SiliconPV 2023, 13th International Conference on Crystalline Silicon Photovoltaics
Module Characterization and Simulation
https://doi.org/10.52825/siliconpv.v1i.952

Published: 22 Feb. 2024

Performance Assessment of Cell-Separation Processes for Rear-Contact Solar Cells: Comparison of Indoor and Outdoor Measurements

Manuel Meusel[1], Amir A. Abdallah[2], Marko Turek[1], and Christian Hagendorf[1]

[1]Fraunhofer Center for Silicon Photovoltaics CSP, Germany

[2]Qatar Environment and Energy Research Institute – Hamad Bin Khalifa University, Qatar

Abstract. Half-cell and third-cell modules are the current module technology standard due to their enhanced electrical performance. Also, special module layouts for building or vehicle integrated photovoltaics rely on non-standard cell formats obtained by separation techniques. For either application, interdigitated back-contact (IBC) solar cells are one of the promising cell technologies due to their higher performance and more aesthetic appearance. Thus, a cell separation process, usually employing laser tools, is needed that splits the cells as partial cells are manufactured from full cells. However, this cell cutting also induces additional electrical losses. In this work, we analyze the performance of third cell mini-modules made of IBC cells in comparison to PERC cells as reference. Under standard test conditions (STC), an overall performance gain can only be found for the PERC cells, while current and recombination losses dominate the IBC mini-modules. Outdoor measurements under non-STC conditions reveal reduced performance gains under lower illumination. We show a detailed analysis regarding the performance differences of the IBC and PERC cell technologies at indoor STC and outdoor non-STC test conditions.

Keywords: Third cells, IBC, PERC, Laser cutting, Standard test conditions STC, Non-STC

1. Introduction and motivation

During the past few years, a clear trend towards larger solar cells formats has been observed. These larger cell sizes also imply larger currents generated by each cell. As series resistance losses are related to the absolute current values, larger cell formats directly imply larger electrical losses in a PV module. Therefore, a significant share of all standard PV-modules is manufactured based on half- or even third-cell technologies as these reduce the series resistance losses thus increasing fill-factor and efficiency.

Besides standard applications, other applications such as building- or vehicle-integrated PV also require non-standard cell formats. Here, the optical appearance of the PV modules plays an additional important role. Thus, all these applications require a cell separation which relies on a laser process usually implemented after all other cell processes. The cell cutting induces additional electrical losses, for example carrier recombination at the new cell edge, which reduce or even overcompensate the gains achieved in the module. These losses depend on several factors such as the laser process itself but also the cell technology, the number of laser cuts, and the test or operating conditions [1-4]. Further studies on the performance of half-cell modules also include simulations on reduced irradiance levels as well as a cost-of-ownership discussion [5, 6].

IBC technology is a further route to high efficiency solar cells besides the predominant PERC- and passivated-contacts-technologies. In addition to their improved performance, IBC solar cells also provide a more aesthetic appearance which makes these cells perfect candidates for special applications in building-integrated or vehicle-integrated photovoltaics. The effect of laser-cutting IBC solar cells has been discussed, for example, in references [7, 8].

Hence, an analysis of the applicability of laser-based cell separation techniques to back-contact solar cells is of significance. In contrast to conventional PERC cells, the more complex rear side metallization can impose some severe limitations regarding the applicability of a laser separation process. In our work, we present a performance analysis of a laser-scribe-and-cleavage (LSC) process applied to IBC solar cells in comparison to conventional PERC solar cells which serve as a reference. We show, that for the cells under investigation and STC measurements, the identical cell separation technology leads to the expected gains for third-cell mini-modules in case of the PERC cells while the losses dominate in case of the IBC cells. We compare these results to measurements performed under non-STC in an outdoor environment. We will present an in-depth analysis of the I-V-characteristics comparing STC and non-STC measurements explaining the observed differences between indoor and outdoor power assessment.

2. Experimental approach and data analysis

Our experiments are based on a set of commercially available IBC solar cells of size 125 x 125 mm^2. As reference cells, we have chosen PERC M3-sized solar cells with 5 busbars. Using these cells, we have manufactured a set of one-full-cell mini-modules and equivalent third-cell mini-modules by connecting the partial cells in series, see Figure 1. For the cell separation, we have implemented a laser process using an optical finder system in a 3DMicromac laser workstation that allows for the positioning of the laser scribe with very high lateral precision. This is required for the IBC solar cells because of their extremely fine-structured rear-side metallization layout.

In a first step, the cells are laser-scribed on their rear side with a scribe depth of approximately 40% of the cell thickness. Then, in a second step, the cells are mechanically cleaved to separate the partial third-cells from each other. The same approach has been applied to the reference PERC cells with an adapted set of laser parameters. Each step of third cell manufacturing is accompanied by a STC measurement. This measurement has been performed for full cells, laser scribed cells, cleaved cells, and laminated cells (mini-modules). In the end, there are three mini-modules with full cells and third cells for both cell types, IBC and PERC. Figure 1 (left) shows an overview over the experimental workflow using the example of the IBC cells.

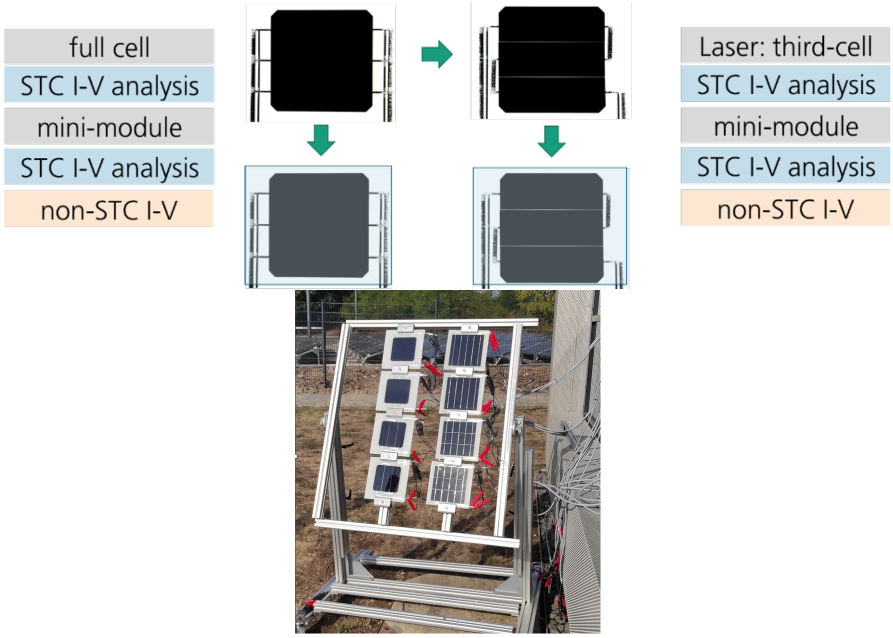

Figure 1. (left) Schematic overview over the experimental workflow for the comparison of full-cells with third-cells. (right) Bill-of-materials (BOM) tester setup for simultaneous measurement of mini-modules under non-STC outdoor conditions.

The cell and mini-module power measurements under STC have been performed with a LOANA solar cell characterization tool (pv-tools GmbH). Additionally, outdoor performance measurements were conducted with a bill-of-materials (BOM) tester which allows for a simultaneous measurement of up to 16 mini-modules under realistic outdoor conditions, see Figure 1 (right). The BOM-tester includes a high-precision measurement electronics (WAVELABS GmbH) used in indoor cell testing. This BOM-tester setup can bridge the indoor power measurements under STC towards outdoor conditions with different light intensities, temperatures, or angles of incidence.

To obtain results that are independent of the specific solar cell sample, performance indicators *PI* are introduced. These performance indicators are determined for all relevant electrical parameters according to

$$PI = (P_{MiMo,third} / P_{Cell,third}) / (P_{MiMo,full} / P_{Cell,full}) \quad (1)$$

where the parameter P = {I_{sc}, V_{oc}, FF, η} represents short circuit current, open circuit voltage, fill factor, and efficiency or power, respectively. Thus, for each of these key cell performance variables, the performance indicator *PI* is calculated and represents the gains (or losses) in the third-cell approach compared to the full-cell setup independently of the cell performance itself.

3. Results

During the manufacturing of the mini-modules, an electrical characterization at STC has been performed at several intermediate steps which allows for an in-depth analysis of loss mechanisms that occur for each cell technology. In Figure 2 (left), the two most affected quantities, i.e., short circuit current and pseudo-fill-factor, are shown. They have been chosen as the short circuit current represents any size mismatch of the partial cells while the pseudo-fill-factor is related to recombination losses independent of the influence of the series resistance.Regarding the short circuit current, the PERC cells show only a minor loss of about

0.2% caused by the laser scribe which is within the measurement uncertainty. On the other hand, the IBC cells show a loss in short circuit current of about 1%. This increased loss is related to a de-activation of certain cell regions due to the separation of the complex rear-side metallization pattern, see Figure 3. This complex rear-side metallization pattern of the analyzed IBC cells leads to an electrical isolation of some cell regions due to the laser scribe. This can be clearly observed in the electroluminescence images. The orange arrows point to regions close to the contacts that are electrically isolated, see microscopy image in Figure 3 (right). Furthermore, the laser cut lines have to be placed in between two metallization lines. Hence, also along the laser-cut lines a small fraction of the active area might be isolated depending on the exact positioning of the laser relative to the metallization, see green arrow in Figure 3 (left). Also, a size mismatch between the center third-cell compared to the left and right third-cell is also related to the constrains due to the metallization pattern. Thus, in addition to the effect on the individual third-cells, the series connection of IBC third-cells after complete cell separation reduces the current furthermore by another 2% due to the metallization pattern induced size mis-match of the three partial cells.

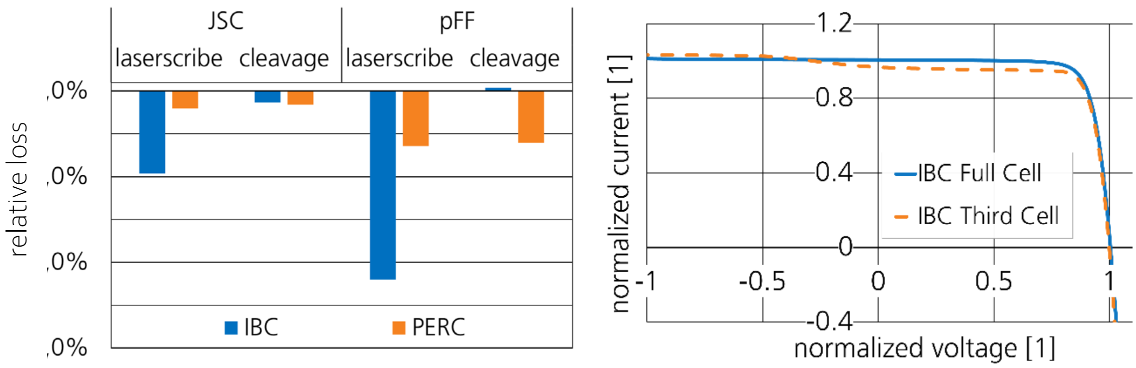

Figure 2. (left) Electrical losses of the third-cells related to short-circuit current and pseudo-fill-factor caused by the two-step cell separation. (right) Comparison of I-V-curves for full-cell and third-cell IBC cells with a pronounced step near short circuit current in the case of third cells.

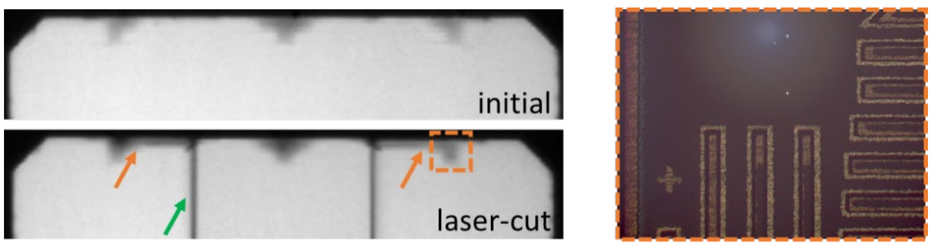

Figure 3: Electroluminescence imaging of the IBC-cell before laser-cutting (initial) and after laser-cutting. The orange and green arrows mark the typical positions that are prone to a current loss as certain regions of the cell are electrically isolated due to the metallization and contact pattern shown in the right part of the image.

The fill-factor is the second relevant parameter describing the electrical losses. It is related to series resistance losses as well as recombination losses. To analyze recombination losses without the effect of the series resistance, the pseudo-fill-factor pFF is investigated under STC. The laser-scribe process leads to a loss of about 2.2%$_{rel}$ in pFF for the IBC cells without any further losses due to the second cleavage step. This compares to the PERC cells where a loss of about 0.6%$_{rel}$ in pFF due to the laser scribe and a further loss of another 0.6%$_{rel}$ due to the cleavage is observed. Thus, the recombination induced losses for the IBC cells are directly related to the laser scribe itself and appear to be larger than for the PERC cells by about 1%$_{rel}$.

For IBC cells, a low break-through voltage of about -1.5 V can be observed which directly impacts the I-V-curve of series connected cells. In a series connection between three IBC third-cells that are not entirely equal in size, a step (approx. 6% of I_{SC}) in the I-V-curve close to U = 0 V, i.e., in the region of I_{SC}, is visible as presented in Figure 2 (right). On the other hand, the fill-factor is determined from the maximum power, short circuit current, and open circuit voltage. This implies that in case of series connected IBC cells or mini-modules, a loss analysis regarding the fill-factor needs to compensate for this current effect in the vicinity of the short-circuit current which is related to the low break-through voltage and varying cell sizes.

The overview of the major performance indicators PI of the laminated mini-modules is shown in Figure 4. The STC results are represented by the wide-striped bars. It can be observed that there is an overall power gain for the PERC cells under STC (filled orange boxes, vertical stripes) of about 3% due to the increase in fill-factor which compensates the losses in the other parameters. This reflects the well-known result of reduced series resistance losses. It contrasts the overall power loss of about 2% observed for the IBC cell (filled blue boxes, horizontal stripes). In this case, the recombination losses (pFF) and current losses (I_{sc}) of the third-cells caused by the laser process, see Figure 2 (left), are not compensated by the reduced series resistance effects. This is related to the fact that the absolute current values are about twice as large for the PERC cells compared to the IBC cells. This makes the PERC cells significantly more prone to series resistance losses which are then clearly reduced by the third-cell approach. In addition to these differences in absolute current values, the interconnection scheme between the PERC cells and the IBC cells is very different in our setup. The PERC third-cells are connected to each other with the same number of cell-interconnectors than the PERC full-cells. This leads to a reduction of current density in the interconnectors for the third-cells thus reducing the series resistance effects. On the other hand, the IBC cells are series connected with a reduced number of cell-interconnectors, i.e. one interconnector per third-cells vs. three interconnectors per full-cells. Hence, the current density per interconnector remains rather unchanged thus leading to no significant series resistance loss reduction.

An indoor measurement with reduced intensity of 0.5 suns reveals that current and voltage performance indicators remain rather unchanged compared to the 1 sun results. On the other hand, the gains in the fill-factor are reduced due to the lower absolute current values, as expected. For the PERC cells, this leads to a vanishing net-gain in efficiency. In case of the IBC cells, the overall losses are increasing as there is no FF-gain observed which could compensate the current losses.

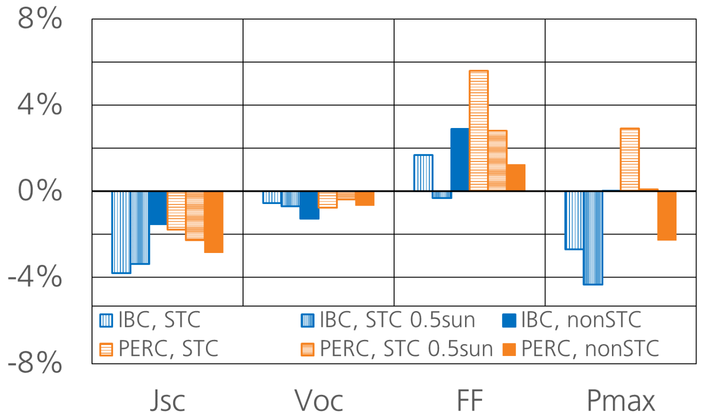

Figure 4. Performance indicators obtained for the mini-modules for short circuit current I_{sc}, open circuit voltage V_{oc}, fill-factor FF and maximum power P_{max}. The IBC technology is represented in blue while PERC is represented in orange. Striped boxes represent STC while filled boxes correspond to outdoor non-STC.

For the PERC cells, the outdoor non-STC results show a similar trend for the fill-factor as the indoor measurements under 0.5 suns. This is also related to the lower outdoor illumination intensity which was estimated to be about 0.25 suns only. The other parameters, i.e. I_{sc} and V_{oc}, are not significantly affected. Therefore, the outdoor results are consistent with the indoor observations in case of the PERC cells.

The short circuit current losses for the IBC cells are not as prominent for the outdoor setup as for indoor STC measurements. As mentioned earlier, the I_{SC} determination is affected by the step-like artefact in the I-V-curve due to the size mismatch and lower break-through voltage. Since the I_{SC} is part of the fill-factor calculation, the step-like behavior in the I-V-curve of third-cell mini-modules influences the performance indicator *PI* of the FF as well. While the power values of the PERC cell also decrease with decreasing irradiance, this behavior is observed for the IBC cells only under STC conditions. The non-STC (outdoor) performance indicator related to P_{max} for IBC cells is near zero implying that the third-cell mini-module is not much different from the full-cell mini-module if the measurements are compensated for differences in individual cell performance.

4. Discussion

We have shown that the separation process of the solar cells leads to different kinds and amounts of electrical losses for PERC and IBC technology. While the IBC cells show a high pFF decrease caused by the laser scribe process and nearly zero pFF change by cleavage process, these two steps of the cell separation show a comparable pFF loss for PERC cells. Furthermore, the overall pFF loss due to cell separation is lower for PERC cells than for IBC cells. Thus, it can be concluded that the laser process induces a larger edge damage to the IBC cells compared to the PERC cells.

Focusing on the I_{SC}, the observed changes for the PERC cells are within the measurement uncertainty and can be neglected. The IBC cells, on the other hand, show a significant current loss due to the laser scribe process. There are two main reasons for this current drop directly related to the specific metallization pattern. On the one hand there are constrains regarding the position of the laser scribe between two fingers. Together with the pseudo square design of the solar cell, the cell sizes of the third cells do not match perfectly. On the other hand, the separation of the cell in three parts causes certain smaller cell regions being disconnected to the contacting grid due to the complex metallization layout. These current losses could be avoided by adjusting the metallization pattern for third-cell applications.

A detailed analysis of the I-V-curves of the third-cell mini-modules with IBC cells shows a current step of approx. 6% near I_{SC}. This step is caused by the area mismatch between the three cell stripes accompanied by the low reverse breakdown voltage of approximately -1.5 V for IBC cells. STC measurements with increasing irradiance levels show a decrease of the voltage value at which this current-step feature occurs. Thus, the short circuit current value get more significantly affected by this feature for lower intensities. Therefore, the determination of the short circuit current I_{SC}, and thus indirectly the fill-factor FF = P_{max} / (I_{sc} V_{oc}), is affected by this step and needs to be compensated for. The internal back reflection from the white backsheet may also cause a further current effect depending on the optical properties of the backsheet and the module glass.

A performance indicator *PI* is introduced to quantify the impact of the third-cell approach for mini-modules. This performance indicator *PI* is determined for all major I-V-parameters. It quantifies the parameter changes from full-cell to third-cell and corrects for the specific cell parameters of the initial cell which is used to build a sample. In this way, the effect of the third-cell approach is separated from the specific cell and can be investigated under various measurement conditions.

The current-*PI* values (obtained from I_{sc}) for PERC cells decrease with lower intensity which is observed when changing the intensity from 1 sun (STC) to 0.5 sun and to non-STC with approximately 0.25 sun. The current-*PI* for the IBC cells shows the opposite behavior due to the irradiance dependent step-like feature in I-V-curve. The voltage-*PI* (obtained from V_{oc}) is nearly unaffected by the third cell technique.

For PERC cells, the fill-factor-*PI* shows a positive value for STC measurement which is caused by a decrease in series resistance losses due to the lower current of the third-cells compared to the full-cells. This means, that there is a significant performance gain when employing third-cells. This effect decreases with lower irradiance because the overall current and thus the resistance losses of the full-cell setup decrease, too. Regarding the fill-factor, the IBC cells do not show a similar clear trend as the PERC cells. On the one hand, the absolute current is smaller, which is caused by the smaller cell area of the cells analyzed in this study. Furthermore, the contacting scheme employed in this work is completely different from the PERC cells as not only the size of the individual cell is reduced to one third but also the number of cell-interconnectors is reduced from three to one. Thus, only the cross-connectors might induced some minor series resistance effects while no gains for the cell-interconnectors are to be expected. The non-STC measurement of the IBC cells show some increase in the fill-factor FF. This increase is caused by a high P_{max} value, which overcompensates the effect of the step-like feature in the I-V-curve.

For PERC cells, a P_{max} gain due to the third-cells is observed for irradiances higher than 0.5 sun. For lower irradiances, no power gain for PERC cells is observed. The high I_{SC} losses and missing gains in FF lead to a P_{max} loss even for STC conditions for IBC cells. The observed outdoor power-*PI* value for IBC cells of 0% is not fully understood, yet. It is not directly related to low light irradiation conditions. In future experiments, temperature conditions or IBC specific cell-to-module effects have to be taken into account.

5. Conclusions

We present an analysis of power losses and gains caused by laser cutting of solar cells. In particular, we compare rear contact solar cells with the PERC technology. STC measurements show a power gain for the PERC cells as expected. These gains are reduced for lower intensities corresponding to lower currents. For the investigated IBC solar cells, the losses dominate in the third-cell setup. One reason is the different cell interconnection scheme for third-cells with equally reduced number of cell-interconnectors. Hence, no significant series resistance gains are expected as there is no current density reduction related to the cell-interconnectors. Also, the smaller cell size of the cells investigated reduces the potential for power gains related to a third-cell setup as smaller current values generally lead to smaller benefits regarding series resistance losses. On the other hand, rather high pseudo-fill-factor losses can be observed which are caused by carrier recombination induced by the laser process. Finally, the metallization pattern needs to be optimized to avoid size mismatches and electrical isolation of certain cell parts. Without these cell design optimizations, a performance gain cannot be expected for the IBC cells when using third-cells.

Data availability statement

All data related to this work can be provided by the authors upon request.

Funding

This publication was made possible by NPRP grant # [NPRP11S-1220-170110] from the Qatar National Research Fund (a member of Qatar Foundation). The findings herein reflect the work, and are solely the responsibility, of the authors.

Author contributions

Manuel Meusel has been contributing to this work regarding conceptualization, data curation, software, formal analysis, investigation, visualization, and writing. Amir A. Abdallah has been contributing to conceptualization, funding acquisition, validation, and writing. Marko Turek has been contributing to this work regarding conceptualization, formal analysis, supervision, funding acquisition, validation, investigation, methodology, writing, and project administration. Christian Hagendorf has been contributing to conceptualization, supervision, funding acquisition, validation, and writing.

Competing interests

The authors declare that they have no competing interests.

References

1. F. Kaule, et al., "Mechanical damage of half-cell cutting technologies in solar cells and module laminates" Silicon PV 2018: The 8th International Conference on Crystalline Silicon Photovoltaics, 2018, DOI: 020013 https://doi.org/10.1063/1.5049252.
2. S. Eiternick, et al., "Loss analysis for laser separated solar cells", Proceedings of the 4th International Conference on Crystalline Silicon Photovoltaics, p. 326-330, 2014, DOI: https://doi.org/10.1016/j.egypro.2014.08.094.
3. S. Krause, M. Meusel, S. Eiternick, M. Turek. "Laser cutting of solar cells by using the stress cut approach", 38th European Photovoltaic Solar Energy Conference and Exhibition, 2021, DOI: https://doi.org/10.4229/EUPVSEC20212021-2EO.3.3.
4. S.Y. Guo, et al., "Investigation of the short-circuit current increase for PV modules using halved silicon wafer solar cells", Solar Energy Materials and Solar Cells, 133, pp. 240-247, 2015, DOI: https://doi.org/10.1016/j.solmat.2014.11.012.
5. M. Mittag, et. al., "Techno-economic analysis of half-cell modules - the impact of half cells on module power and cost". 36th European Photovoltaic Solar Energy Conference and Exhibition, Marseille, France, 2019.
6. H. Hanifi, et. al. "Techno-economic assessment of half-cell modules for desert climates: An overview on power, performance, durability and costs", Energies 15, 2022. DOI: https://doi.org/10.3390/en15093219.
7. R. Kopecek, et. al., "Interdigitated back contact technology as final evolution for industrial crystalline single-junction silicon solar cell", Solar 3, 2023. DOI: https://doi.org/10.3390/solar3010001.
8. N. Chen, et. al., "Mitigating cut losses in interdigitated back contact solar cells", IEEE Journal of Photovoltaics, vol. 12, 2022, doi: 10.1109/JPHOTOV.2022.3208507.