SORTING CRITERIA FOR BIFACIAL PERC CELLS FOR IMPROVED MODULE CLASSIFICATION

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ABSTRACT: With the increase of bifacial solar cells' market share a major question for solar cell characterization is whether it is beneficial to determine the solar cells rear side efficiency together with the by default measured front side efficiency. In this work we investigate how a regularly and a heavily fluctuating rear side efficiency in production influence module power and the choice of sorting categories ("bin"). A sample batch of 1000 industrial bifacial solar cells with a regular production efficiency spread was produced and bifacially measured in an inline *IV* flasher. A module simulation was built, which creates virtual modules from *IV* curves of the cell batch with defined sorting criteria. Monofacial and bifacial sorting criteria were compared showing advantages for the bifacial criteria. To validate the simulation model and results eight bifacial 60-cell glass-glass modules were fabricated. Subsequently the given cell pool was virtually extended to production scale (100.000 cells) to evaluate the approach's sorting-benefits for a quasi-infinite cell pool. The study's result is that the inclusion of the bifacial efficiency into the sorting criteria makes it possible to diversify a monofacially determined module class into several clearly distinguished bifacial module classes while the average module power of the whole pool remains constant. Moreover the power spread of each module class gets significantly sharpened, which can reduce downgrading in sales The robustness of the module power towards changing illumination conditions increases and the effects of certain choice of sorting bins and illumination conditions on module classes are directly made visible through the developed simulation.

Keywords: bifacial solar cell, bifacial module, cell sorting, PERC

1 INTRODUCTION

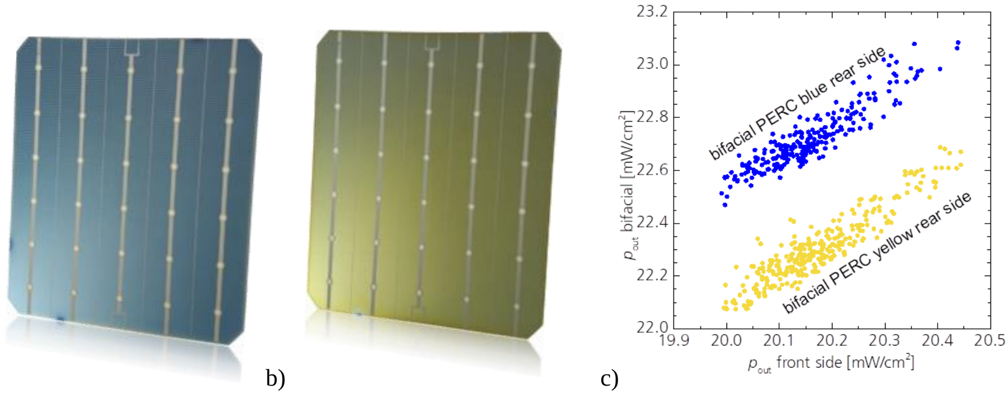
Solar cell production always exhibits a more or less strong variation in the product quality, which is reflected in a (smaller or bigger) spread of the *IV* parameters. This is accommodated by sorting the cells in quality classes ("bins") before module assembly. This ensures a low cell mismatch and the adherence of predefined module power output. If a solar cell is designed bifacially, which is easily possible for PERC cells [1], it has by definition two energy generating sides, which may or may not correlate in its light collection efficiency. Therefore, the solar cell's rear side creates not only a second source of power but also of uncertainty to the resulting module power output. With this work we make use of our recently acquired ability of bifacial inline cell testing at Fraunhofer ISE [2] to investigate the actual impact of the above mentioned rear side efficiency variations on the module power.

The innovation of the used approach lies in the combination of: (i) a very relevant cell power distribution coming from an industrial research line and industrial cell processes, (ii) the simultaneous knowledge of each cell's mono- and bifacial output power, which makes it possible to derive the projected module power for different knowledge-states and various sorting scenarios, (iii) a full validation chain from cell *IV*-measurement, module *IV*-simulation and module *IV*-measurement and insight into every valuable detail.

2 EXPERIMENT

A cell batch of 1000 bifacial PERC was produced by SolarWorld Industries according to our intention to display two production features: The efficiency fluctuation of a regular production process (within each group) and of a heavily offset process impacting the rear side carrier generation. This may be caused by a drift or an error in production parameters (e.g. surface topology, rear capping layer thickness) or simply the comparison of two different production lines. We provoked this by simply choosing the rear capping layer thicknesses for a blue and a yellow optical appearance.

The cells' *IV*-curves were measured with two irradiances G which are applied inline during a single flash sequence: $G_{front} = 1000$ W/m², $G_{front} + G_{rear} = 1000 + 200$ W/m². The measured front side



a) b) c)

Figure 1: Rear side images of the produced 5-busbar bifacial PERC solar cells: Blue rear side with roughly 61% bifaciality, yellow rear side with 51% bifaciality. The front side efficiency for the bifacial cells have a median of η = 20.15% (degraded). The yellow rear side was chosen additionally as its process was available from the monofacial rear passivation stack.

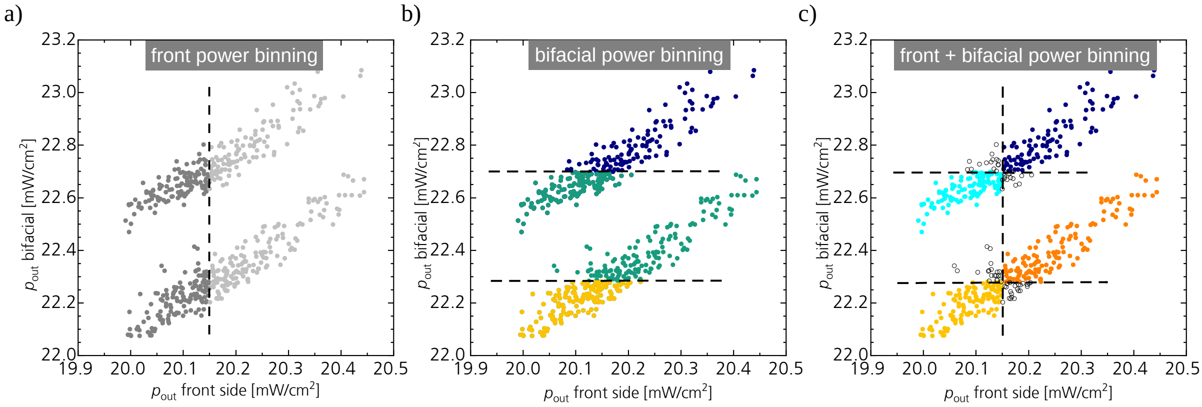


Figure 2: The three sorting criteria for this experiment: a) conventional front side binning, b) bifacial-only binning with a sum of 1200 W/m² true bifacial irradiance, c) combined binning of front and bifacial criteria.

efficiency after light-induced degradation was η = 20.15±0.25%, the bifaciality was β = 61±3% (blue rear surface, see Figure 1a) and β = 51±3% (yellow rear surface, see Figure 1b). The front side and bifacial power output of the cells is plotted in Figure 1c. It is notable that the power output variation of the front side efficiency has a width of 0.45 mW/cm² while the bifacial power varies over 0.65 mW/cm² for both the blue and the yellow group. So the cell power increased by 10-13% due to rear side generation, the fluctuations however increased by 44%. Hence by good measure the rear side power exhibits a significantly larger efficiency variation (even in a single color croup) than the cells' front side power.

The measured *IV*-curves were fitted with a conventional 2-diode-model to extract the necessary parameters for *IV*-modelling: short-circuit current density j_{sc}, recombination parameters j_{01} and j_{02}, series and parallel resistance R_s and R_p.

Next a module simulation was set-up to pre-evaluate the cell sorting and predict the module power resulting from different cell sorting methods. The basics of this simulation was presented in Ref. [3] and the used sorting criteria will be given in the following section 4. The simulation calculates the modules' *IV*-curves and thus considers cell mismatch at the modules' working point. Parameters like optical influence of the module glass or interconnection losses are not considered.

3 CELL SORTING

Three options for cell sorting were investigated:

I) Front power binning: Only efficiency/power (here equal) criteria under 1000 W/m² front side illumination are considered (see Figure 2a). Rear side contribution is neglected. In the given sample set we used two power bins of the width Δp_{front} = 0.25 mW/cm².

II) Bifacial power binning: The power output at $G_{front} + G_{rear}$ = 1000 + 200 W/m² is used for setting the bins (Figure 2b). We set three power bins of Δp_{bi} = 0.4 mW/cm²

III) Front + bifacial power binning: Both of the above criteria are combined leading to the two-dimensional binning scheme visible in Figure 2c. This results in six theoretical bins: two bins of the width Δp_{front} = 0.25 mW/cm² times three bins Δp_{bi} = 0.4 mW/cm². However two of the bins remain almost empty and were thus neglected.

According to the given sorting strategies we built eight modules with a maximum of cross comparison possibilities between them. The rest of the cells were required for pretests and as backup in module assembly.

4 RESULTS

4.1 Module simulation

For every binning strategy the cells were virtually sorted into modules depending on their bin class, which is represented by the color codes in Figure 2. It may be added that the cell pool was dimensioned so that eight modules could be built so there is no statistical uncertainty visible in the simulated power output. This will be extended in section 4.2. The results for a virtual irradiance of $G_{front} + G_{rear}$ = 1000 + 200 W/m² are given in Figure 3

In the simulation the cell pools' average module (A) yields 327.5±1 W under bifacial irradiance simulation (1200 W/m²), with ±1 W being cell mismatch and simulation uncertainty.

I) Front power binning

The modules B and C sorted according to strategy I) (front power bins) end up within a power difference of 2.5 W between each other and inside the uncertainty margin of the average module A.

II) Bifacial power binning

D together with E and F represent the three bifacial bins. The consecutive power difference of the modules is 4.5 W each.

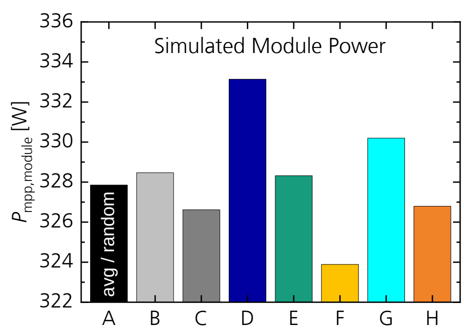


Figure 3: The simulated modules without impacts of module glass or interconnection resistance loss. The column colors match with the cell bins in Figure 2. The black column of A is the average module built without bin classes.

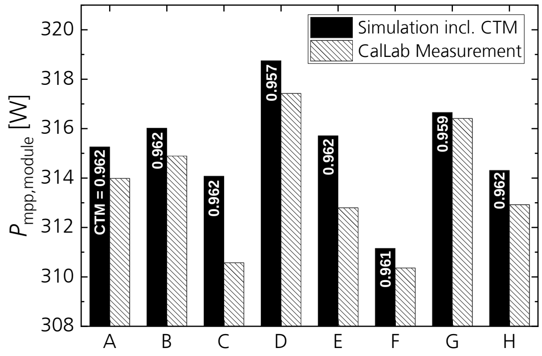


Figure 4: The simulated modules including CTM and the bifacial CalLab measurements. The numbers in the black columns display the calculated CTM used for the simulations. The remaining difference between simulation and measurement can be accounted to simulation uncertainty and (mostly) manufacturing errors.

III) Front + bifacial power binning:

Modules D, F, G and H represent this strategy and show power steps of 3 W, spanning a 9 W range around the average power module (A) of 328 W.

After manufacturing the modules with the exact same cell sorting as in the simulation, the modules were measured at ISE CalLab with the same bifacial irradiance as in the simulation. From these measurements a cell-to-module (CTM) loss was calculated for the different module types as follows: CTM of every single *IV* parameter (I_{SC}, V_{OC}, FF) was calculated using a best-in-class approach: CTM_{Isc} was taken from the best blue rear module for D and G, the best yellow rear module for F and H, and the best mixed rear module for A, B, C and E. For CTM_{FF} the highest FF of all modules was chosen as reference. CTM_{Voc} is 1 for all cases. Influences of clear handling errors like cell breakage were excluded by analyzing the *IV* curve. The resulting total CTM was applied onto the simulated results to compare it to the CalLab measurements (Figure 4).

The simulation results including the calculated total CTM match the CalLab measurement within 1.5 W, which is roughly 0.5%$_{rel}$ deviation. The modules C and E exhibit a cell breakage (verified by the luminescence imaging) so the measured module power falls 3 W short of the simulation.

4.2. Industrial scale simulation

The cell pool of 1000 cells was then extrapolated to 100.000 cells maintaining the statistical variance of the “blue” and “yellow” cell group. The module simulation according to the criteria I, II, and III from section 2 was repeated with the 100.000 cells yielding the power distribution histograms in Figure 6. This basically adds a statistical distribution to the module power plot from Figure 3 (again without the CTM loss).

It is clearly visible that the pure front power sorting creates a Gauss-like distribution with a bottom width of roughly 2.5 W. The bifacially sorted modules have a much narrower spread of 1.5 W, the front + bifacial sorting even leads to only 1 W distribution spread. Such a small spread at the bottom of the distribution is not possible with front efficiency sorting of bifacial cells as the impact of the varying rear side efficiency is neglected. However the front + bifacial sorting also shows an overlap of the light blue and the orange bin, which is not anticipated in the single-module simulation (Figure 3) also the two formerly empty bins (compare section 3 III) are filled with some modules now (Figure 5). This will be discussed in the next section.

5 DISCUSSION & CONCLUSION

As stated in a previous publication [3], the average module power from the same cell pool can’t be altered by changing the cell binning (given insignificant mismatch loss). However, the power distribution between modules can be tailored leading to more diversified module classes. Our approach to include the measured bifacial cell power into the cell sorting demonstrates two important things:

a) Reduced power spread: The absolute rear side power variation of these industrial cells is larger than the front side’s. If this is not taken into consideration when sorting the cells the modules’ power output spread at bifacial illumination is considerably widened. In this experiment this spread could be confined by a factor of two (1-1.5 W versus 2.5 W) if the sorting takes place with bifacial sorting criteria. This can considerably reduce downgrading losses within each module class, which happens when the guaranteed module power in sale is oriented at the lower margin of each module class.

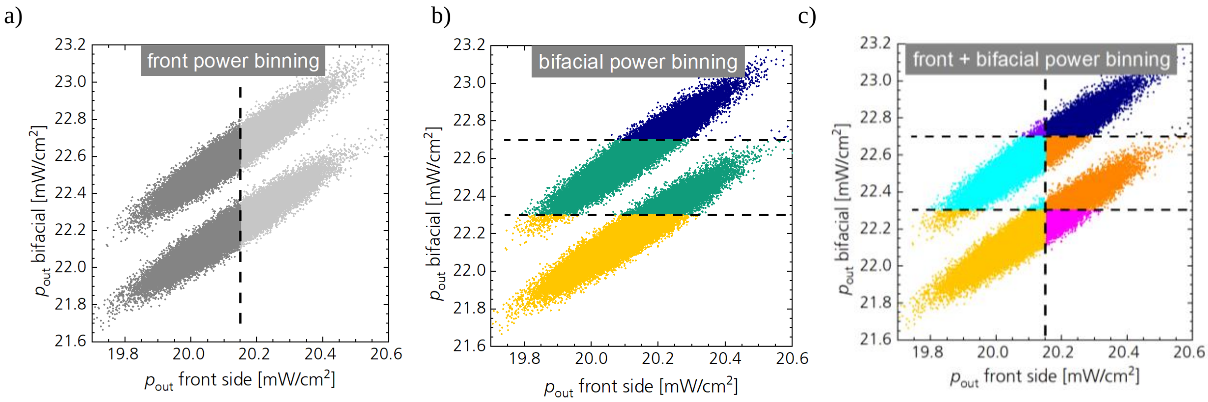


Figure 5: The three sorting criteria for this simulation experiment: a) conventional front side binning, b) bifacial-only binning with a sum of 1200 W/m² true bifacial irradiance, c) combined binning of front and bifacial criteria.

b) More module classes: The bifacial sorting requires more bins due to the larger power spread due to the inclusion of the rear side power spread. This creates more power classes and thus a larger diversification of module classes from the same cell pool. This implies module classes at absolute higher power than in the front side sorting strategy, which can be sold at a premium.

Looking at Figure 3 and Figure 6 the best diversification of module power in 5 W steps together with reasonably sharp module classes is reached by the bifacial sorting (strategy II). The front + bifacial sorting (strategy III), which also seem to have a clear diversification, shows an overall rather unsuitable distribution of module power with high downgrading losses. Two effects come together here: First, the few cells first neglected in Figure 2 (open circles) have become a considerable number of cells due to the scaling factor 100. Two formerly empty bins now create modules (Figure 5). Above that a number of cells extend from one bin into neighboring bins distorting the power distribution of modules. What can be learned from this is that a successful binning strategy has to be adapted to every new cell distribution even if it only changes a little.

This is why the shown module simulation is ultimately valuable. The sorting strategy needed for each individual cell production scenario can be developed easily with little effort. The additional power distribution gained by rear side irradiance and observed by bifacial inline measurement offers a lot of creative options to tailor the desired power classes in module manufacturing suited for any irradiance scenario in the field.

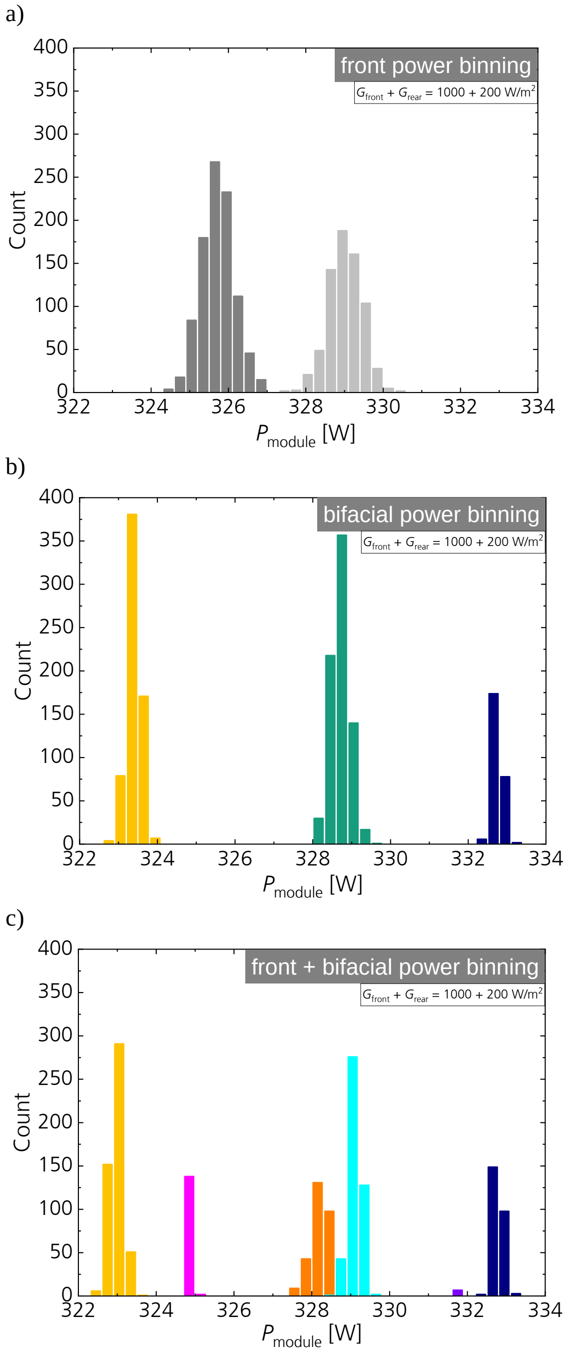


Figure 6: Simulated modules in larger numbers ("production scale") the color codes match the sorting in Figure 2 and Figure 3.

ACKNOWLEDGEMENT

This work was conducted within the project "BiZePS" (FKZ: 0325909), supported by the German Ministry for Economic Affairs and Energy.

We thank SolarWorld Industries for providing the bifacial PERC cells for this experiment and SI Module GmbH for the collaborative module assembly.

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