Presented at the WCPEC-8, 8th World Conference on Photovoltaic Energy Conversion, 26-30 September 2022, Milan, Italy

INTERCONNECTION TECHNOLOGY IN PV MODULES: IMPACT OF RIBBONS, TAB CONNECTORS AND ELECTRICALLY CONDUCTIVE BACKSHEET ON MODULE PERFORMANCE

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ABSTRACT: The interconnection technology is one of the aspects that is being continuously researched and developed in photovoltaic (PV) modules [1–4]. The aim of this study is to analyze the impact of the used interconnection technology in the PV module such as ribbons, tab connectors and electrically conductive backsheet (ECB) on cell-to-module (CTM) power losses [5, 6]. To that end, we adapt and develop analytical models that consider the geometry of the contact metallization of the solar cell as well as the geometry and properties of the interconnector being it rectangular ribbon, round ribbon, tab connector or ECB. The study considers different loss and gain channels of the CTM analysis such as power loss due to solar cell's active area shading and ohmic resistance of the interconnection. Simulation results show a maximum PV module power improvement of about 4% by using back contact solar cells interconnected using ECB compared to PV modules with solar cells interconnected using conventional rectangular ribbons. PV module with tab connectors exhibit a power improvement of about 3.4% compared to conventional cell interconnectors. That is a result of clearly less power loss due to ohmic resistance of the tab connectors, because of shorter current path as well as because of the larger cross section area of the current path using ECB. Furthermore, PV modules with back contact solar cells exhibit no loss due to shading of the interconnectors, because of the position of all contact pads on the backside of the solar cell compared to about 6 W power loss in case of rectangular ribbons. CTM analysis shows that the PV module with round ribbons exhibit about 3.6 W power gain due to light coupling by interconnectors compared to 1.5 W for the PV module with rectangular ribbons.

Keywords: PV Modules, Interconnection Technology, Ribbons, Electrically Conductive Backsheet (ECB), CTM

1 INTRODUCTION

The PV market expands and becomes more complex with all components and technologies of the module being permanently optimized to achieve higher power and efficiency [7]. Considering different loss channels in the PV module, the electrical losses due to cell interconnection can be reduced using different approaches and technologies. Typically, solar cells in the PV module are interconnected using rectangular SnPb-coated copper ribbons as shown in Figure 1 (left).

Since the ribbons are commonly placed on the front side of the solar cell, the width of the ribbon should be minimized to reduce the shading effect on the solar cells active area that leads to less power and efficiency. Minimizing the width of the interconnection ribbon decreases its cross-section area and therefore increases its ohmic resistance resulting in higher module electrical losses. Round ribbons as shown in Figure 1 (right) can increase the optical gain due to higher light coupling [1, 2].

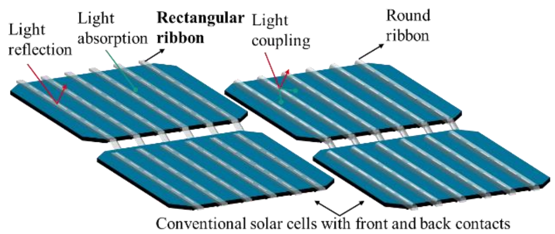

Figure 1: Solar cells interconnected using (left) rectangular and (right) round ribbons.

One way to optimize the PV modules electrical losses without compromising optical losses due to shading is the use of back contact solar cells such as interdigitated back contact solar cells (IBC) or metal wrap through solar cells (MWT) [8, 9], which offer larger active area on the solar cells front side due to missing metallization. Depending on the cell's metallization, such cells can be interconnected using tab connector or an electrically conductive backsheet as shown in Figure 1 (left, right), respectively.

The ECB is normally made of copper, that has a certain pattern to separate negative and positive contacts. Integrating back contact solar cells into PV modules can be realized using specially designed conductive backsheet that exactly matches the metallization pattern of the solar cell [10]. Using electrically conductive adhesive (ECA), back contact solar cells can be simply fixed on the conductive backsheet to be interconnected to each other.

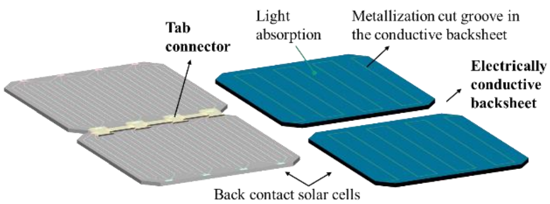

Figure 2: Back contact solar cells interconnected using (left) copper tab connector and (right) electrically conductive backsheet (ECB).

Based on the solar cell's metallization, the ECB pattern, and its thickness, the ohmic resistance of the current path and therefore the electrical loss can be calculated. The pattern of the ECB can be designed in a way that maximizes the width of the busbar current path and therefore minimizes its ohmic resistance. Increasing the thickness of the ECB increases the cross-section area of the current path and therefore decreases the electrical losses.

On the other hand, increasing the thickness of the conductive backsheet negatively affects the overall price of the PV module resulting in higher specific PV module cost [€/W_p].

2 MODELLING

In this section, the approach used in developing and adapting different models to simulate PV modules using different interconnection technologies is presented. First, the geometry of the solar cell and its metallization is parameterized for further calculations.

Table I: Geometrical parameters and their description of a solar cell with contact pads.

Parameter	Description
l_{cell}	Length of solar cell
w_{cell}	Width of solar cell
d_{psq}	Pseudo-square diameter
l_{pad}	Length of contact pad
w_{pad}	Width of contact pad
d_{pads}	Vertical distance between contact pads
d_{busbars}	Horizontal distance between busbars
$d_{\mathrm{left/right}}$	Left/right distance between contact/busbar pad and cell edge
$d_{\mathrm{top/bottom}}$	Top/bottom distance between contact pad/busbar and cell edge

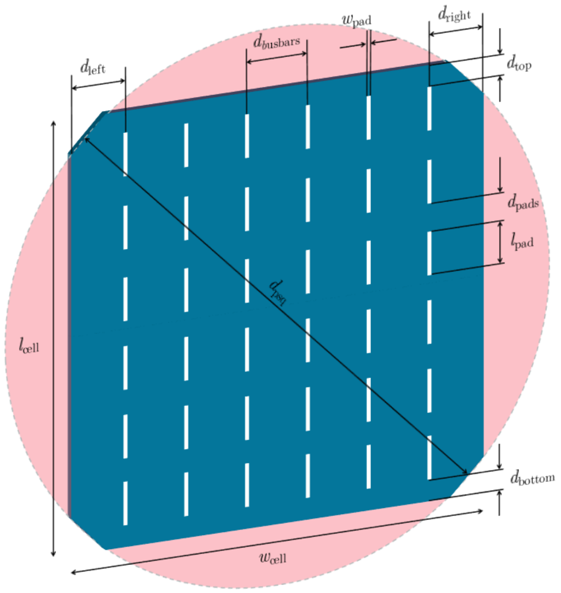

Figure 3: Illustration of the geometry of a solar cell with contact pads.

Basically, the calculation of the power loss P_{loss} due to the ohmic resistance is done using the following equation, where R is the ohmic resistance and I is the flowing electrical current.

$$P_{\mathrm{loss}} = RI^2 \qquad (1)$$

First, the magnitude of the electrical current collected by each metallization element, (in this case contact pad), is calculated. Since the magnitude of the current can be assumed to be linearly related to the solar cell active area, the calculation is based on the position of the contact pad and therefore on the area of interest ($\mathrm{AOI}_{\mathrm{i,j}}$) shown in Figure 4. i and j are the indices of the pad and busbar, and $\mathrm{N}_{\mathrm{pad}}$ and $\mathrm{N}_{\mathrm{busbar}}$ represent the number of pads and busbars, respectively. In case of continuous busbar i and $\mathrm{N}_{\mathrm{pad}}$ are equal to 1. In the following equation, the calculation of the current's magnitude of an exemplary contact pad (highlighted in red in Figure 4) is shown.

$$\mathrm{AOI}_{2,3} = (l_{\mathrm{pad}} + d_{\mathrm{pads}})\, d_{\mathrm{busbars}} \qquad (2)$$

The same approach is used for the front and back side of the solar cell. In case of using back contact solar cells, the geometry of the metallization for both n and p contacts is considered on the back side.

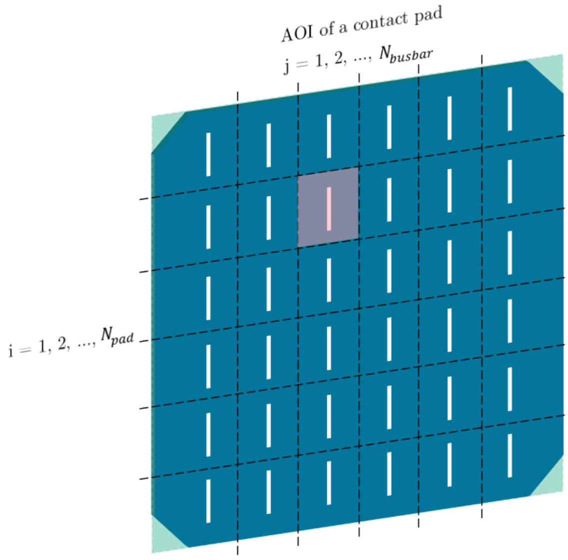

Figure 4: Area of Interest (**$\mathbf{AOI_{i,j}}$**) used to calculate the current's magnitude.

To calculate the collected current by a specific metallization element, the following equation is used, where I_{mpp} is the solar cells current at the maximum power point.

$$I_{\mathrm{i,j}} = \mathrm{AOI}_{\mathrm{i,j}}\, I_{\mathrm{mpp}} \qquad (3)$$

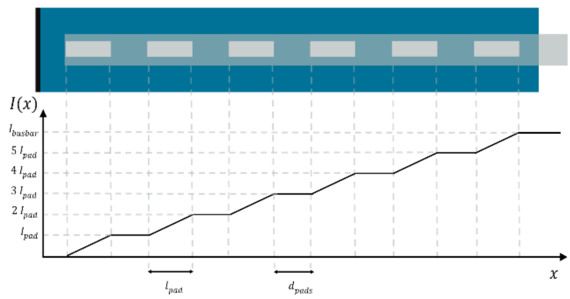

Figure 5: Description of electrical current increase through a cell interconnector (ribbon) soldered to a non-continuous busbar over distance.

The electrical current is generated from the solar cells active area and transported into the busbars or contact pads. Therefore, the magnitude of the electrical current flowing in the electrical current path, i.e. the ribbon in Figure 5, grows over the distance for the sections where the ribbon is soldered onto the metallization. By neglecting the effect of the fingers conducting the current, a constant current for the unsoldered ribbon sections is assumed.

The electrical current increment in a soldered ribbon section can be described by the following relation, where x describes the distance and I_{pad} is the collected current in the contact pad.

$$I(x) = \frac{I_{pad}}{l_{pad}} x \tag{4}$$

Considering solar cells with rectangular ribbons, round ribbons or tab connectors as shown in Figure 6, besides the electrical resistivity ρ, the width w and the thickness t of the cell interconnector are constant and therefore its cross-section area A. That means only the magnitude of the electrical current changes over the distance as explained in Figure 5.

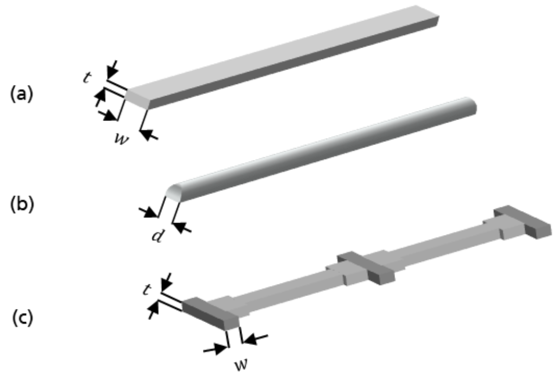

Figure 6: Illustration of different cell interconnectors; (a) rectangular ribbon, (b) round ribbon and (c) tab connector (elements of current path are dark gray).

To assess the ohmic loss in a soldered connector section, it is calculated by integrating the dissipated power in the connector over the length of the metallization element, i.e. the contact pad. The power loss calculation in soldered sections is presented using the following equation [5].

$$P_{\text{loss}} = \frac{\rho}{A} \int_0^{l_{\text{pad}}} I(x)^2 \, dx = \frac{1}{3} \frac{\rho \, l}{A} I_{pad}^2 \tag{5}$$

Since the magnitude of the collected current in unsoldered connector sections is constant (see Figure 5), the power loss in these sections is calculated as shown in the following equation.

$$P_{\text{loss}} = \frac{\rho \; l}{A} I_{pad}^2 \tag{6}$$

Beside the tab connector, back contact solar cells can be interconnected using ECB. Such a backsheet is made of copper and has a certain groove pattern to match the metallization contacts on the solar cell's backside [8]. The cut groove separates the n- and p-contacts from each other to realize the series or parallel connection between solar cells or strings in the PV module as shown in Figure 7.

In addition to the electrical current function, Figure 8 shows the change in the current path width in an electrically conductive backsheet. The width starts from a minimum value of w_0 and increases linearly to reach a maximum value of w. The maximum width w depends on the horizontal distance between two busbars d_{busbars} and the minimum cut groove width w_0 and can be expressed as follows.

$$w = d_{\text{busbars}} - w_0 \tag{7}$$

The width change function of the cut groove $w(x)$ can be described using the following equation, where $d_{\text{ECB,top}}$ and $d_{\text{ECB,bottom}}$ are the top and bottom distance between the cut groove and the edge of the solar cell as illustrated in Figure 9.

$$w(x) = w_0 + \frac{w - w_0}{l_{\text{cell}} - d_{\text{ECB,top}} - d_{\text{ECB,bottom}}} x \tag{8}$$

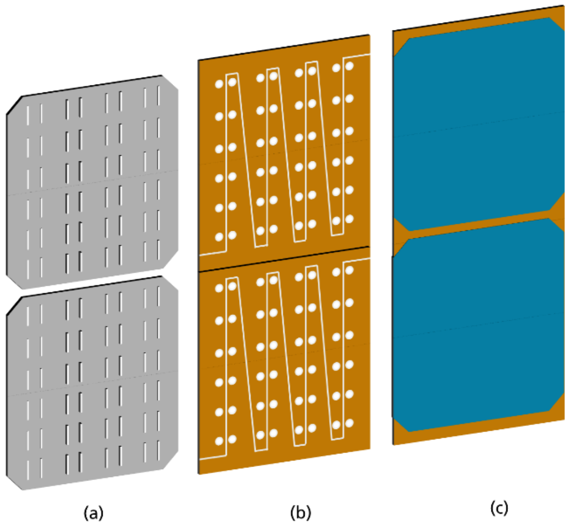

Figure 7: Illustration of (a) two back contact solar cells, (b) an ECB with exemplary cut groove and (c) two back contact solar cells interconnected in series using ECB.

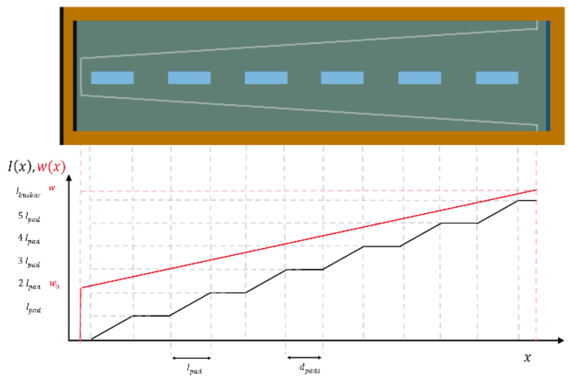

Figure 8: Description of electrical current increase through an ECB section (black) and width of current path increase (red) over distance.

To exemplarily calculate the ohmic power loss in the ECB of the top contact pad section shown in Figure 9, the following equation is used, where ρ and t are the electrical resistivity and the thickness of the ECB, respectively.

$$P_{\text{loss}} = \frac{\rho}{t} \int_{d_{\text{ECB,top}}}^{d_{\text{ECB,top}} + l_{\text{pad}}} \frac{I(x)^2}{w(x)} \, dx \tag{9}$$

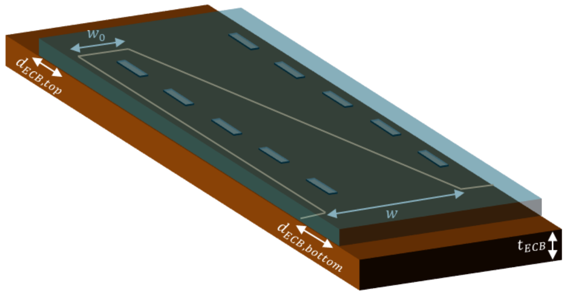

Figure 9: Illustration of an ECB section with an exemplary trapezoidal cut groove underneath a back contact solar cell section.

In addition to the power loss due to the ohmic resistance of the cell interconnector, the power loss due contact resistance because of soldering or ECA gluing is considered. To calculate the total ohmic power loss due to interconnection in a solar cell, the power loss is calculated for each connector section and finally summed up. The calculation is done for both p- and n-polarities. To scale up the calculation into a PV module level simulated under standard test conditions (STC), the solar cell power loss is multiplicated by the number of solar cells in the PV module.

3 SIMULATIONS AND RESULTS

To make a comparison between the different interconnection technologies studied in this work, firstly, the common simulation parameters as shown in Table II are set.

Table II: Common simulation parameters of the PV module.

Parameter	
Number of solar cells	60 cells
Solar cell format	Full cells (166×166 mm^2)
Solar cell power	5.5 W
Connection type	Series (10×6)
Type of busbar	Contacts pads
Cell and string distance	2 mm
Interconnector/ECB thickness	0.15 mm
Electrical resistivity	1.8 μΩ cm
Ribbon/tab connector width	1.5 mm
Round ribbon diameter	0.3 mm
ECB cut groove pattern	Trapezoidal (w_0 = 5 mm)

For each interconnection technology, the type of the solar cell and its typical parameters are chosen. For a PV module with rectangular ribbon interconnection, 5 busbars H-pattern solar cells are simulated. In case of round ribbons, multi busbar solar cells with 12 busbars are used. For PV modules with tab connector, back contact solar cells with three terminals are used. PV modules with ECB are simulated with back contact solar cells with four non-continuous busbars.

The simulation is done under standard test conditions (STC) using SmartCalc.Module, a software developed by Fraunhofer ISE by applying a bottom-up multi-physics model [11, 12]. The model used considers loss and gain channels that take place in the PV module when interconnecting the solar cells. That includes geometrical losses, optical losses and gains, and electrical losses [5, 13]. The comparison results are shown in Figure 10.

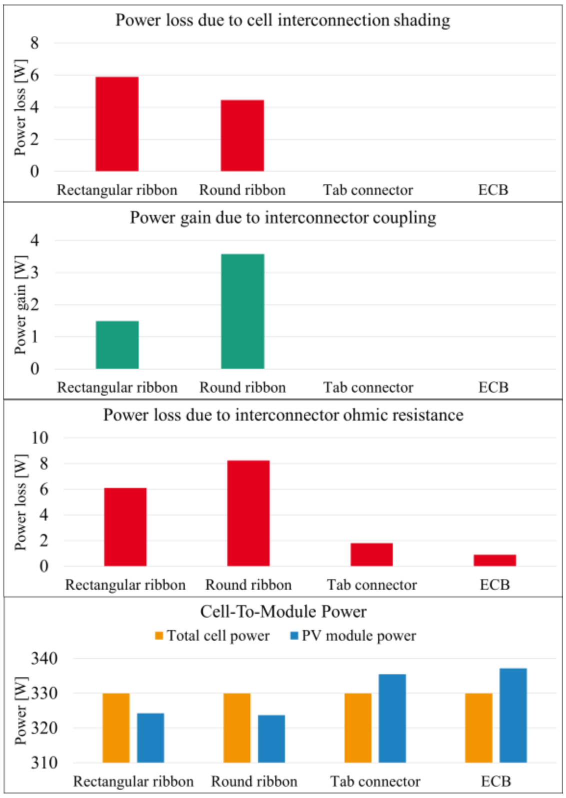

Figure 10: Comparison between different interconnection technologies regarding power loss due to interconnection shading, power gain due to interconnector coupling, power loss due to ohmic resistance and CTM power.

Considering the different loss and gain channels of the CTM analysis, the power loss due to shading of solar cells active area by the interconnection, power gain due to light coupling by the interconnection and the power loss due to ohmic loss are the main channels affected by the interconnection technology in the CTM analysis. Based on the used simulation parameters, the rectangular ribbon has the highest power loss due to shading with about 6 W. Using round ribbons reduces the power loss due to shading to about 4.5 W. Since interconnecting the back contact solar cells using tab interconnectors or ECB does not cover any active area of the solar cell, the power loss due to shading in both cases is 0 W.

Compared to rectangular ribbons, round ribbons reflect more light into the solar cells active area. Therefore, the PV module with round ribbons exhibit more than twice power gain due to light coupling compared to the PV module with conventional rectangular ribbons. Since back contact solar cells are interconnected from the backside, they do not exhibit any power gain due to light coupling on the front side of the solar cell.

Regarding the power loss due to ohmic resistance of the interconnector, the PV modules with IBC solar cells using tab connectors and ECB exhibit a clear lower loss compared to the rectangular and round ribbon. This is due to lower ohmic resistance, because of a shorter current path of the tab connector and the larger current path cross section area of the ECB. The exemplary PV module with ECB shows about 83% less power loss compared to the PV module with the conventional rectangular ribbons.

As a result, and by considering other CTM gain and loss channels [1, 2], the PV module with the ECB shows the highest CTM power with about 337.2 W_p compared to about 335.5 W_p for the PV module with tab connectors, 323.7 W_p for the PV module with round ribbons and 324.3 W_p for the PV module with the conventional rectangular ribbons.

4 CONCLUSIONS AND OUTLOOK

Based on the results shown in the previous section, the PV modules with back contact solar cells exhibit a higher module power compared to the PV modules with conventional H-pattern solar cells. The higher PV module power is mainly due to the lower ohmic resistance of the current path using tab connectors and ECB compared to the rectangular and round ribbons. Furthermore, interconnecting back contact solar cells results in zero loss because of cells active area shading due to cell interconnectors.

On the other side, other aspects should be considered and studied such as the durability and mechanical stability of the solar cell interconnections. Furthermore, production challenges and cost analysis should be studied and evaluated for each interconnection technology to have a holistic comparison between the different interconnection technologies.

ACKNOWLEDGEMENTS

Current study was prepared in the framework of the project HighLite, which was funded by the European Union’s Horizon2020 Program under Grant Agreement No 857793.

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