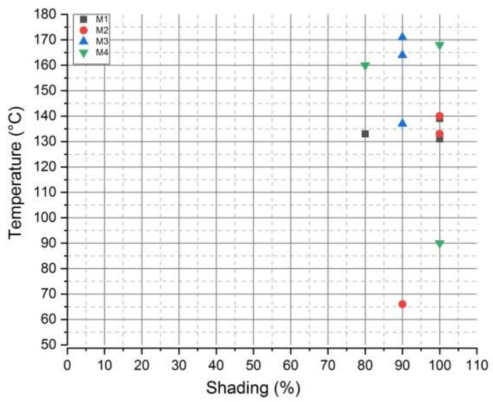


Figure 7: Approach 3 – three cells per module shaded on the rear side. For high-shunt resistance cells, the highest temperatures are typically measured at shading levels > 80 %.

Table IV: Max. measured hot-spot temperatures for each module and approach. **Bold**: highest temperature

Test approach	Max. temperature [°C]			
	M01	M02	M03	M04
1	**152.5**	150.0	148.5	144.8
2	134.0	131.8	**161.4**	121.8
3	139.5	**167.8**	140.1	**171.6**

Experiment II – Influence of irradiance level

Approaches 1 and 2 were repeated on one module from experiment I, but at higher (close to 1100 W/m²) and lower (close to 900 W/m²) irradiance, which represents the upper and lower range of the allowed intensity acc. to IEC 61215-2:2016. In the following they are referred to as approach 1' and 2', respectively. The exact irradiance intensities are given in Table VI.

The results (Table V) show that the changes in irradiance correlate with significant changes in the maximum hot-spot temperature, which range between 8 and 25 K. However, the increase in temperature seems also to be depending on the approach.

Table V: Results of experiment II

Cell ID	Shading [%]	max temp. at high irrad. [°C]	max temp. at low irrad. [°C]	change [K]
		Approach 1'		
19	20	134.5	122.6	11.9
22	20	134.5	118.8	15.7
24	10	124.5	116.6	7.9
		Approach 2'		
24	60	119.3	94.2	25.1
29	60	117.5	97.6	19.9
45	60	121.8	100.9	20.8

Table VI: Irradiance intensity in experiment II (W/m²)

	Approach 1'		Approach 2'	
	high	low	high	low
Front (avg.)	1097	920	1097	920
Rear (avg.)	0	0	200	165

4 SUMMARIZED FINDINGS AND CONCLUSION

In the first experiment, the hot-spot temperatures of bifacial modules with and without 20 % rear side illumination were determined. Considering the degree of shading which leads to the highest measured temperature, the results correspond to theoretical considerations. But although the highest temperatures were measured in situations with rear side illumination (either approach 2 or 3) on three of the four modules, it was not expected that on one module (M01) the highest temperature was measured without rear illumination. Also, hot-spot temperatures were unexpectedly higher for M02 and M04 in approach 1 (without rear illumination) compared to approach 2 (with). However, for these modules the highest temperature was measured in approach 3, where the cell is shaded on the rear side. Although no temperature-induced defects could be observed on any of the tested modules, the absolute differences in hot-spot temperatures for the applied shading approaches range from 20 to 30 K – a range which could be significant in terms of a pass/fail evaluation, depending on the used materials.

Theoretical considerations indicate a direct correlation between overall irradiance and dissipated energy leading to hot spots. Although experiment I partially yielded other worst-case hot-spot temperatures than predicted on the grounds of this assumption, a corresponding relation could be observed in experiment II where hot-spot tests at around 900 and 1100 W/m² were conducted. However, the results also show that the irradiance level affects the maximum hot-spot temperatures differently for different cells. They also depend on whether only the front or both sides are illuminated. In the modified irradiance approach 1', without rear light, the increase in irradiance led to an increase in hot-spot temperatures between 8 and 16 K. In case of approach 2', with rear illumination, the increase in hot-spot temperatures ranges from 20 to 25 K.

Summarizing the results, it is obvious that both the level of front and rear side irradiation and the location and degree of shading are significant for the maximum hot-spot temperature. These factors may well substantially influence whether a module passes or fails the standard hot-spot test, even if the test equipment conforms to the requirements for monofacial modules specified in IEC 61215-2:2016. Measurement results did not always fit the expectations derived from theory. These deviations could be explained by several factors. They could be related to the equipment and test procedure (e.g., homogeneity of the light source – see Table I – or isolating properties of the shading element) or the individual test sample (e.g., bifaciality, presence of permanent shading elements on the rear side such as the j-box, and temperature-dependent changes of the reverse characteristic of shaded cells).

For the hot-spot test on bifacial modules, the following conclusions are drawn from these experiments and considerations:

- Following the idea of the standard to address worst-case situations, it seems necessary to somehow factor in rear side irradiance during the hot-spot test, as it can have significant influence on temperature.
- However, to determine a reasonable level for this additional illumination it is necessary to reconsider the provisions for hot-spot testing of monofacial modules. The current standard allows a wide irradiance range between 900 and 1100 W/m², which is already significant in terms of pass/fail.
- To cover all possible scenarios for worst-case temperatures as shown in Table IV, it seems necessary to both, illuminate the front and rear sides simultaneously and shade different cells along the lines of the three approaches outlined in this paper.

In addition to these conclusions, attention is drawn to the overall level of irradiance in the testing of bifacial modules in adapted standard versions. Although the influence of irradiation on temperature could be shown, fixing a reasonable degree of rear side illumination cannot be settled by scientific considerations alone. The authors of this study propose two possibilities: Either the standard specifies the overall irradiance for testing of bifacial modules (e.g., front irradiance: 1000 W/m² and add. 25 % from rear side). In this case, the end user would have to be made aware that installations allowing a considerably higher degree of rear side irradiance are no longer covered by the standard. This could be done by a provision in the standard specifying the conditions the test is designed for. Or, alternatively, the manufacturer could state design limits for his product, which could then be used as references to configure the irradiance settings in the hot-spot test and other safety-relevant stress tests related to the current generated in a PV module, such as the bypass diode test.

6 ACKNOWLEDGEMENTS

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7 REFERENCES

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[2] Kurtz, S. et al. (2011): Evaluation of high-temperature exposure of photovoltaic modules. In: Prog. Photovolt: Res. Appl. 19 (8), S. 954–965. DOI: 10.1002/Pip.1103.