Reassessment of Cell To Module Gains and Losses: Accounting for the Current Boost Specific to Cells Located on the Edges

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Abstract. The power produced by a photovoltaic module is not simply the sum of the powers of its constituents cells. The difference stems from a number of so-called “cell-to-module” (CTM) gain or loss mechanisms. These are getting more and more attention as improvements in cell efficiency are becoming harder to achieve. This work focuses on two CTM mechanisms: the gain due to the recapture of light hitting the apparent backsheet in the “empty” spaces around the cells and the loss from the serial connection of “mismatched” cells i.e. with different maximum power points. In general, for insulation purposes, the spaces on the edges of modules are larger than the spacing between cells. This study reveals that, when reflective backsheets are used, these “edge spaces” provide an additional current boost to the cells placed at the edges that can lead to a 0.5% gain in the output power of modules (with 60 or 72 cells). This location-dependent current boost adds to the usual variations in cell characteristics dictated by the binning size and results in larger “cell-to-cell mismatch losses”. However, the simulations reveal that for short-circuit current bin size smaller than 5%, this additional mismatch loss is lower than 0.05%. All considered, this study demonstrates that the spaces at the edges of PV modules have a significant impact on the cell to module ratios ($\approx$+0.5%$_{abs}$ or $\approx$16% of the CTM gains) when reflective backsheets are used.

1. INTRODUCTION

Several earlier studies demonstrated that a fraction of light incident on the spaces between cells in a module is reflected back onto the cells and eventually collected [1–7]. Also, there is typically some extra space (at least 1 cm) on the edges of modules for insulation purposes. This additional area of apparent backsheet results in larger current boosts from the light reflected on the surrounding backsheet for the cells located at the edges (and the corners) of modules. This effect of module edge spaces has been very rarely mentioned in the literature and earlier works [8, 10] expressed that the gain would be marginal at module level because of the serial interconnection of the cells. In this work, we evaluate the impact of these module edge spaces on the CTM factors and demonstrate that the non-uniform optical gain is not lost because of the serial interconnection of the cells but results in a boost of FF at the module level.

2. METHODS

The recaptured fraction from the spaces between cells is simulated in this work assuming a Lambertian reflection on the backsheet. The angular dependence of actual backsheets may differ from that of a Lambertian scatterer but the angular measurements in [8] indicate that the Lambertian approximation seems reasonable and in any case does not overestimate the light trapping. The recaptured fraction after reflection on the apparent backsheet between the cells is calculated using:

$$fraction\ recaptured = \sum_{k=0}^{\infty} R_{BS} \times (1-\left(n_{air}{}^{2} / n_{glass}{}^{2}\right)) \times (1-geom) \times (1-R_{cell}) \times \left[geom \times R_{BS} \times (1-\left(n_{air}{}^{2} / n_{glass}{}^{2}\right)) \right]^{k}$$

where R_{BS}, R_{cell} and *geom* are the backsheet reflectance, the cell reflectance and a geometrical factor that depends on cell spacing and glass width. The ratio of refractive indices, $n_{air}^2/n_{glass}^2 \approx 0.44$, gives the fraction of light in the escape cone at the glass/air interface. The results, shown in Fig. 1 are in line with those of earlier studies (e.g. [5]) and are consistent with Laser Beam Induced Current (LBIC) measurements made on dedicated samples. Test modules are prepared using 6 inches M2 silicon heterojunction (SHJ) solar cells encapsulated with an inter-cell spacing of 3 mm between a white backsheet and 3 mm thick glass. The backsheet and the cell reflectance are measured using a UV/vis/NIR spectrophotometer (Perkin Elmer Lambda 950) at 635 nm which corresponds to the laser's wavelength used in the LBIC measurements. The spectral reflectance of the backsheet weighted by the photon flux density of the AM1.5 spectrum is 84%. Note that the interface reflectance measured in air is different from the encapsulant-backsheet interface [9].

In order to quantify experimentally the extra light recollected by cells placed at the edges and corners of modules, test modules with individually connected cells are fabricated. The cells are measured before encapsulation at 25°C using a two-lamp (halogen and xenon) class AAA WACOM sun simulator with an AM1.5 G irradiance spectrum at 1000 W m^{-2}. The space between the module edges and the cells is set to 18 mm in this study. For each module (with a specific cell spacing), cells are selected to have identical short circuit currents (at cell level). The test modules are then placed under a homogeneous light source and the short circuit currents of center, edge and corner cells are measured.

In general, because the cells are serially connected, cell-to-cell variations of their current at maximum power point (I_{mpp}) result in power loss at the module level. To quantify this so-called cell-to-cell mismatch loss, a simulation tool is developed in Matlab. The code sums the voltages of the constituent cells at every current level to reconstruct the IV curve of a module.

Finally, to confirm the order of magnitude we calculate for the effect of the edges of modules, two commercially available 60-cells modules are measured with an indoor solar simulator before and after the spaces at their edges are made opaque with a black tape.

3. RESULTS AND DISCUSSION

- **Recapture from apparent backsheet in module: impact of the edge margins**

Fig. 1a shows the recaptured fraction from the spaces between cells. The amount of reflected light depends on the reflectance of the backsheet (R_{BS}). After each bounces, about 44% (n_{air}^2/n_{glass}^2) is lost through the escape cone. The remaining light is reflected at the glass/air interface either onto a neighboring solar cell or it is reflected back onto the backsheet apparent between the cells (i.e. the spaces between the cells) and undergoes another reflection. This is why the fraction of light incident upon the apparent backsheet that can be recaptured decreases as the cell spacing increases. One can notice that this decrease is relatively slow. LBIC measurements on encapsulated devices show that 13% of the light shined on a white backsheet one centimeter away from a cell edge can be collected (and about twice as much if there are cells on both sides), data not shown. In a module with an inter-cell spacing of 3 mm and a backsheet reflectance (R_{BS}) of 87%, a recapture fraction of 46% was measured via LBIC which is in line with the simulations shown in Fig. 1a. These results highlight the necessity of correctly masking the 1-cell modules that are routinely fabricated in R&D to predict the CTM losses of full scale modules. Indeed, 1-cell modules are usually fabricated using 20x20cm glasses and backsheets which result in large areas of apparent backsheet around the cell. The masking should be of the cell length plus the cell spacing on each side. When pseudo square cells are used, the diamond shaped spaces between the corners of the cells should be accounted for as these areas also contribute to light recollection. This is done ideally with a mask with the corresponding shapes[1] or alternatively with a mask of similar area (the light recollection might be slightly overestimated with the second approach because the recapture fraction is a decreasing function of the distance to the cell edge as shown in Fig. 1a).

Fig. 1b shows the power gain corresponding to the additional light collection from the apparent backsheet as a function of cell spacing. The curves correspond to the power gained by a center cell, i.e. a cell surrounded by other cells, for different backsheet reflectances. The gains calculated in this work with R_{BS}=0.87 are quite similar to those published in [5]. However, there is typically some extra space (usually > 1 cm) on the edges of modules for insulation purposes. This additional area of apparent backsheet results in larger current boosts from the light reflected on the surrounding backsheet for the cells located at the edges (and the corners) of modules. This effect of module edge spaces has been very rarely mentioned in the literature and earlier works [8, 10] expressed that the gain would be marginal at module level because of the serial interconnection of the cells. In the second part of this work, we show by simulation that the loss caused by this additional cell-to-cell mismatch is negligible and thus the module edges provide in fact a significant power boost. First, in order to quantify the module edges impact, the short circuit currents of test modules with individually connected cells (of identical short circuit currents at cell level) were measured under a homogeneous light source. The ratios of short circuit current between the different cell positions enable to calculate the power gains plotted in orange and red on Fig. 1b. For example, in a module with cells spaced 2 mm apart and with spaces of 18 mm on the edges, the edge cells benefit from a boost in current of 0.95% and the corner cells of 1.94% compared to center cells.[2] This has a significant impact on the performances of a module since the cells on the edges and corners correspond to 47% of the total number of cells in a 60-cells module (and 45% in a 72-cells module). Averaging the different contributions, one get the data shown in green in Fig. 1b for a 60-cells module (results are very similar a 72-cells modules). With a white reflective backsheet (reflectance of 87%) and a standard cell spacing of 2 mm, one can expect a CTM gain of 2% due to light recycled from the apparent backsheet. This value is 0.5% larger than what has been previously reported for this recapture effect in [5], possibly because the extra spaces at the module edges were not taken in consideration.

However, it could be that this gain is not fully realized because this effect creates a mismatch in the short circuit currents of the cells depending on their position in the module. The next section describes the impact of this additional mismatch on the so-called "cell-to-cell mismatch loss" which is the loss that comes from the serial connection of cells with different IV characteristics.

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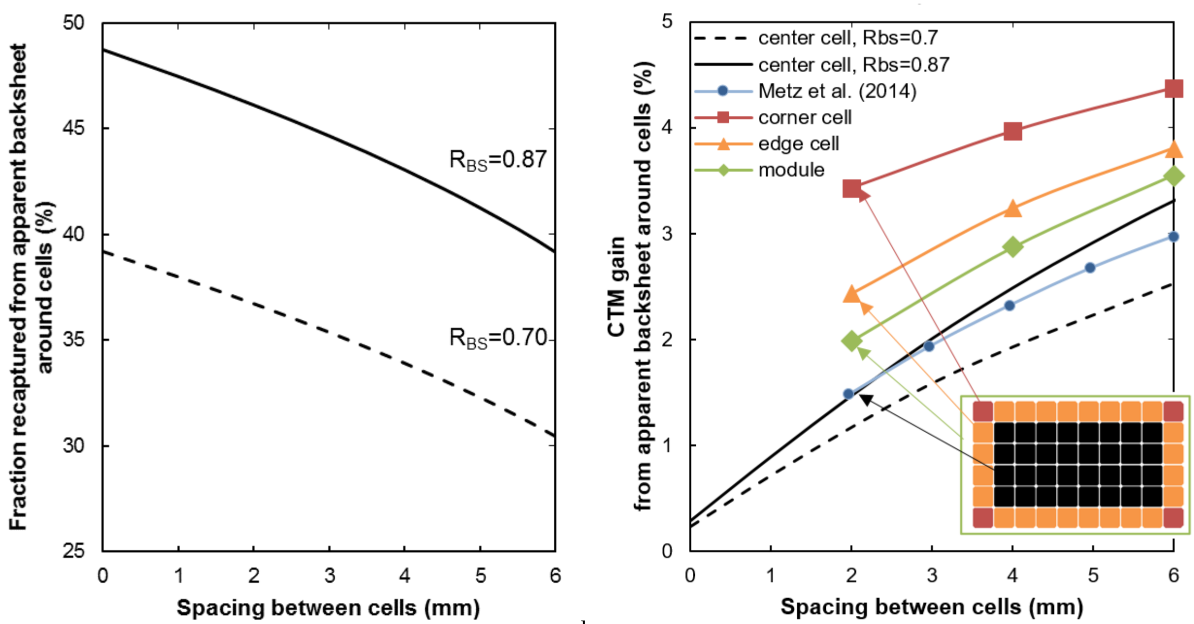
[1] i.e. a square mask with diamonds at each corners so that light is incident on the apparent backsheet area around the cell in a real module. The mask's bottom surface should be as little reflective as possible in order to minimize the internal reflections below the mask.

[2] These results are consistent with an earlier ray-tracing simulation [10] where I_{sc} boosts of 1.3% and 2.6% were obtained for edge and corner cells respectively, assuming a cell spacing of 3 mm and an edge space of 10 mm.



a. b.

FIGURE 1. a. Probability of collection of the light incident on spaces between cells as a function of cell spacing for different backsheet reflectance R_{BS}; b. Power gain from the light collected from the space around the cells as a function of cell spacing. Pseudo-square cells (M2) were considered which explains why the power gain is not zero for a 0 mm cell spacing. The space between the module edges and the cells was set to 18 mm in this study.

- **Positioning induced mismatch and impact on performances**

When cells with different individual current at maximum power point (I_{mpp}) are serially connected, the resulting I_{mpp} of the string (or the module) lies somewhere between the maximum and the minimum I_{mpp} of the cells. This means that most of the cells do not operate at their MPPs as Fig. 2a illustrates. The sum of the losses due to cells operating away from their individual MPPs is called cell-to-cell mismatch loss [11] and depends on the spread of the I_{mpp} of the cells and thus on the cell manufacturer binning strategy.[3] In order to quantify this mismatch loss, four thousand 60-cell modules with different I_{sc} bins were simulated. The resulting distributions are shown in Fig. 3a in grey.[4] In a second step, the additional mismatch caused by the current boost of the cells located on the edges and in the corners of the modules was accounted for in the simulations and the results are the colored distributions in Fig. 3a. It can be observed that the additional mismatch caused by the position of the cells in the module increases the average power loss but also the spread of the power loss distribution. Fig. 3b shows the average power loss due to mismatch as a function of bin size. For a bin size of 0.8A, the additional mismatch from the “module edge effect” increases the average mismatch loss by 0.11%. However, for a bin size of 0.2A, the “edge effect” only increases the mismatch loss by 0.04%[5]. Note that a range of I_{mpp} of 0.2A is more representative of modern industry standards [12] (even with binning in cell power). It can be concluded that, with small enough bins, the additional spaces around the edges of PV modules (with white

[3] Fig. 2b illustrates how series and shunt resistances also affect the mismatch loss: increasing series resistance (R_s) broadens the peak of the PI curves while decreasing shunt resistance (R_{sh}) narrows it. As can be inferred from Fig. 2a, the shape of the peak of the PI curves effectively impacts the mismatch loss of a module. For example, for a bin size of 1A, increasing R_s from 1.13 to 3 Ω cm^2 decreases the average mismatch loss from 1.1% to 0.7% and decreasing R_{sh} from 10^4 to 100 Ω cm^2 increases the mismatch loss from 1.1% to 1.2%. However, the effect of R_s and R_{sh} on mismatch loss is negligible (<0.01%) for a typical industrial bin size of 0.2A so it will not be mentioned thereafter.

[4] These results are in line with earlier literature (e.g. in [12]: also ≈0.05% average mismatch loss for a real batch of 3000 solar cells with an I_{mpp} range of 2%)

[5] These simulations highlight the very limited potential gain (0.04%) of selecting cells from different I_{sc} bins to be placed on the edges of modules.

backsheets) does not increase cell-to-cell mismatch losses and thus effectively boost the output power of the modules by about 0.5% as shown above. This value mainly depends on the reflectance of the backsheet and the module design (the area of apparent backsheet on the module edges). Two 60-cells commercially available modules (with different edge spaces) were tested with an indoor solar simulator. Power losses of 0.6% and 0.4% were measured when the edges of the modules were made opaque with a black tape. The losses come mainly from reductions in FF as the mismatch between the cells is reduced. To illustrate this phenomena, Figure 4a shows the IV curves of 60 cells with different I_{sc} and that of the module constituted by these cells serially connected. One can observe that, on one hand, the I_{sc} of the module is less than the average I_{sc} of the cells (closer to the minimum I_{sc}) but on the other hand, the FF of the module is larger than the average FF of the cell. This exemplify why the extra I_{sc} of the cells located at the edges of a module is converted in a power gain for the module via an increase of its FF. In fact, such a phenomena is important to analyze the CTM factors of modules even when the cell-to-cell mismatch is small. This is illustrated in Figure 4b where the distributions of the CTM factors of power, FF and I_{sc} are shown of 5000 simulated modules comprised of cells with I_{sc} in a 4% range. While the loss in power is low (CTM P_{mpp}<-0.15% on average), the cell-to-cell mismatch causes a strong negative CTM_I_{sc} (≈-1%) partially counterbalanced by a positive CTM_FF (≈+0.85%).

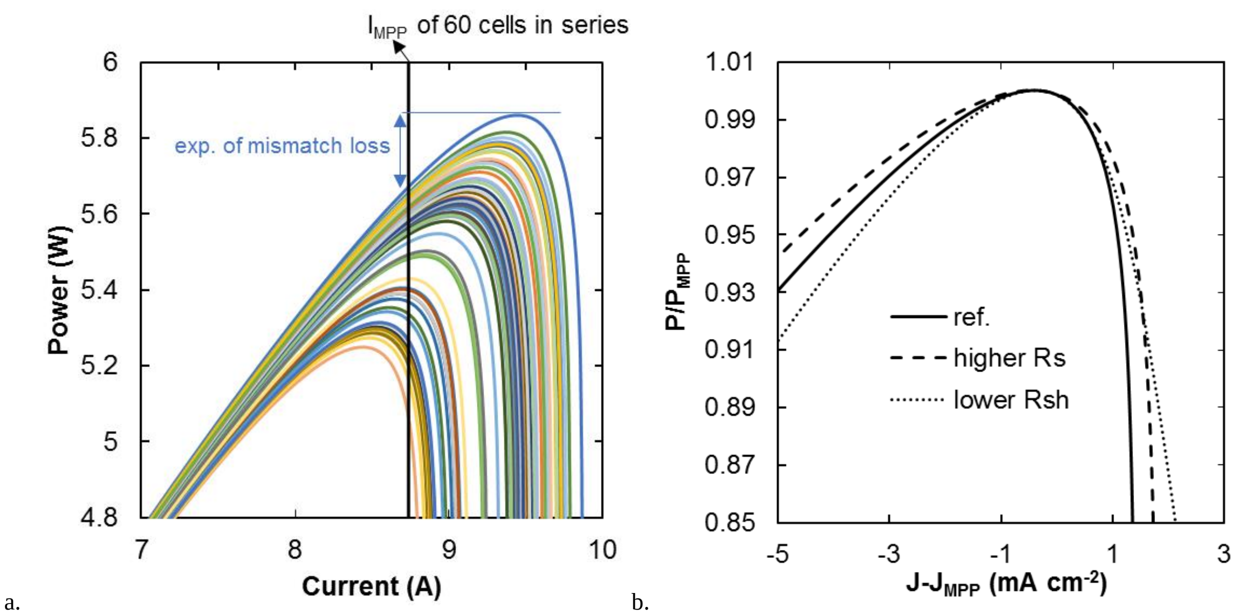


FIGURE 2. a. PI (power as a function of current) curves of 60 simulated solar cells (where only I_{sc} is varied for the sake of illustration). The vertical line shows the I_{MPP} of these 60 cells serially connected; b. PI curves of three solar cells with different series and shunt resistances. The simulations shown here are done with Matlab. The IV curves of the solar cells are calculated from a two diode model and the resulting module characteristics are found by summing at each current point the voltages of the serially connected cells.

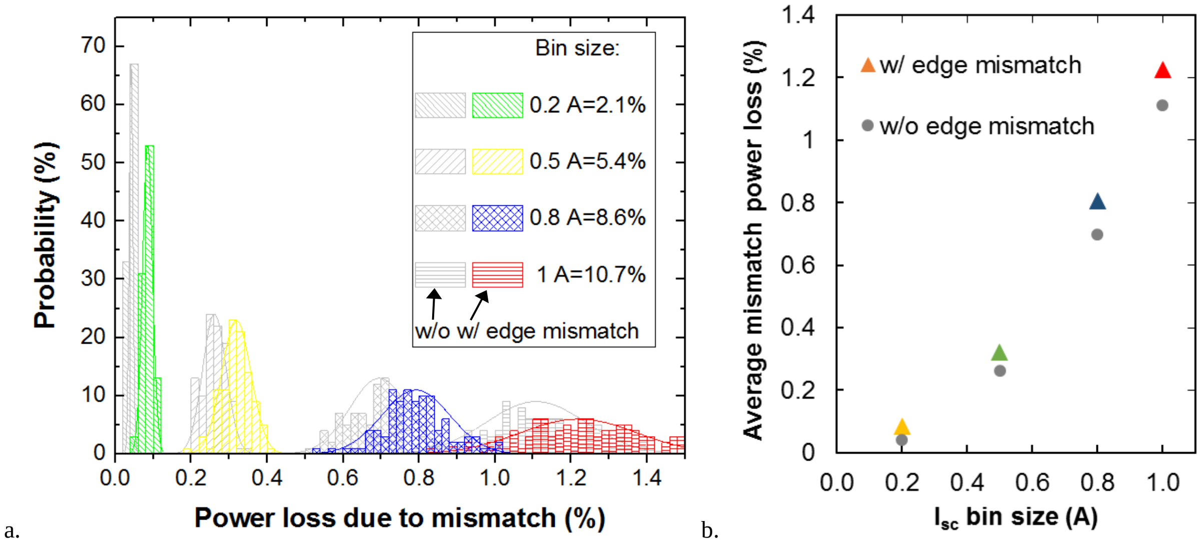


FIGURE **3.** a. Distributions of the power loss due to mismatch of modules comprised of cells from different I_{sc} bin sizes when neglecting (in grey) or accounting for (in color) the current boost of the cells located at the edges of modules; b. Average of the power loss due to mismatch as a function of bin size.

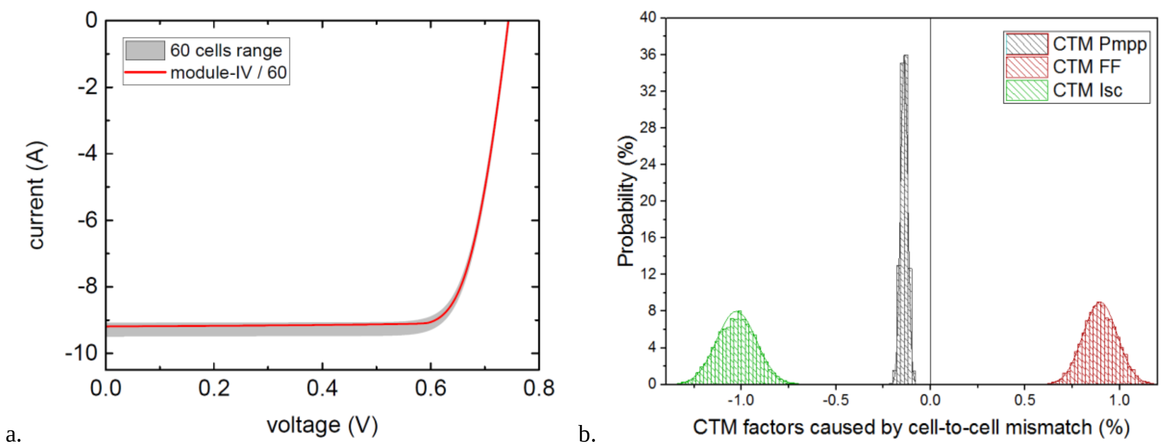


FIGURE **4.** a. In grey: simulated IV curves of 60 cells with identical characteristics but for I_{sc} randomly picked in a 4% range. In red: simulated IV curve of the module constituted of these 60 cells serially connected. b. Distributions of the CTM factors of power, FF and I_{sc} of 5000 simulated modules comprised of cells with I_{sc} in a 4% range.

4. CONCLUSION

This manuscript presented a study on two components of the Cell-To-Module ratio. The light recaptured after reflection on the backsheet surrounding the cells was measured by LBIC and simulated for different backsheet reflectances. The results demonstrate the importance of this light recollection mechanism in the CTM of modules with reflective (e.g. white) backsheets. About 45% of the light incident in these areas can be recollected for standard cell spacing (2-3 mm) and a backsheet reflectance of 87%. The significance of this recapture mechanism also emphasizes the importance of correctly masking 1-cell modules fabricated in R&D to determine CTM ratios. A novel finding of this study is that the spaces at the edges of modules, which is usually larger than the cell spacing for insulation purposes, have a significant impact on module performances. A gain of 0.5% from these edges was evaluated for a module with 18 mm at the edges and 2 mm cell spacing. Furthermore, the current boost from the surrounding backsheet for the cells at the edges of modules does not significantly increase the cell-to-cell mismatch loss as long as the bin size is small enough. With a I_{sc} bin size of 0.2A, the average cell-to-cell mismatch loss is below 0.05%. The different results presented in this manuscript can be used to reassess module designs and binning strategies and eventually serve as guidelines for optimizing the CTM ratios.

5. ACKNOWLEDGMENTS

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