RESEARCH ARTICLE



Performance of shingled solar modules under partial shading

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Abstract

Significant progress in the development and commercialization of electrically conductive adhesives has been made. This makes shingling a very attractive approach for solar cell interconnection. In this study, we investigate the shading tolerance of two types of solar modules based on shingle interconnection: first, the already commercialized string approach, and second, the matrix technology where solar cells are intrinsically interconnected in parallel and in series. An experimentally validated LTspice model predicts major advantages for the power output of the matrix layout under partial shading. Diagonal as well as random shading of a 1.6-m² solar module is examined. Power gains of up to 73.8 % for diagonal shading and up to 96.5 % for random shading are found for the matrix technology compared to the standard string approach. The key factor is an increased current extraction due to lateral current flows. Especially under minor shading, the matrix technology benefits from an increased fill factor as well. Under diagonal shading, we find the probability of parts of the matrix module being bypassed to be reduced by 40 % in comparison to the string module. In consequence, the overall risk of hotspot occurrence in matrix modules is decreased significantly.

KEYWORDS

matrix modules, partial shading, shingle solar cells

INTRODUCTION 1

In recent years, the market for solar modules significantly changed from more or less exclusively ribbon-based interconnection of fullsquare solar cells to a wide variety of cell formats and interconnection technologies which continuously increased power outputs.¹ At the same time, the worldwide energy transition requires utilizing additional surfaces for solar power generation. Activation of already existing artificial surfaces like building envelopes offers a technical potential to install around 900 GW in Germany² without further land consumption. Additional potential is identified for instance in the bodies of electric vehicles and in noise barriers. However, operation requirements in urban surroundings differ from those in solar power plants. Especially partial shading becomes an important issue with a huge variety of objects casting shades on solar modules any time of the day and the year. Jahn and Nasse report that in Germany, 41 % of the PV systems on buildings face shading capable of reducing the annual energy yield by over 20 % in peak operation.³ Further studies confirm that partial shading affects around half of all installed systems.⁴ Vegetation often is a source,⁵⁻⁷ as well as objects like poles and antennas.^{4,8} Work on partial shading of vehicle-integrated PV in motion emphasizes the interest for technical solutions to such challenges.9,10

In this work, we aim to show that shingled solar modules offer a solution to partial shading losses. At the same time, they feature a highly aesthetic appearance making them especially interesting for

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integrated applications. In this work, we investigate the operation of shingle modules manufactured in a state-of-the-art industrial approach using strings of shingled solar cells. Additionally, we compare this with modules using the matrix technology¹¹ and examine the fundamental reasons for the shading tolerance of both shingling approaches. We present a simple LTspice model capable of predicting power outputs under any kind of shading conditions and validate the approach with experiments on lab-scale solar modules. Extended simulation studies on 1m · 1.6m solar modules subjected to shading scenarios of installed and random objects complete this work.

SHADING OF SHINGLED SOLAR CELLS 2

Shingle solar cells are stripe-like solar cells cut from conventional fullsquare solar cells, usually to 1/5th or 1/6th of their original size, for example, by thermal laser separation (TLS).^{12,13} The key attribute of this technology is the interconnection by slightly overlapping neighboring solar cells and formation of a cell-to-cell bond by electrically conductive adhesive (ECA). To meet the current-voltage output of conventional solar modules, n serial-interconnected shingle solar cells form a string, from which *m* are combined in parallel interconnection (Figure 1A). By shifting the solar cells from row to row by half a cell length, an additional parallel interconnection of all solar cells within each row is achieved (Figure 1B). Half-cut shingle solar cells at the edges compensate for this lateral shift and form a uniform rectangular matrix of solar cells. Therefore, this approach is called matrix technology.

2.1 Modeling of the solar cell IV characteristics

The two-diode equation is a widely used approach to model the solar cell behavior under illumination. Figure 2 shows the equivalent circuit including both diodes D_0 and D_1 , the current source with its photocurrent density $J_{\rm ph}$ and the resistors $R_{\rm s}$ and $R_{\rm p}$. Since it is sufficient precise and easier to translate into an equivalent circuit, than the commonly used Bishop model,¹⁴ we chose to extend the characteristics into the negative bias regime by adding a reverse breakdown characteristic to D₀₂ following Rauschenbach.¹⁵ In contrast to Rauschenbach, in this, work we propose to not eliminate the shunt resistance R_p , but instead to assume the reverse breakdown takes



FIGURE 2 Two-diode equivalent circuit of a solar cell. A reverse breakdown characteristic according to Rauschenbach¹⁵ extends the behavior of D_{01} (highlighted by the red dashed box) into the reverse bias regime [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 1 Schematic drawing of the two shingling approaches (A) string-type in which n serial-interconnected shingle solar cells form m parallel-interconnected strings. (B) in matrix-type in which each of the n serial-interconnected rows contain m parallel-interconnected solar cells by shifting cells by half their length perpendicular to the stringing direction. Half-cut shingle solar cells at the edges complete a regular rectangle [Colour figure can be viewed at wileyonlinelibrary.com]

place in the junction diode D_{02} . In this way R_p still considers increasing currents in the negative bias regime before the breakdown occurs. This leads to Equation 1, where J_{01} , I_{02} , and J_{Br} are the saturation current densities of D_{01} , D_{02} , and the reverse breakdown of D_{01} , respectively. The Boltzmann constant k_B , the elementary charge e, the absolute temperature T, the ideality factors $n_0 = 1$ and $n_1 = 2$, and the series resistance R_s for ohmic losses are incorporated in the exponential function of each diode term. Additionally, R_p describes the shunt resistance of the solar cell. In case of the reverse breakdown D_{02} , we combine the reverse breakdown factor a_{Br} and n_1 to $n_{Br} = n_1 a_{Br}$ and treat n_{Br} as a fit factor.

$$\begin{split} J(V) &= J_{ph} - J_{01} \left(\exp\left\{ \frac{e(V + JR_{s})}{k_{B}Tn_{0}} \right\} - 1 \right) \\ &- J_{02} \left(\exp\left\{ \frac{e(V + JR_{s})}{k_{B}Tn_{1}} \right\} - 1 \right) \\ &+ J_{Br} \exp\left\{ - \frac{e(V + JR_{s} - V_{Br})}{k_{B}Tn_{Br}} \right\} - \frac{V + IR_{s}}{R_{p}} \end{split}$$
(1)

We use Equation 1 to fit measured data presented in Section 2.3 and incorporate the IV characteristics into the LTspice model of shingle solar modules.

2.2 | The LTspice model

The linear representation of the solar cell characteristics allows us to virtually split the shingle solar cells in two half-sized shingles as highlighted in Figure 3A. This allows the model in LTspice for both topologies to consist of 2-mn solar cells and switching between string

and matrix layout is achieved by simply adjusting the surrounding network of resistors. These resistors represent the busbar metallization on the front (FS, gray) and the rear side (RS, red) of the solar cells. Other than in a string, where currents can only flow from one solar cell in the string to the next, the matrix layout allows currents to travel through the network of busbars perpendicular to the direction of the string. Note that we refer to string also when speaking of the direction of serial interconnection and vice versa. Alternately, one FS busbar connects two RS busbars of neighboring physical solar cells and the other way around. This results in a parallel interconnection of all solar cells within each row. As input parameters, we measure the IV characteristics and the lateral resistance of 30 industrial PERC-based shingle solar cells as described in the following sections. In the LTspice simulation, we randomly assign measured characteristics to each solar cell to account for slight variations as they commonly occur from fabrication.

We consider shading by reducing the mean illumination of each virtual half-sized shingle solar cell. The photocurrent $I_{ph,sh}$ under shading is adjusted depending on the ratio of shaded cell area A_{sh}/A_0 and the chosen shading opacity O_{sh} as given in Equation 2. Quaschning showed that with this assumption the error on the generated current is less than 2% in the maximum power point (MPP).^{16,17}

$$I_{ph,sh} = I_{ph,0} \left(1 - \frac{A_{sh}}{A_0} O_{sh} \right)$$
(2)

The model includes bypass diodes (BPDs) at flexible positions along the string, described in more detail in the model validation section. BPDs are used to limit reverse bias voltages^{18,19} in shaded solar cells. Unlimited reverse bias operation can cause a local breakdown of the semiconductor and lead to high temperatures in PERC-based solar



FIGURE 3 Modeling solar modules in shingle technology in LTspice implementing two virtual sub-cells connected in parallel for each physical solar cell for (A) string-type and (B) matrix-type interconnection. Lateral currents are conducted via the lateral resistors representing busbars and ECA in the joint on the front and the rear side of the solar cell [Colour figure can be viewed at wileyonlinelibrary.com]

cells well above 200°C without even being encapsulated.²⁰ Witteck et al. report temperatures for module laminates of up to 176°C for state of the art solar modules.²¹ Thus, bypass diodes reduce but not prevent heating due to reverse biasing. In conclusion, operation points driving individual solar cells into reverse bias must be avoided to exclude damages entirely.

2.3 | Measurement of solar cells

Forward bias measurements under STC conditions are conducted using a *Halm cetisPV Celltest3* solar cell tester. We measure a group of 30 industrial solar cells with an initial efficiency of 22.1% and 5.4 W of the host full-square cell. After separation into $1/5^{\text{th}}$ shingle solar cells adopting either a cleave or a TLS process,¹² the average power output in case of cleaved shingle solar cells is (1.032 ± 0.014) W. Since the reverse breakdown is not reached with conventional measuring systems, we obtain the full IV characteristics by measuring the reverse bias regime in a laboratory setup in the dark (zero illumination). Shifting the reverse bias data to the photocurrent level of the forward bias curve results in the full characteristics, which we then fit



FIGURE 4 Exemplary complete IV curve of an industrial PERC solar cell used in the simulations. Data points show the experimentally obtained data. The solid line shows the solution Equation 1 with the fitted parameters. The dashed line shows the solution of the equivalent circuit shown in Figure 2 with LTspice [Colour figure can be viewed at wileyonlinelibrary.com]

using Equation 1. Figure 4 shows an exemplary IV curve of an industrial PERC shingle solar cell. The data points represent measured and shifted data. The solid line shows the solution of 1 with the fitted parameters. The dashed line shows the solution of the equivalent circuit (Figure 2) in LTspice. We find measurement and the simulations to be in very good agreement. Minor deviations occur only in the transition from linear to exponential current behavior at the reverse breakdown under reverse bias operation. Mean values for the group are given in Table 1.

2.4 | Lateral resistance

Besides the extended two-diode representation, the LTspice simulation requires lateral resistances R_{lat} for the current between two adjacent solar cells via the joint. We have three different types of joint shapes to consider. Firstly, the conventional string joint, where front and rear side busbar together with the ECA form a lateral resistor. Secondly and thirdly, the matrix joints, where either the front side or the rear side busbar, are intermitted at the transition to the neighboring, parallel-interconnected solar cell. We want to emphasize that the absolute values obtained for R_{lat} are dependent on the busbar shape and architecture of the joint and are therefore not universally valid. Here, we characterize eight samples per group and nine groups per ECA. Their current conduction length corresponds to half the size (78 mm) of the solar cells used in the experiments and simulations. After stencil printing (100 µm) of three different ECA patterns (four pads of length $I_{FCA} \in [2; 5; 10]$ mm) the samples are cured at 160°C for 3 min. We compare two commercial available ECAs, one with a high specific resistance ρ of $3.7 \cdot 10^{-3} \Omega$ cm and one with a low specific resistance ρ of $1.9 \cdot 10^{-4} \Omega$ cm, which enclose the range of today's available products.

Figure 5 plots the measured R_{lat} against the printed ECA length I_{ECA} and the three different joint types. The absolute resistance for the given joint geometry for both ECAs correlates with I_{ECA} . An increasing I_{ECA} causes R_{lat} to decrease. This trend is more distinct for the high ρ ECA. The combination of both observations indicates that the electrical properties of the ECA, ρ and ρ_c affect the lateral conductivity. However, variations of both in FEM simulations predict only a minor influence on R_{lat} and a negligible contribution of the ECA in lateral current transport. According to the numerical results the metallization transports most of the lateral currents.

When measuring the line resistance of the solar cell metallization isolated, we find line resistances of $R_l\,{=}\,(6.62\,{\pm}\,0.16)\,m\Omega mm^{-1}$ on

TABLE 1Fitted parameters of theequivalent circuit model for 30 industrialPERC 1/5th shingle solar cells

Forward bias	Value	Reverse bias	Value
$J_{\rm ph}/{\rm mAcm^{-2}}$	39.64 ± 0.0003	$J_{\rm Br}/{\rm Acm^{-2}}$	562.97 ± 143.58
$J_{01}/pAcm^{-2}$	$0.11 \!\pm\! 0.01$	V_{Br}/V	-29.74 ± 1.52
$J_{02}/nAcm^{-2}$	23.60 ± 5.45	n _{Br} /1	$\textbf{27.84} \pm \textbf{5.21}$
$R_{ m s}/\Omega{ m cm^2}$	0.57 ± 0.07		
$R_p/k\Omega \mathrm{cm}^2$	130.53 ± 128.07		

the front busbar. On the rear side, we measure two different line resistances. Over short distances, the silver busbar only conducts the charge carriers resulting in $R_I = (4.30 \pm 0.16) \text{ m}\Omega \text{ mm}^{-1}$ for I < 10 mm. For distances l > 10 mm, we find a significant drop to $R_l =$ $(0.83\pm0.0038)\,\text{m}\Omega\,\,\text{mm}^{-1}$ which is due to the full-area aluminum rear side of the solar cell dominating the current transport. For the given bulk resistances of $\rho \in \left[1.9 \cdot 10^{-4}; 3.7 \cdot 10^{-3}\right] \Omega$ cm, the line resistances for typical ECA cross sections of 0.6mm 0.05mm in lateral direction calculate to $66 \text{ m}\Omega \text{ mm}^{-1}$ to $1666 \text{ m}\Omega \text{ mm}^{-1}$. A significant contribution of the ECA to R_{lat} therefore seems unconceivable. Similar results prevail for the contact resistance ρ_c . In order to contribute to the observed trends, the contact resistance between ECA and busbar has to be in the range of $\rho_c \in [5 \cdot 10^{-2}, 5 \cdot 10^{-1}] \Omega \text{cm}^2$, which is well outside of typical values of $\rho_c \in \left[1 \cdot 10^{-4}, 1 \cdot 10^{-2}\right] \Omega cm^{2.22}$

However undisputable, the experimental values for high and low ρ ECAs differ considerably from each other, attributing them at least a quantifiable share in the formation of R_{lat}. Nevertheless, all groups



ECA Pad length I_{ECA} / mm

FIGURE 5 Lateral resistances for different types of joints in string- and matrix-interconnected shingle solar cells. Type 1 corresponds to half a cell length in string interconnection, Types 2 and 3 to matrix interconnection with intermitted RS and FS busbar, respectively [Colour figure can be viewed at wileyonlinelibrary.com]

except $I_{FCA} = 2 \text{ mm}$ for type two and three feature narrow distributions of R_{lat} ranging from $(140.1\pm7.5)\,m\Omega$ to $(240.4\pm30.2)\,m\Omega.$ Since we use $l_{ECA} = 10 \text{ mm}$ for module fabrication, we chose the corresponding measured data for types one, two, and three joints as input parameters for the LTspice model. Since we cover the divergence between observation and expectation with additional variations of R_{lat} in the LTspice simulations (see Section 4), we leave further investigations of the formation of R_{lat} to future studies.

MODEL VALIDATION 3

To validate the results obtained with the LTspice simulation, solar modules for both interconnection types are fabricated at Fraunhofer ISE. Each one consist of 72 Tongwei TW1565B PERC 1/5th monofacial shingle solar cells ($w_{cell} \cdot I_{cell} = 31.2 \text{ mm} \cdot 156.75 \text{ mm}$) with $P_{\text{Cell}} = (1.032 \pm 0.014) \text{ W},$ $I_{SC} = (1.95 \pm 0.009) \text{ A},$ and $V_{OC} = (680.6 \pm 2.0)$ mV, distributed in two serial interconnected blocks. Each block contains 9×4 serial and parallel-interconnected solar cells, respectively, and one bypass diode. Shingle strings are produced with a Teamtechnik TT1600 ECA industrial stringer and interconnected manually to blocks. Matrix blocks are produced with a pick and place routine executed with a Universal Robot UR5 after manual screen-printing 5 mg of an acrylate-based ECA per joint. The overlap is set to 1.2 mm, and the resulting active module area in both cases is 0.35 m². For module encapsulation, we use a standard BOM with a 3.2-mm front glass without anti reflection coating, EVA as encapsulant with UV cut-off and a transparent back sheet. Bypass diodes are placed in the junction box.

Electroluminescence images in Figure 6 after module fabrication show no cell cracking or other mechanical damages in (a) the string and (b) the matrix module. The luminescence distribution indicates homogeneous electrical contacting of all solar cells. The STC power (Table 2) is equal for both modules within the range of the measurement uncertainty, which makes them comparable in shading experiments. We attribute differences in the I_{sc} after lamination to optical losses in the front sheet and the encapsulant. Together they account for 7.7% optical losses which we explain by the usage of front glass sheets without anti reflecting coating and reduced transmissivity in

FIGURE 6 Electroluminescence images of the modules manufactured for experimental validation of the LTspice simulation (A) string module and (B) matrix module. Sketched circuit symbols indicate the bypass diodes [Colour figure can be viewed at wileyonlinelibrary.com]



the UV regime. For the simulations, we adjusted the solar cell photocurrent accordingly.

3.1 Shading experiments

We conduct shading experiments under AM 1.5 spectrum and 1000 Wm⁻² irradiation in an *Eternalsun Spire BBA* light soaker. During the experiments, we monitor the module temperature on the module rear side with a PT100 sensor. IV data are recorded with a Halm cetis-PV-CT-F1 IV curve tracer. Shading of the samples is realized by placing sheets of black cartridge directly onto the front glass, which corresponds to $O_{sh} \cong 1$. However, we find that due to the measurement setup, the illumination does not incident perfectly perpendicular on the sample surface, and inclined light slightly reduces the effective shading width at its edges. This is especially relevant for very small shading widths and leads to increased currents.

We investigate four different shading scenarios with different shading directions: horizontal (H), vertical (V) and two diagonal (D0 & D1) scenarios. Within each, six sub-scenarios adjust the shading width w_{sh} according to Table 3. Note for a better understanding, for horizontal and vertical shading scenarios we chose w_{sh} to be fractions of the corresponding cell dimension, for example, $\frac{1}{2} \cdot I_{cell}$ (V) or $\frac{1}{3} \cdot w_{cell}$ (H) covered in the given direction.

Figure 7A shows an electroluminescence image of the modules overlaid by the investigated shading scenarios. While H and V cover the module from its horizontal and vertical edges, D0 is the exact diagonal of the complete module and D1 the diagonal of the upper block. In Figure 7B the illumination input for each cell for the LTspice simulation is shown for all shaded sub-scenarios of D0.

Note again that the smallest unit considered in the simulations is a half-shingle cell. However, we precisely calculate the shaded area

TABLE 2 STC power rating of modules for validation of the LTspice model

	String	Matrix
I _{SC} /A	$\textbf{7.17} \pm \textbf{0.11}$	$7.23 \!\pm\! 0.11$
V_{oc}/V	$\textbf{12.13} \pm \textbf{0.08}$	$12.16 \!\pm\! 0.08$
FF /%	$\textbf{77.50} \pm \textbf{1.09}$	75.22 ± 1.06
P /%	67.46 ± 1.22	66.11 ± 1.20

	Scenarios X			
Sub-scenario i	Horizontal (H)/w _{cell}	Vertical (V)/ I_{cell}	Diagonal (D0 & D1)/mm	
1	1/6	1/2	50	
2	2/3	1	100	
3	1	2	150	
4	9 1/6	3	300	
5	9 2/3	4	400	
6	10	-	500	

fraction of each cell and adjust its photocurrent according to Equation 2. This includes the precise positions of each solar cell and hence also the gaps between strings. However, in the laboratory samples, small deviations in the cell position occur according to the machine precision of $\pm 200 \,\mu$ m.

Results and discussion 3.2

During our experiments, module temperatures vary between 38°C and $45^{\circ}C$ with an average of $(42.0 \pm 1.5)^{\circ}C$ for the matrix sample and between 45° C and 52° C with a mean of $(48.2 \pm 2.0)^{\circ}$ C for the string module. In order to compensate for dT between simulation and experiment we compare the normalized power outputs $\overline{P_X}$ for each scenario X by $\overline{P_X} = P_{X-i}/P_{X-0}$ with P_{X-0} being the unshaded reference in each X. We therefore determine the error on the measured power to be as big as $max(dT_X)$, which for both string and matrix interconnection is \sim 7 K. With the data sheet temperature coefficient of -0.36%K⁻¹ for the solar cell power this leads to $\varepsilon_{\rm P} = 2.52\%$. We underline that this error can only be an estimate since the temperature measurement is located at one position and we expect the module temperature to be inhomogeneous over its surface. Every data point is the mean of three measurements with average relative errors $\varepsilon_{P,rel}$ of 0.3% and 0.5% for string and matrix, respectively. Therefore, the overall expected error is $\epsilon_{P,tot} = \epsilon_{P,rel} + \epsilon_P \cong 3\%$. Throughout the experiments on both modules, we notice slightly increased currents compared to our simulation. As discussed earlier this is linked to the measurement setup where the incident light is emitted on an area of 3m · 2m in 1.5-m distance to the samples. Inclined light from the solar simulator penetrates the shaded area under the cartridge at the edges and therefore causes higher photocurrents in the current limiting solar cell. We find this to be most prominent when shading very small fractions of the modules only, for example, in the case of H1 and H2. Additionally, the modules feature a transparent back sheet, which allows scattered light from the chamber rear side to enter the module.

The experimental results are displayed in Figure 8. The experimental data match nicely with the simulations with an average deviation of (1.8 ± 1.5) %_{abs}. The error bars are hidden behind the symbols. In case of the V and the H scenario, both module types react similar to partial shading, which was expected to happen. Significant differences arise when shading does not follow the edges or covers areas within the module. For both the D0 and the D1 scenario, we

> TABLE 3 Summary of all shading scenarios X used for model validation including their sub-scenarios i with respect to the shading width w_{sh}



FIGURE 7 (A) Indication of the four different shading scenarios: Horizontal (H green), vertical (V yellow), diagonal whole module (D0 black), diagonal upper half of the module (D1 red). (B) Exemplary depiction of the irradiation data for each virtual sub-cell in the LTspice simulation for D0-x with increasing shading widths w_{sh}. Green areas indicate full illumination, red parts correspond to 100 % shading [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 8 Normalized power outputs for string-type (continuous line and circles) and matrix-type (dotted line and triangles) modules at the operated shading scenarios. Lines indicate simulations, symbols the experimental obtained values. Note that the hidden error bars due to overlapping with the symbols. For H and V scenarios (left graph) the lines for both string and matrix interconnection overlap [Colour figure can be viewed at wileyonlinelibrary.com]



measured and calculated a significant higher power outputs for the matrix layout. For narrow shadow shapes with small w_{sh} the matrix approach yields up to 60 % and 95 % more power for D0 and D1, respectively. This is especially relevant since the absolute power output of the shaded module in these cases is still a significant fraction of the unshaded reference; 65 % and 85 % in case of D0 and D1, respectively. We find two effects relevant for these differences and devote the following two sections to a detailed explanation.

3.2.1 | Current extraction

Let us first assume that for the following considerations, no ohmic losses in the interconnection exist and the solar cells work as an ideal interconnected circuit element. As a good approximation, the generated photocurrent is linear to the incident irradiation E and therefore it is linked to the share of shading directly. Additionally, for state of the art PERC solar cells the IV characteristics is at constant current

level I^* between 0V and reverse breakdown voltage V_{Br} and in good approximation device currents > I_{sc} cause operating points in the reverse breakdown region.

$$I^* = \text{const.}|_{\mathsf{V}_{\mathsf{Br}} < \mathsf{V} < \mathsf{OV}} \tag{3}$$

The modules considered for the following discussion consist of n rows and m columns of solar cells as shown in Figure 1, bypass diodes are not considered. In case of string interconnection, the module features m parallel-interconnected strings that each contains n serial-interconnected solar cells. The matrix technology on the other side consists of n serial-interconnected rows, which each consist of m parallel-interconnected solar cells. We constrain n to meet

$$n - 1 < V_{\text{Br,cell}} / V_{\text{MPP,cell}}$$
 (4)

so that reverse breakdown V_{Br} of a single cell cannot occur while the string is under forwards bias. From this and I^* follows that all operating points in the power generation quadrant are limited to the lowest I_{ph} within the string. In case of the string layout, this leads to Equation 5, where the generated current from the module I_{St} is the sum of the generated currents from *m* strings. Since these are proportional to the incident irradiation *E*, this leads to

$$I_{\text{St}} = \sum_{j=1}^{m} I_{\text{m}} = \sum_{j=1}^{m} \min_{i=1...n} (I_{i,j}) \sim \sum_{j=1}^{m} \min_{i=1...n} (E_{i,j})$$

=
$$\min_{i=1...n} (E_{i,1}) + ... + \min_{i=1...n} (E_{i,m})$$
 (5)

In the matrix layout, every complete row *i* is a serialinterconnected generator of currents, and we therefore need to consider the row of minimal photocurrent.

$$I_{Ma} = \min_{i=1...n} (I_i) = \min_{i=1...n} \left(\sum_{j=1}^m I_{i,j} \right) \sim \min_{i=1...n} \left(\sum_{j=1}^m E_{i,j} \right)$$

=
$$\min_{i=1...n} \left(\sum_{j=1}^m E_{1,j}; ...; \sum_{j=1}^m E_{n,j} \right)$$
 (6)

with the \hat{i}_j defined as the row *i* of minimum current generation within column *j* and therefore also of minimum *E*

$$\widehat{i}_{j} = i_{\min(l_{ij})} = i_{\min(E_{ij})}$$
(7)

We introduce the notation

$$\widetilde{E}_{j} = \min_{i=1\dots n} (E_{i,j})$$
(8)

With $i \neq \hat{i}_i$ we get Equations 9 and-equally valid-10

$$E_{i,j} \ge \widetilde{E}_j$$
 (9)

$$E_{i,j} = \widetilde{E}_j + \delta_j, \ \delta_j \ge 0 \tag{10}$$

If for all *j* applies $\hat{i}_j = i$, thus all minima in *j* columns are located in the same row *i* and Equation 6 becomes

$$I_{Ma} \sim \min_{i=1...n} \left(\sum_{j=1}^{m} E_{i,j} \right) = \sum_{j=1}^{m} \widetilde{E}_{j}$$

=
$$\min_{i=1...n} (E_{i,1}) + \dots + \min_{i=1...n} (E_{i,m}) \sim I_{St}$$
 (11)

Have in mind that the proportionality between current and irradiation under the given assumptions is equal regardless of the interconnection type. Therefore, 11 shows that the matrix and string respond equally, when minimal irradiation is found in the same row *i*. But if only in one column $\hat{i}_j \neq i$, we insert Equation 10 as one summand in Equation 6 which leads to

$$I_{\mathsf{Ma}} \sim \min_{i=1...n} \left(\delta_{j} + \sum_{j=1}^{m} E_{i_{j,j}} \right) = \delta_{j} + \sum_{j=1}^{m} \widetilde{E}$$

$$\geq \min_{i=1...n} (I_{i,1}) + \dots + \min_{i=1...n} (I_{i,m}) \sim I_{\mathsf{St}}$$
(12)

Applied on the validation experiments this states that in case of horizontal shading maximum shading is found in the first row starting from the edge regardless of the layout and results in equal current generation. In vertical shading, every row experiences the same insolation; thus, every row generates the minimum current and again both modules behave equally. However, a diagonal shade will affect solar cells in different rows. In string interconnection, the row of the fully shaded solar cell is of no importance, since the minimum within the entire string defines the current extractable under forward bias. Since the minima occur in different rows there will be no row containing all minima at once. Thus, the matrix will generate a higher photocurrent compared to the string module. The level of current generation is limited by the row of minimal insolation. This effect naturally becomes irrelevant when the size of the shading becomes big enough to cover an entire row of the matrix module.

Another approach to explain the differences in current generation is to consider the probability of shading scenarios leading to zero extractable currents. In the matrix layout, exactly m neighbouring, parallel-interconnected solar cells have to be affected, whereas in string interconnection, one arbitrary solar cell per string already leads to the same result. Therefore, the effect of randomly shaded solar cells is examined in Section 4.2.

So far, bypass diodes and electrical losses due to lateral current transport between adjacent solar cells of the same row have not been subject of this consideration. However, the results from Section 3.2 already did consider the influence of ohmic losses in the joint and bypass diodes and the matrix module showed clear advantages under diagonal shading. Moreover, the studies presented in Section 4 include measured values and variations for R_{lat} to rank ohmic losses for lateral currents against the enhanced current extraction.

3.2.2 Fill factor

Experimental and computational data show another differing behavior of matrix and string shingled solar modules under partial shading. Resulting from it, higher fill factors are found for the matrix module for some cases.

Figure 9 shows measured and simulated IV characteristics of both string and matrix module for validation scenario D1-3. Although the shading is equal for both modules we find a significant higher fill factor (37.0 %) for the matrix compared to the string module (31.3 %). Note that the overall low FFs are caused by $V_{OC} \sim 11 V$ while the MPP is found at \sim 4V. Also note that the module temperature measurement during experiments occurred only at one position. The data shown are corrected by a mean $dT_{\text{Matrix}} = 24 \text{ K}$ and $dT_{\text{String}} = 18 \text{ K}$ towards STC. We use temperature coefficients of $T_{k,V_{OC}} =$ $-3.6 \cdot 10^{-3}\%$ K⁻¹ and T_{kJsc} = $0.6 \cdot 10^{-3}\%$ K⁻¹ given by the cell manufacturer. Due to a two-wire measurement setup, there is an additional $R_{\rm s}$ contribution from the (heated) cabling which explains the development of the characteristic close to V_{OC}. However, in both measured and simulated data, the region around the MPP of the matrix module features a very sudden transition from approximately constant current to the R_s-controlled section of the characteristics. In case of the string module, this transition is more distinct and consequently results in a lower fill factor and, respectively, lower power output.

We explain this with a different impact of current mismatch in the examined topologies. An example for current mismatch in a string of solar cells is shown in Figure 10. The graph plots the characteristic of 10 serial-interconnected shingle solar cells which are one by one set to 500 Wm⁻² illumination. The first solar cell shaded lowers the string current in the forward bias regime to 50 % (red) of unshaded reference (black). Accordingly, a string operating point in the forward bias regime requires a current match between shaded and unshaded

solar cells on the current level of the shaded solar cell. For an

unshaded solar cell, this is only possible when its operating point shifts to higher voltages. Thus, every unshaded solar cell along the string increases its voltage to match its current with the shaded solar cell, which again results in the kinked characteristic described before. Consequently, this effect reduces along with the number of shaded cells (Figure 10) and hence is most apparent for only one mismatched solar cell per string.

A physical explanation for this voltage overdrive considers the difference between generated and extracted charge carriers inside the shaded and unshaded solar cells. The more charge carriers inside an unshaded solar cell are generated but not extracted since the current through the string is limited to the current in the shaded solar cell, the more the device voltage increases until charge carrier generation and recombination are equalized. The unshaded solar cells can keep this current level constant over increasing voltage up to the point where they themselves reach their R_s-dominated regime and current quickly drops with further voltage increase.

With this in mind, we compare the impact of an identical shading for the string and the matrix interconnection. In Figure 11, the characteristics of four strings as discussed in Figure 10 and interconnected in parallel to form a string layout are shown. Within the first string, the first solar cell is subjected to a 500 Wm⁻² illumination or half covered solar cell, respectively, which corresponds precisely to the shading in Figure 10. Now, in Figure 11, the red dash-dotted line depicts the characteristic of the string containing the shaded solar cell and features the before discussed voltage overdrive caused by the shift of the operating points of all unshaded solar cells. However, this effect is hardly observable in the module characteristic as the unshaded strings (black dash-dotted line) superpose it. It follows that due to the parallel interconnection of the strings, the positive effect of the mismatch is



FIGURE 9 IV data displaying the fill factor effect observed in scenario D1-3 of the validation experiment. The corresponding irradiation map is shown below the legend. The segment of interest is enlarged in the inlay; axes match the ones from the main graph [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 10 A string of 10 solar cells with varying numbers of shaded solar cells. The first cell shaded by 50 % sets the current level of the string under forward bias. With increasing numbers of shaded cells (dotted lines) the transition from constant current to R_s -regime becomes more distinct [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 11 Impact of a 50 % shaded solar cell in the first of four strings in an exemplary string-shingled solar module. The shaded cell only affects its own string by lowering the current level under forward bias. The current mismatch between strings is not critical since currents summarize [Colour figure can be viewed at wileyonlinelibrary.com]



FIGURE 12 The same shaded area (Figure 11) affects the matrix layout with a different result. Due to the parallel interconnection within the individual rows the current mismatch exists between the entire the first and all other rows. The operating points of all unshaded rows shift to higher voltages (Figure 10) under forward bias in order to match the current provided by the shaded row [Colour figure can be viewed at wileyonlinelibrary.com]

limited to the affected string only. On the other hand, in Figure 12, the same shading scenario for a matrix module is shown. Note again that both unshaded module characteristics are identical. However, in the matrix module, the same shaded solar cell lowers the combined current generated in the entire first row. Hence, the mismatch now persists at module level. In Figure 12 again, the red dash-dotted line indicates the characteristics of the shaded element, this time of the first row. The impact of mismatch again applies, only that now complete unshaded rows or four cells respectively undergo a shift of their

operating point and the effect persists on module level. This is in contrast to the string interconnection, where the effect is limited to the string. Since the effect is driven mainly by the number of unshaded solar cells in serial interconnection, we expect it to be most relevant for minor shadings. Further examination by simulations and discussion follows in Section 4.

STUDIES ON 1.6 m² SOLAR MODULES 4

Integrated applications, especially vehicle integrated PV (VIPV) and building integrated PV (BIPV), face a vast number of shading scenarios that are nearly impossible to predict. However, in the following section, we use the verified model to study two typical cases of shading on a $1m \cdot 1.6m$ solar module. The modules consist of 51×6 solar cells, organized in three blocks of 17 solar cells each. A bypass diode secures each block. Firstly, we consider a case similar to the validation scenarios D0 & D1, corresponding, for example, to shading caused by lampposts or antennas. Secondly, we repeat solving the model while randomly shading single shingle solar cells. It addresses selective shading caused by leaves or bird droppings covering the module. Moreover, random shading is supposed to validate the proposition in Section 3.2.1 that the probability of shading one entire row is lower than shading one solar cell within each string.

Figure 13A sketches the string module and the diagonal shading study with its parameters shading angle α_{sh} and shading width w_{sh} . α_{sh} corresponds to the angle between shade and the horizontal m-axis and varies from 5° to 85° in steps of 5° . Since 0° (horizontal) and 90° (vertical) yield the same results for both modules, they are excluded from the study. w_{sh} covers 10 mm to 200 mm in 7 and 200 mm to 1000 mm in another 14 non-equidistant steps, overall resulting in 357 scenarios. Figure 13B shows the matrix layout and the random shading scenario. Ash is the overall shaded area fraction of the solar module. Since we randomly pick individual half shingle solar cells, it corresponds to an integer number N. Therefore, the area covered by shading contains an error reciprocal to the number of solar cells N used in the module $\varepsilon_{\rm A} = 1/N.$ In this specific case. $\varepsilon_A = 1/(2 \cdot 6 \cdot 51) = 0.0016.$ We assign values of $A_{sh} \in [0.01; 0.05; 0.1; 0.2; 0.4; 0.6; 0.8]$. The number of shaded solar cells is chosen accordingly. One hundred computations per area fraction provide a reasonable base to consider statistical fluctuations. Both shading scenarios are applied for both interconnection types.

Based on the work of Sattler and Sharpies,²³ we chose $O_{sh} = 0.8$ in the studies. Additional variations of $O_{sh} \in [0.5; 0.8; 1.0]$ and $\tilde{R}_{lat} =$ $[0.2; 1; 5; 50] \cdot R_{lat}$ examine the robustness of the results to changes in the input data.

4.1 Results of the diagonal shading scenario

In Figure 14, we show a map of the power gain P_+ , where x- and yaxes outline the variations in α_{sh} and w_{sh} , respectively. P_{+} is calculated according to Equation 13 and is expressed in the color code. Positive

FIGURE 13 Schematic drawing of the solar module topologies and shading scenarios for the simulation study. (A) String module with ordered diagonal shade rotating around the center with $\alpha_{\rm sh}$: 5° to 85° and $w_{\rm sh}$: 10mm to 1000mm. (B) Matrix layout with random shading of single solar cells varying the total shaded area from A_{sh} : 1% to 80%. Note that both shading scenarios are applied to both interconnection types [Colour figure can be viewed at wileyonlinelibrary.com]





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FIGURE 14 Map of the power gain under diagonal shading for variations of α_{sh} and w_{sh} . Bold dashed isolines indicate the relative power P/P_0 of the matrix module compared to its unshaded reference. Shade opacity $O_{sh} = 0.8$, R_{lat} as measured [Colour figure can be viewed at wileyonlinelibrary.com]

values correspond to a higher power output in favor of the matrix technology, negative values to a better performance of the string module.

$$P_{+} = \left(\frac{P_{Mtr}}{P_{Str}} - 1\right) \cdot 100\% \tag{13}$$

Within this study, we find the power output of the matrix under diagonal shading to exceed the string module in every data-point. This

is explained, as proposed before, by the ability of the matrix technology to conduct charge carriers past the shaded area rather than blocking them inside the strings. This is not possible in the string approach and leads to significant losses in I_{MPP} or worse revers biasing parts of the module increasing the risk of hotspots.²⁰ Operation points including at least one forward biased bypass diode occur in 46.8% of the scenarios for the string module and only in 27.2% of the scenarios in case of the matrix module. We conclude that besides higher power outputs the risk of hotspot occurrence is reduced by 40% for the matrix module. This is determined by comparing MPP voltages and conductive bypass diodes for both modules. In 40% of the considered scenarios, the matrix module operates without conductive bypass diode and close to its unshaded V_{MPP} while the string layout in the same scenario already operates under reduced voltages, hence reverse biasing of solar cells.

We find substantial regions of the map for shading angles between 30° and 70° to display significant power gains for the matrix module. Overall in 72% of the cases, P_{Mtr} exceeds P_{Str} by > 5% from which 61.2% are linked to bypass diodes in conductive/blocking state and 61.2% to a higher I_{MPP} . Where both effects superpose, we find the highest benefits of the matrix module with a peak value of $P_{+,\text{max}} = 73.8\%$. This value is found under 45° for a shading width of 160 mm. Additional absolute power outputs of $P_{Mtr} = 241.69 \text{ W}$ compared to $P_{\text{Str}} = 139.03 \text{ W}$ under this shading condition underline the high relevance for the energy yield.

Variations of R_{lat} by a factor of 5 yield only minor changes in the results. Qualitatively, the P_+ map is not changing, and again we find only minor changes in the absolute values. To compare the mappings P_{\pm} , $P_{\pm,max} > 5\%$ and bypass diodes in conductive state are chosen as characteristic values. Table 4 summarizes the results from the robustness variations. Only when increasing R_{lat} by factor 50 we find substantial changes in the characteristic values. The increased fill factor

TABLE 4 Characteristic values of the maximum power gain $P_{+,max}$, percentage of cases with $P_+ > 5\%$ and percentage of operation points with conductive BPD for shingle modules under a diagonal shading scenario. Variations of O_{sh} and R_{lat} examine the robustness of the input data

$O_{\rm sh}/1$	$\widetilde{\textit{\textbf{R}}}_{lat} / \textit{\textbf{R}}_{lat}$	$m{P}_{+,max}/\%$	P ₊ > 5%/%	Conductive BPD string/ %	Conductive BPD matrix/ %
0.8	0.2	74.4	72.5	46.8	27.5
0.8	1	73.8	72.0	46.8	27.2
0.8	5	70.5	69.2	46.8	28.6
0.8	50	43.2	47.6	47.1	37.8
0.5	1	51.2	47.1	12.0	7.6
0.8	1	73.8	72.0	46.8	27.2
1.0	1	90.7	82.9	65.3	45.1

loss due to the high module R_s reduces the advantage of the matrix technology. But even under these conditions, we find $P_{+,max} = 43.2\%$. We observe also minor effects on the values for string interconnection. Those can be explained by losses in lateral current conduction between the two virtual sub cells, which for example occurs when shading affects only one half of a solar cell.

We conclude that the increased current generation enabled by the matrix technology is robust against even highest resistances for lateral current conduction and the effect is unlikely to be compensated by increasing module series resistance and fill factor losses. This offers the possibility for reduction of the silver metallization from the electrical point of view. However, from the production and reliability point of view, the silver busbar is an important feature to ensure robust mechanical interconnection between the solar cells and metallization reduction needs to be pursued with care.

Variations of O_{sh} again affirm that the difference between string and matrix is driven by the elevated current extraction and consequently a decreasing O_{sh} links to a strong reduction of $P_{+,max}$. On the other hand, an increasing O_{sh} increases the differences. Since the matrix concept allows us to access photocurrents that would be blocked in their respective strings, it follows that the difference in power output maximizes with the difference in irradiation and minimizes when irradiation inhomogeneity decreases.

4.2 | Results of the random shading scenario

In Figure 15, we plot the absolute output power for both module types against the shaded area fraction $A_{\rm sh}$. Without shading and including the $I_{\rm ph}$ correction due to optical losses in the front sheet, the solar modules initially have a power output of 289 W. Gray dash dotted lines indicate the range between initial state with zero shading and 100 % shading at an opacity of 0.8. Data points and error bars represent the mean results for $\tilde{R}_{\rm lat} = 1R_{\rm lat}$ and 1σ range, respectively. The highlighted areas border the range between $\tilde{R}_{\rm lat} = [0.2,5] \cdot R_{\rm lat}$. Likewise, the diagonal shading we find the expected power outputs in case of the matrix technology to outperform the string module. Highest differences occur for $A_{\rm sh} \in [0.2, 0.4]$. While at 40% shaded area the string module approaches the 100 % shading line, the matrix module still produces 42% of its unshaded power output. Only when



FIGURE 15 Module power output plotted against the shaded area fraction A_{sh} for random shading of solar cells. Data points represent the results for the measured R_{lat} values. The colored area borders the range of expected power outputs for variations of $\tilde{R}_{lat} = [0.2; 5] \cdot R_{lat}$. The unshaded reference as well as the 100 % shaded case for $O_{sh} = 0.8$ are plotted as dot-dashed lines [Colour figure can be viewed at wileyonlinelibrary.com]

80 % of the solar module is shaded the matrix module approaches its fully shaded reference.

The qualitative results are stable against changes of R_{lat} , and the advantages of the matrix interconnection persist also for increased lateral resistances. As expected, the impact on string interconnection is negligible, where current transport only takes place between the two virtual sub-cells. A significant dependency is found for the matrix module. For a factor five, increased lateral resistance additional losses of up to 30 W at 40 % shading occur. However, the matrix module still ranges well above the power outputs of the string module.

Additionally, we find the proposed impact on the fill factor for minor shading fractions confirmed. For shaded area fractions of 1 %, we find FFs of $(76.8 \pm 3.0)\%$ and $(69.9 \pm 4.5)\%$ for matrix and string, respectively. This results in a mean ΔP of 27.3 W between matrix and string layout. For higher shading fractions, the comparison of the FF gets distorted since MPPs especially in case of string interconnection

are partly found under lower voltages in combination with conductive bypass diodes. Therefore, we find this effect to be most relevant, for example, in case of bird droppings, which on the one hand only cause minor power losses but on the other hand typically stay on the solar module for a long time.

5 | CONCLUSION

In this study, we investigated the power output under partial shading for shingle modules featuring the standard string and the matrix layout. An LTspice model including the interconnection and resistance of lateral current transport between adjacent (virtual) solar cells yields insights to the response of both modules to shading. For this purpose, we characterize the lateral conductivity of different joint geometries for two commercial ECAs. Solar cell characteristics including a reverse breakdown based on a breakdown of the junction diode are presented and used in the simulations. Shading experiments on 0.35 m² laboratory samples are in very good agreement with the simulations.

In shading scenarios parallel to the module edges, we find similar power outputs which were expected in the first place. However, in all other cases, including especially diagonal and random shading, we find significant advantages of the matrix technology. The intrinsic serial and parallel interconnection of the solar cells leads to an increased current extraction. This is caused by currents bypassing the shaded area via the busbar metallization crosswise to the normal current flow. Besides higher power outputs, this leads to significantly less MPPs where reverse biasing of parts of the modules increases the risk of hotspot occurrence. Under minor shading conditions, the matrix approach benefits from increased voltages in unshaded solar cells leading to higher fill factors and thus higher power outputs. At only 1 % random shading we find fill factors (76.8 ± 3.0)% and (69.9 ± 4.5)% for matrix and string shingled modules, respectively, resulting in a mean ΔP of 27.3 W.

Since the main advantage of the matrix technology is an increased current extraction, we expect that such PV modules would be also beneficial in power plant applications, where multiple serial interconnected solar modules are controlled by a string inverter. However, we emphasize that such a statement requires more detailed studies and data acquisition, which is left to future work.

We did not address heating due to reverse biasing of individual solar cells. This is beyond the scope of this publication to be addressed in an adequate level of detail. However, work by Kunz et al.²⁰ and Clement et al.²⁴ discuss this in detail. They state that also in shingle solar cell modules, critical heating is caused by reverse biasing occurs. However, as discussed in Section 4.1, the matrix module reduces the risk of reverse biasing and hence solar cell heating.

We find the matrix technology particularly interesting for integrated applications such as building and vehicle integration. Huge potentials for solar power generation meet a huge variety of irregular shading conditions, making shading tolerance a very important aspect. Above this, matrix modules fulfill other requirements like a highly PHOTOVOLTAICS -WILEY

aesthetic appearance without losing power due to, for example, coloring or printing patterns on the front sheet.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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