Impact of Bifacial Illumination and Sorting Criteria of Bifacial Solar Cells on Module Power

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Abstract. As the market share of bifacial cells and modules grows, solar cells measurements under bifacial illumination are increasingly becoming a focus of interest. In this work, we present an analysis of four different sorting criteria for bifacial solar cells with the aim of evaluating the impact of these criteria on the power of the modules assembled with the sorted cells. First, we develop a simulation model for bifacial modules based on the two-diode model. Secondly, we generate a representative virtual data bank made up of 50000 cells, whose parameters are determined in account with empirical parameter distributions measured on a group of 300 bifacial solar cells with passivated emitter and rear (PERC) manufactured industrially. Third, we sort and bin all cells according to the current density under front illumination at maximum power point (MPP) (j_{mpp}^{front}). Fourth, we assemble modules from all bins, calculate the module power under bifacial illumination for five different scenarios with varied front and rear irradiation and evaluate the average module power as well as the distribution of module power. The sorting of the cells (3rd step) and the calculation of the module power (4th step) are repeated for sorting the cells according to the current at MPP under bifacial illumination (j_{mpp}^{bi}) and the maximum power under front only and bifacial illumination (p_{mpp}^{front} and p_{mpp}^{bi}). With respect to the average module power, a very small gain of less than 2 W (in the most extreme illumination scenario) can be achieved if a bifacial instead of a monofacial sorting parameter is taken as sorting criterion. However, a strong effect on the distribution of the module power is manifested, obtaining either one homogeneous group of modules with broad power distribution or several classes/bins of modules, depending of the cell sorting criterion. Therefore, the choice of the sorting criteria of the cells depends on the interest of the solar manufacturers and has a great potential to reduce module mismatch in PV arrays.

INTRODUCTION

Bifacial cells and modules are more and more in the spotlight of the photovoltaics market. It is expected that the percentage of bifacial cells will increase to about 30% by 2027 and the trend for bifacial modules seems to be similar [1].

Before module assembly, the solar cells have to be sorted according to their performance characteristics to ensure maximum module performance. There are several methods of sorting solar cells used by manufacturers of photovoltaic modules, which all aim at minimizing the cell mismatch [2]. The common method for classifying or binning solar cells consists in the measurement of the *IV* curve of the cells and afterwards the cells with similar *IV* characteristics are assigned to classes or bins. So far, the *IV* measurements are performed under monofacial illumination. However, for bifacial cells, power output is not only influenced by the characteristics under front illumination but also by its characteristics under rear illumination. Thus, with the increasing market share of bifacial cells and modules, the question arises how bifacial cells have to be sorted ideally.

In this work, we examine different sorting criteria based on measurements under monofacial as well as under bifacial illumination and investigate the impact of these criteria on the achievable module power with respect to the average value as well as the power distribution.

APPROACH

Experimental

We worked with a group of 300 solar cell precursors provided by SolarWorld Innovations, Freiberg, Germany, which were metallized at Fraunhofer ISE, obtaining front efficiencies of around 20.5%. As these solar cells had an intentional variation of the rear side metallization layout, the samples showed a comparatively wide distribution of the rear side efficiency, which was mainly caused by different shadings on the rear side. Thus, the bifaciality (ratio of front to rear side efficiency) of the cells varied between 65 and 77%. We measured the cells' *IV* characteristics under 1 sun illumination and fitted the two-diode model (2DM). The next step was to determinate the distributions of the 2DM parameters (short-circuit current densities j_p^{front} (1000 W/m² front side illumination only) and j_p^{rear} (1000 W/m² rear side illumination only), recombination parameters j_{01} and j_{02}, series resistance R_s and parallel resistance R_p), which proved to be approximately Gaussian distributions (see Fig. 1 and Table 1).

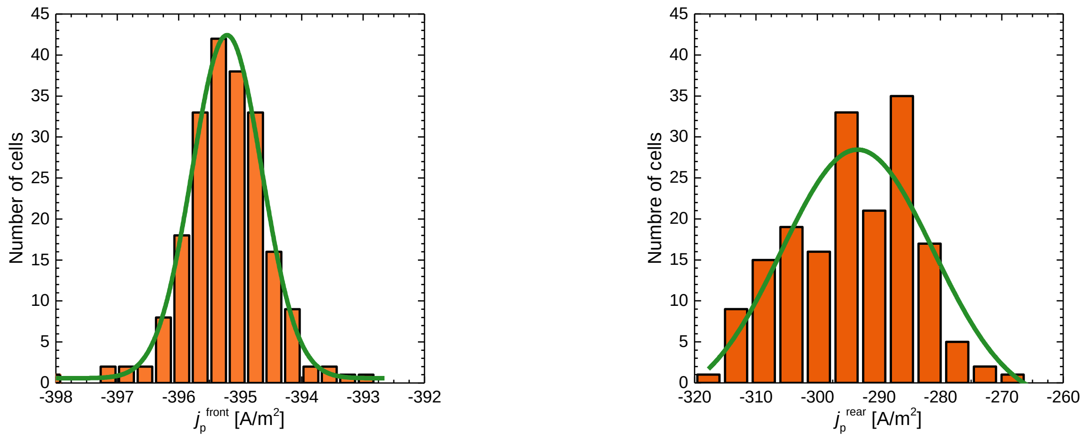

FIGURE 1. Distribution of j_p^{front} and j_p^{rear} (orange) and fit of the Gauss distribution (green).

TABLE 1. Gaussian distributions of the 2DM parameters.

	j_p^{front} [A/m²]	j_p^{rear} [A/m²]	j_{01} [pA/cm²]	j_{02} [nA/cm²]	R_s [Ωcm²]
mean *x*	-395.21	-293.48	0.23	15.36	0.44
standard deviation σ	0.567	12.355	0.019	1.573	0.066

Development of a simulation model for modules

We developed a model for bifacial module simulation. Within the module, each solar cell is modelled with the 2DM. This model allows us to define for each cell individual values for R_s, R_p, j_{01}, j_{02}, and

$$j_p = j_p^{front} \cdot \frac{E^{front}}{1000\ \mathrm{W/m^2}} + j_p^{rear} \cdot \frac{E^{rear}}{1000\ \mathrm{W/m^2}}, \quad (1)$$

with E^{front} and E^{rear} being the front and rear illumination intensities of the module, respectively. An additional series resistance contribution from the cell interconnections and the bypass diodes are accounted for.

The program flow is shown in Fig. 2. The input parameters for the simulation model of the cells are read from a file which contains the user-definable 2DM parameters of all cells of the module. Within the model, 20 of these cells are connected in series via an enclosing script forming the cell string (see Fig. 2). One module consists of three strings, i.e. 60 cells in total. The module simulation tool thus provides the real interconnection of the cells in the module from the characteristic curves of the cells and the fitted 2DM parameters.

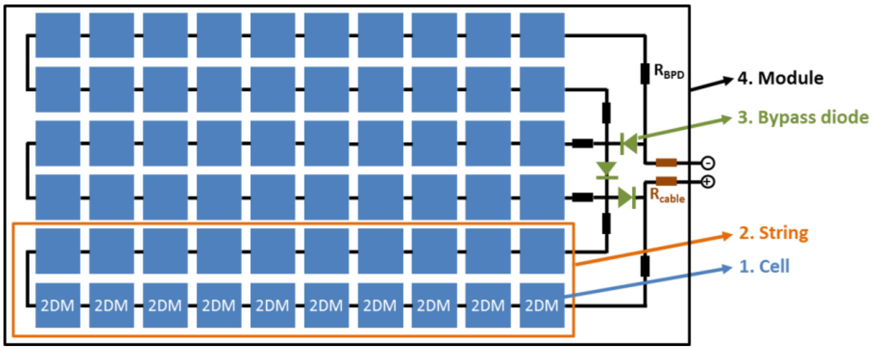

FIGURE 2. Scheme of the module.

Lastly, from the characteristic curves of each cell, which are interconnected in series, and considering the bypass diodes and the resistance of each element (cells, cables and bypass diodes), the model calculates the *IV* curve of the module and its parameters at MPP (maximum power point), i.e. the current density j_{mpp}, the voltage V_{mpp} and the maximum power density p_{mpp}.

Sorting Algorithm

A program was developed that aims at deriving optimal sorting criteria. The 2DM parameters required for the simulation were chosen according to the corresponding measured distributions determined by means of a Gaussian fit to the experimental data and based on this, the generation of simulated data for 50000 cells. The next step was to use this test data set to simulate module characteristics curves for different types of sorting criteria and compare the average module power. Four different sortings of cells were compared according to j_{mpp}^{front}, j_{mpp}^{bi}, p_{mpp}^{front} and p_{mpp}^{bi}. Here, the index "front" denotes a front illumination intensity of 1000 W/m² and the index "bi" (bifacial) an additional rear irradiance of 200 W/m² (both for AM1.5g spectrum). To this end, the solar cells first had to be sorted into quality classes or bins for each sorting parameter. To define the binning widths *w*, we took the values that are normally used in the industry [3], i.e. $w_j = 0.2$ mA/cm^2 for the current density j_{mpp} and $w_p = 0.2$ mW/cm^2 for the maximum power density p_{mpp}. In addition, a larger width of the classes was analyzed, i.e. $w_j = 0.3$ mA/cm^2 and $w_p = 0.3$ mW/cm^2. After the binning of the 50000 cells for the four criteria, virtual modules were assembled each module being composed of cells of the same bin.

RESULTS AND DISCUSSION

Fig. 3 shows the distributions of the 50000 modelled cells and the definition of the bins or classes for the four sorting criteria, whose respective sorting magnitudes are:

(a) j_{mpp}^{front}
(b) j_{mpp}^{bi}
(c) p^{front}
(d) p^{bi}

The width of the classes or bins of the cells was chosen after the industry standard, i.e. a width of $w_j = 0.2$ mA/cm^2 for j_{mpp} and $w_p = 0.2$ mW/cm^2 for p_{mpp} (see black arrows in Fig. 3). Additionally, a larger width of the classes was analyzed, i.e. $w_j = 0.3$ mA/cm^2 and $w_p = 0.3$ mW/cm^2 (see blue arrows in Fig. 3).

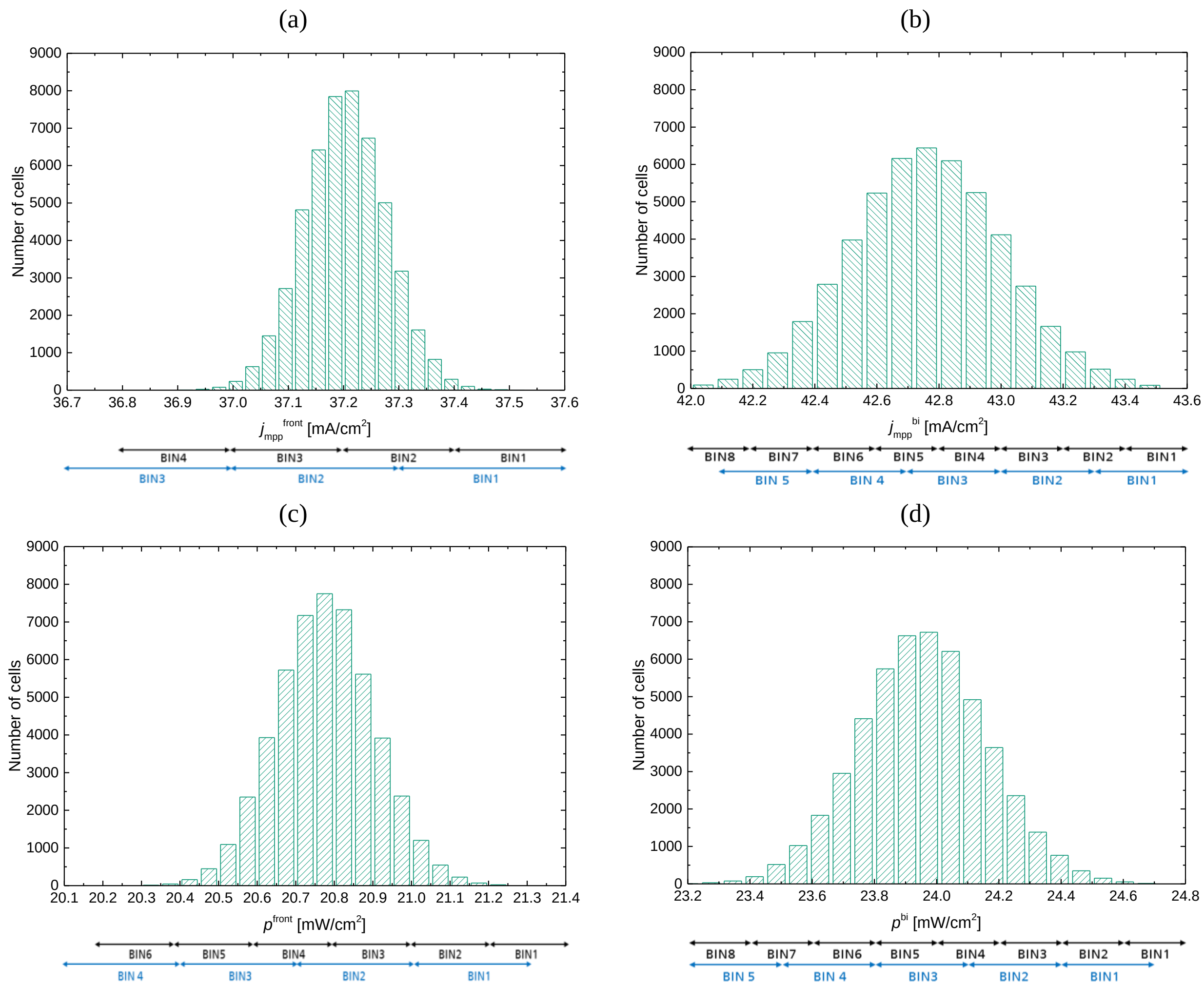

FIGURE 3. Distribution of the cells and definition of the bins or classes for the width $w_j = 0.2$ mA/cm^2 and $w_p = 0.2$ mW/cm^2 (black) and for $w_j = 0.3$ mA/cm^2 and $w_p = 0.3$ mW/cm^2 (blue).

The modules built from 50000 cells (831, 830, 831 and 828 modules for the criterion (a), (b), (c) and (d), respectively) were simulated for every scenario and sorting criterion using our developed program. In the following table the simulated average module power is given for $w_j = 0.2$ mA/cm^2 and $w_p = 0.2$ mW/cm^2.

TABLE 2. Average module power *P* [W] for the four sorting criteria (a-d) and five scenarios.

	Irradiance	**Scenario**				
	front [W/m²]	1000	1000	1000	750	250
	rear [W/m²]	200	300	500	250	750
Criterion	(a) j_{mpp}^{front}	349.74	372.84	418.85	283.09	240.98
	(b) j_{mpp}^{bi}	349.82	373.01	419.29	283.25	242.76
	(c) p^{front}	349.71	372.80	418.81	283.06	240.95
	(d) p^{bi}	349.77	372.90	419.03	283.15	241.79

The difference in the average module power between the four criteria in this study is not significant. For the "standard" bifacial scenario (1000 W/m^2 front + 200 W/m^2 rear) a gain of 0.08 W (between (a) and (b)) and 0.06 W (between (c) and (d)) was achieved, when a bifacial instead of a monofacial sorting criterion is used. These gains are considered as negligible. In the case of the east-west scenario, in which the rear side is clearly stronger illuminated (250 W/m^2 front + 750 W/m^2 rear), the difference is greater (1.8 W between (a) and (b) and 0.8 W between (c) and (d)).

However, the question arises whether the choice of the sorting criterion has an effect on the form and width of the distribution of the module power, which would be relevant for the industrial manufacture and the module mismatch on array level [4,5].

Following is shown the module power arisen from 50000 cells. Figure 4 shows the results for the bin width $w_j = 0.2$ mA/cm^2 and $w_p = 0.2$ mW/cm^2 and Fig. 5 for $w_j = 0.3$ mA/cm^2 and $w_p = 0.3$ mW/cm^2, both for a front irradiance of 1000 W/m^2 and a rear irradiance of 200 W/m^2. In the legend the bin classes of the cells are displayed, every module consists of 60 cells of the same class.

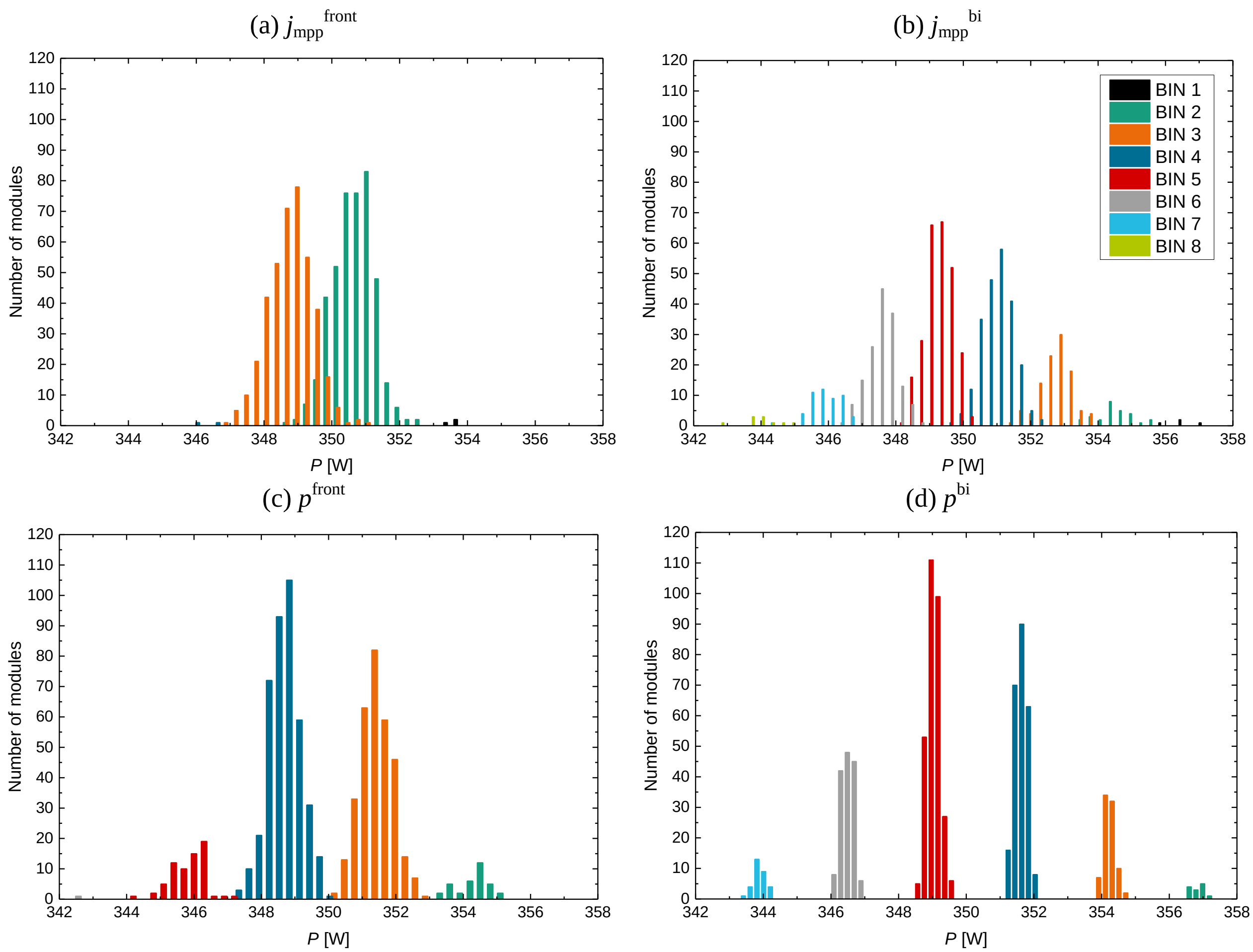

FIGURE 4. Module power for a width of the classes $w_j = 0.2$ mA/cm^2 and $w_p = 0.2$ mW/cm^2 for the four sorting criteria (a-d). Irradiance front: 1000 W/m^2. Irradiance rear: 200 W/m^2.

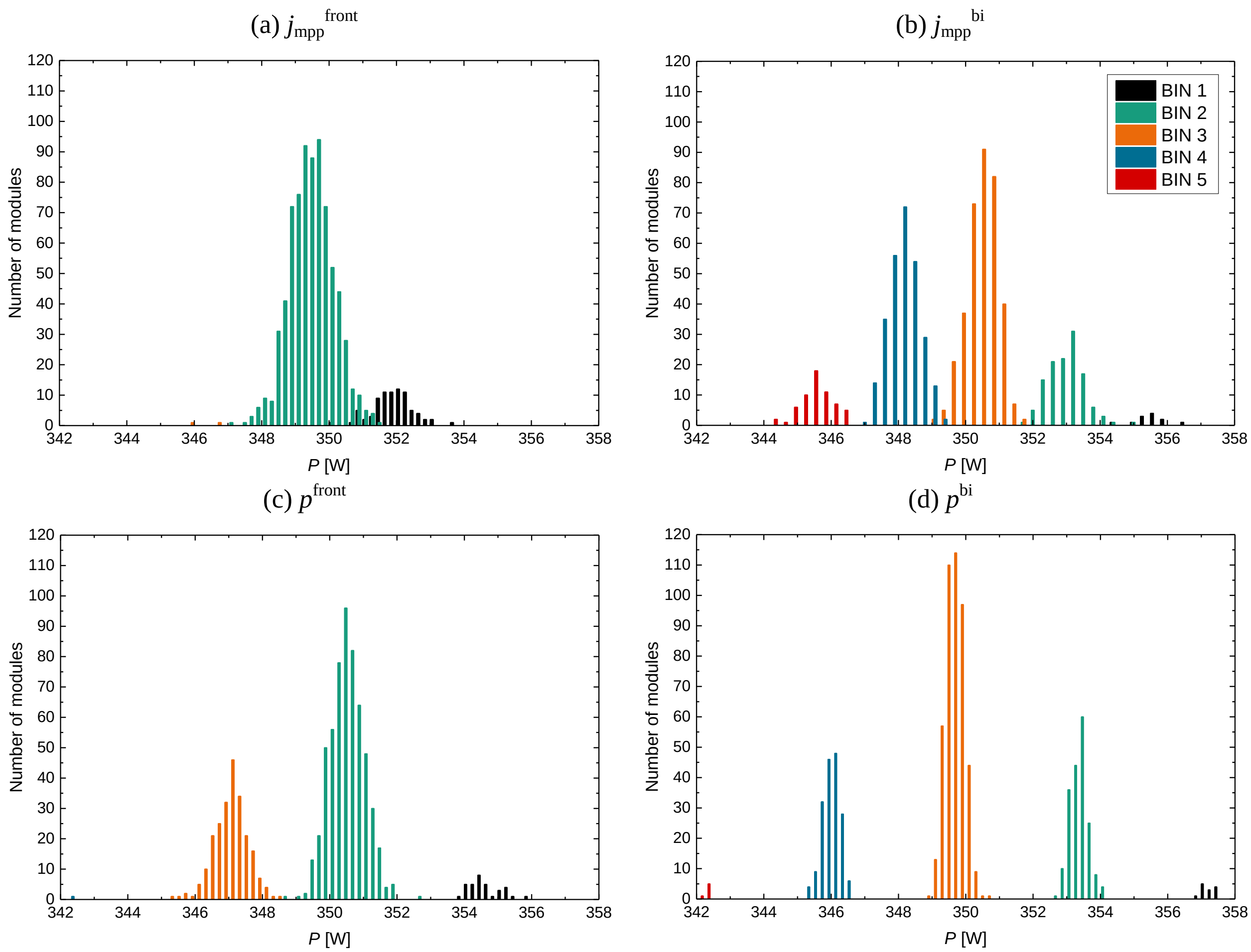

FIGURE 5. Module power for a width of the classes w_j = 0.3 mA/cm^2 and w_p = 0.3 mW/cm^2 for the four sorting criteria (a-d). Irradiance front: 1000 W/m^2. Irradiance rear: 200 W/m^2.

The modules are grouped relatively clearly together according to the classes of their cells and thereby forming module classes. By choosing the sorting criterion the manufacturer can influence the form of the distribution of the module power. If from the total series production (here 50000 cells) the manufacturer wants to build a single homogeneous module group, the criterion (a) would be appropriate (see Fig. 4(a) and Fig. 5(a)). If, instead, the manufacturer wants to build modules of different qualities (power classes), the criteria (b) or (d) would be appropriate. For example, in the case shown in Fig. 4(d) modules with a bin width of 2 W would be built, while in Fig. 5(d) the bin width would be of 4 W. Furthermore, the criterion (d) leads to narrower class distributions as the criterion (c), where each module class would produce homogeneous power and thus, the module mismatch on array level decreases. Here the bifacial criterion brings clear advantages over the monofacial criterion.

CONCLUSION

Bifacial sorting criteria take into account fluctuations in the efficiency of the rear side (bifaciality of the cells between 65 and 77%) are reflected, which overlap when a monofacial criterion is used. Bifacially sorted cells lead to more module classes with different module power (up to 8 bins or classes when the industry standard binning width of w_p = 0.2 mW/cm^2 is taken) and lower variations within the power class (less than 1%) for bifacial irradiation, meaning lower mismatch losses in the photovoltaic arrays. However, mean module power cannot be increased significantly by applying bifacial sorting algorithms, with a gain under 0.1 W (by E^{front} = 1000 W/m^2 and E^{rear} = 200 W/m^2) when a bifacial instead of a monofacial sorting criterion is used.

After all, no sorting criterion is wrong or right. The choice of an appropriate criterion depends only on the demands for the power distribution of the modules.

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