

Design aspects in consideration of hotspot phenomena in high-performance photovoltaic modules featuring different silicon solar cell architectures

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ABSTRACT

Mitigating degradation or failure of high-performance photovoltaic modules due to hotspot phenomena requires the knowledge of the reverse bias behavior of different architectures like the passivated emitter and rear cell (PERC), tunnel oxide passivated contacts (TOPCon), silicon heterojunction (HJT) and perovskite silicon tandem (PVST) solar cells to understand the hotspot response for various module designs with different interconnection layouts of the solar cells. In this study, the current-voltage characteristics of mini-modules featuring one single PERC, TOPCon, HJT or PVST solar cell are measured in forward and reverse bias direction for different shading ratios and a model for evaluating different module designs is established, allowing the prediction of the hotspot temperature of a shaded solar cell in the worst-case scenario of a hotspot endurance test. It is shown that a strong correlation between the solar cell architecture and the module design in terms of maximum hotspot temperature exists. PERC, TOPCon, HJT and PVST solar cells show very different reverse bias behaviors, leading to different hotspot temperatures under various shading ratios whereas HJT and TOPCon solar cells exhibit higher hotspot temperatures than PERC solar cells. Furthermore, it is shown that alternative module designs with a reduced number of solar cells per string and more bypass diodes, but also with parallel substrings, are beneficial in terms of minimizing the hotspot temperature, especially for PVST solar cells which are more susceptible and prone to degradation at high temperatures.

1. Introduction

Mitigating degradation or failure of high-performance modules due to hotspot phenomena has become an important research question again as novel silicon solar cell architectures with higher efficiencies and larger wafer sizes have gained increasing market shares in recent years [1–5]. Hotspot phenomena are caused by connecting solar cells with a different current, leading a mismatch of the current between solar cells that are connected in series in a string. In most cases, the current mismatch is provoked by partial shading of one solar cell in the string, leading to an operating point of the shaded solar cell in reverse bias regime, forcing the current of the string through the shaded solar cell [6]. Hence, the shaded solar cell dissipates power in the form of heat instead of contributing to the module output power. Bypass diodes, connected antiparallel to the string, can minimize hotspot heating to a large extent, depending on the number of solar cells per string and the presence of parallel substrings [7,8]. Moreover, cracks or local shunts in solar cells can have a detrimental effect on the formation of hotspots [9]. The trend towards larger wafer sizes and half-cut or even third-cut solar cells decreases the current [10–15], but accompanied with it is typically an increase in the number of solar cells per module and, thus, an increase in the number of solar cells per bypass diode. In this context, the splitting

of the solar cells into half-cut solar cells leads to unpassivated edges which in turn can affect the characteristics of the solar cells not only in the forward, but also in reverse bias regime due to higher recombination and lower shunt resistances [16–20]. Furthermore, bifacial modules increase the current of the solar cells and can result in operation conditions with inhomogeneous illumination, leading to current mismatch as well [21].

Photovoltaic modules have to pass the hotspot endurance test according to the IEC 61215–2:2021 MQT 09 standard as part of the certification [22]. The purpose of the test is to determine the ability of the module to withstand hotspot heating effects like solder melting or deterioration of the encapsulation or backsheet, provoked by cracked or mismatched cells, interconnection failures, partial shading or soiling. In the hotspot test each solar cell in the module is completely shaded by an opaque cover to determine the influence of the reverse-bias behavior of the shaded solar cell on the current-voltage (IV) characteristics of the module to select solar cells with a low shunt resistance and solar cells with a high shunt resistance. Afterwards, the output terminals of the module are short-circuited which is the worst-case operating point of the modules in terms of the hotspot risk, and the selected solar cells are subjected to different shading ratios with an opaque cover in 10 % steps at an exposure of 800–1100 W/m² to determine the highest hotspot

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<https://doi.org/10.1016/j.solmat.2024.113058>

Received 1 September 2023; Received in revised form 9 July 2024; Accepted 19 July 2024

Available online 23 July 2024

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temperature with an infrared detector. At the highest hotspot temperature, the solar cell is tested for at least 1 h. The hotspot endurance test is passed when i) no major visual defects are present, ii) the module shows the electrical characteristics of a functional photovoltaic device, and iii) the insulation test and the wet leakage current test are passed. However, the maximum output power loss of the module and the maximum hotspot temperature are no testing criteria. The hotspot endurance test is usually performed for module temperatures of $(55 \pm 15)^\circ\text{C}$ with an ambient temperature of 25°C . Noteworthy, the modules are not pre-stressed before the hotspot endurance test by other tests according to the IEC 61215-2:2021. However, a recent study showed that a pre-stressed module after extended thermal cycling with 600 cycles is more prone to fail the hotspots endurance test [23], meaning that in reality the combination of different stress factors are relevant for hotspot phenomena.

Hotspots are a well-known research topic in photovoltaics but in the past studies mainly focused on multicrystalline silicon solar cells (multi-Si). Multi-Si solar cells are particularly susceptible to hotspots due to very high local power densities arising at grain boundaries, impurities and local breakdown sites [24–27]. As multi-Si solar cells are losing their relevance in the market, the interest in this topic recently shifted towards state-of-the-art monocrystalline solar cells (mono-Si) with more homogenous material quality and higher breakdown voltages. The dissipated heat of a solar cell in reverse bias regime can lead to high temperatures that can degrade the encapsulation and backsheet materials [28] but also the solar cells in the module, especially for HJT and PVST solar cells which are known to be more sensitive to temperature than PERC solar cells [29,30]. Kim and Krein reported that at prolonged reverse bias operation of mono-Si solar cells a significant alteration of the reverse IV characteristics of the solar cells occurred which was attributed to a local breakdown at dislocations or impurities [31]. The destruction of the pn-junction at temperatures well above 200°C is supposed to occur, while for the encapsulation and backsheet material temperatures of more than 150°C cause damaged, for instance, by melting of the encapsulation [32]. Furthermore, at temperatures close to 200°C encapsulation discolorations, desoldering of the solar cell interconnection, backsheet cracking or even glass breakage can occur [3].

Qian et al. compared partial shading in modules with 60 full and 144 half-cut solar cells and showed that for half-cut solar cell modules hotspot temperatures of up to 123°C were simulated compared to 150°C for full solar cells [1,33]. Interestingly, for parallel strings in the module with the half-cut solar cells the partial shading of a solar cell in the one string and the activation of the bypass diode led to an operation condition at which some solar cells in the parallel non-shaded substring were forced into reverse bias. The activation of the bypass diode effectively short-circuited the block of the parallel strings, causing the solar cells in the non-shaded substring to operate at voltages close to the short-circuit current. In this case, small current mismatches forced some solar cells into reverse bias, leading to hotspot temperatures in a substring with 20 half-cut solar cells in the range from 77°C to 145°C [1] while in an experiment the solar cells in a substring with 16 half-cut solar cells revealed hotspot temperatures in the range from 55°C – 66°C [33]. Clement et al. also observed hotspots in parallel substrings in modules with shingled solar cells [34,35]. For a module with 34 shingled solar cells in a string, maximum hotspot temperatures of up to 145°C were determined under short-circuit conditions, while up to 87°C occurred for a shingled solar cell in the parallel substring [34]. Witteck et al. demonstrated that partial shading of a module containing 144 half-cut solar cells ($G1, 158.75 \times 79.38 \text{ mm}^2$) and 24 solar cells protected by three bypass diodes can lead to hotspots or "hot cells". In the solar cells the heat generation was evenly distributed, reaching temperatures of 159°C , causing degradation of the encapsulation material and an increase in the risk of module failure. Simulations revealed that maximum hotspot temperatures of 176°C can be expected for modules with larger wafer sizes, showing that three bypass diodes per module are insufficient to mitigate the risk of critical heating of individual solar

cells. Additionally, partial shading of a module with 144 half-cut solar cells ($M6, 166 \times 83 \text{ mm}^2$) and 24 solar cells protected by one bypass diode resulted in even higher temperatures of up to 196°C , causing a discoloration of the backsheet [3]. Xu et al. investigated the impact of solar cell size (156.75 mm, 166 mm, 182 mm and 210 mm), shape (full, half-cut and third-cut), and number of cells per bypass diode (15, 22, 24, 30) on module power and hotspot response [4]. The study showed that increasing the number of solar cells per bypass diode caused the hotspot temperature to increase by up to 40 K to 170°C , comparing 210 mm third-cut solar cells with 210 half-cut solar cell. Additionally, increasing the solar cell size from 156.75 mm to 182 mm led to a moderate but significant 11 K increase in temperature. Jäckel et al. demonstrated that in a hotspot test of a module with 144 half-cut solar cells ($M2, 156.75 \times 78.38 \text{ mm}^2$), with 24 solar cells protected one bypass diode, the worst-case shading scenario occurred at around 50 % shading of a solar cell, irrespective of its position in the module [16]. Hotspot temperatures exceeding 150°C were recorded under these conditions, although no failures were observed. Noteworthy, during a cyclic hotspot test at which the module was switched between short-circuit and open-circuit conditions every hour, discoloration of the white backsheet was noticed after approximately 60 cycles. This highlights the importance of considering cyclic hotspot tests alongside classical hotspot tests when predicting the hotspot sensitivity of the modules.

In particular, silicon solar cell architectures like PERC solar cells exhibit illumination-dependent leakage currents which alter the behavior of the reverse characteristics of the solar cells. This behavior is important to account for in the module design with different interconnection layouts of the solar cells as their impact on the hotspot temperature can be significant [34]. Therefore, a so-called split-cell model was proposed to describe the reverse characteristics of partially shaded p-type silicon solar cells correctly. The split-cell model divides the solar cell into a parallel-connected illuminated and non-illuminated region whereas each region is described by the one-diode model, taking also into account the reverse characteristics of the solar cells [36]. It was reported that the split-cell model enables more accurate simulations of novel silicon solar cells architectures like TOPCon, HJT and PVST. In this respect, Wolf et al. showed that a substantial advantage of PVST solar cells is that the silicon bottom solar cell increases the breakdown voltage significantly, thus making it possible to increase the number of solar cells per string that is protected by one bypass diode [37]. Nevertheless, the maximum number of PVST solar cells per string was determined to be only 9 as the perovskite solar cells could already degrade at temperature of more than 100°C [29]. This is in contrast to the maximum number of silicon solar cells per string which was determined to be around 21 [37]. It was also reported that increasing the number of bypass diodes for PVST solar cells can significantly reduce the hotspot temperature, preventing local hotspot temperatures of up to 207°C which exceeds known decomposition temperatures of the perovskite layers [38]. Besides, it was shown that a reverse bias of only -1.0 V can lead to a degradation of perovskite top cells and a loss in efficiency which cannot be completely recovered [39,40]. In another study, it was reported that perovskite top cells do not degrade until a reverse bias of -9 V . However, the hotspot temperature can reach up to 100°C where degradation of the perovskite layer can occur [41]. Perovskite top cells were also analyzed for reverse bias from 2.5 V to 30 V and it was shown that local hotspots occurred with temperatures above 160°C [42]. Nevertheless, it was concluded that the silicon bottom cell screens a portion of the reverse bias, potentially limiting the electric field strength and, hence, the impact on the reverse bias of the perovskite top cell [43].

In this work, a model for evaluating modern high-performance modules with different solar cell architectures like PERC, TOPCon, HJT and PVST solar cells is established to determine the operating point of a solar cell at different shading ratios in a hotspot endurance test and to correlate the dissipated power to the hotspot temperature. Therefore, the current-voltage characteristics of mini-modules featuring a single PERC, TOPCon, HJT and PVST solar cell are measured in forward and

reverse bias direction for different shading ratios. Module parameters like the “worst case” shading scenario for the solar cell and the number of solar cells per string in different module designs are analyzed, allowing the identification of module designs that are less susceptible and less prone to hotspot phenomena.

2. Methodology

2.1. Fabrication of mini-modules and measurements of hotspot temperatures

Mini-modules with a size of 20 cm × 20 cm featuring single PERC, TOPCon, HJT and PVST solar cells are fabricated, using a glass-backsheet configuration for PERC, TOPCon and HJT solar cells or a glass-glass configuration for PVST solar cells. Ethylene vinyl acetate (EVA) was used as an encapsulant for PERC solar cells while polyolefin (POE) was used for TOPCon, HJT and PVST solar cells. The PERC solar cells with c-Si(n⁺)/c-Si(p)/local c-Si(p⁺) structure, TOPCon with c-Si(p⁺)/c-Si(n)/SiO_x/poly-Si(n⁺), HJT with ITO/a-Si(n⁺)/a-Si(i)/c-Si(n)/a-Si(i)/a-Si(p⁺)/ITO structure, and PVST solar cells with ITO/SnO_x/C₆₀/FA_xCs_{1-x}Pb(I_yBr_{1-y})₃/2PACz/ITO/a-Si(n⁺)/a-Si(i)/c-Si(n)/a-Si(i)/a-Si(p⁺)/ITO structure were M6 half-cut solar cells and the efficiency was about 22.1 %, 23.2 %, 23.5 % and 24.2 %, respectively, see also Table 1.

The current voltage (IV) characteristics of the mini-modules in forward and reverse bias direction were measured for different shading scenarios under partial and uniform illumination, using a Delta Elektronika SM 52 AR 60 power supply with a voltage and current range of 0–52 V and 0–30 A, respectively. For uniform shading of the mini-modules various illumination levels from 0 to 1000 W/m² in 200 W/m² steps were applied, using the illumination source of a Sinus-220 Wavelabs LED solar simulator with an A+++ rating (20, 40, 60 and 80 % shading means that the solar cells were illuminated at 200, 400, 600 and 800 W/m²). For partial shading the mini-modules were illuminated at 1000 W/m² and an opaque cover was placed onto fractions of the solar cells to obtain shading ratios from 0 to 100 % in 20 % steps (20, 40, 60 and 80 % shading means that the opaque cover was placed on 20, 40, 60, 80 and 100 % of the area of the solar cells). In this case, the effective shading ratio might be slightly lower as oblique incident light from the solar simulator is illuminating areas below the edge of the opaque cover. However, the currents of the solar cells of the mini-modules with uniform and partial shading are very similar (not shown). The IV curves were measured at room temperature with a voltage sweep duration of a couple of seconds, usually 2–3 s, long enough to avoid any influence of capacitance effects of the solar cells on the measured IV curves and short enough to prevent excessive heating of the solar cells. The IV curves of the PERC, TOPCon, HJT and PVST solar cells were fitted by the split-cell model in forward and reverse direction using the two-diode-model using the Levenberg-Marquardt algorithm to calculate the resulting IV curves of the solar cells in various module designs allowing the adjustment of the size of the solar cells. The parameters are the photogenerated current J_{ph} , reverse saturation current for the first and second diode J_{01} and J_{02} , respectively, series resistance R_s at 0 and 1 sun, shunt resistance R_{sh} at 0 and 1 sun, breakdown voltage V_{br} at 0 and 1 sun, the fraction of avalanche leakage current α at 0 and 1 sun and the avalanche breakdown exponent m at 0 and 1 sun. The non-linear and implicit functions for the forward and reverse direction of the IV curve are solved by using the Newton-Raphson algorithm. The bypass

diodes were included in the model by measuring the IV curves of industrially fabricated bypass diodes for photovoltaic applications and fitting them by the one-diode model in a similar manner.

For validation of the model and the determination of the hotspot temperature of a shaded solar cell, a test module with 60 half-cut PERC solar cells in two parallel substrings was fabricated, featuring 30 solar cells per substring. In contrast to conventional modules, both substrings are connected between groups of 15 solar cells, see Fig. 3. Hence, compensation currents are present in case of a shading scenario which affect the maximum power dissipation and the hotspot temperature of a shaded solar cell. A hotspot endurance test was performed by short-circuiting the output terminals according to the IEC 61215–2:202119 MQT 09 test procedure describe above. The hotspot test of the module was performed in a Class B hotspot tester at set irradiance of about 1000 W/m² where the ambient temperature inside the chamber was about 25 °C. The module was subjected to different shading ratios for at least 1 h and afterwards the temperatures of the shaded solar cell were measured from the backsheet side with an infra-red camera, using an emissivity that was calibrated before with a PT100 temperature sensor on a white backsheet.

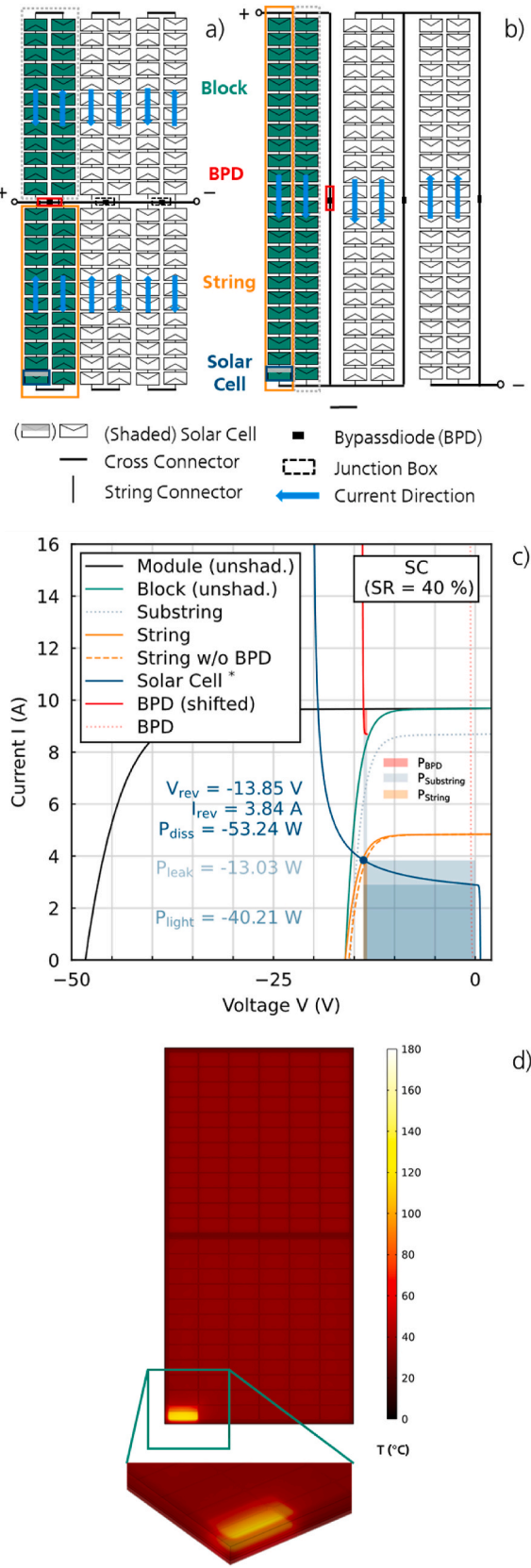
2.2. Modelling of dissipated powers and hotspot temperatures

Under normal operating conditions, a module as illustrated in Fig. 1, operates at the maximum power point, but a shaded solar cell in a series-connected substring under short-circuit conditions represents the worst-case scenario for evaluating the risk of hotspots. This is because a shaded solar cell in a substring forces the solar cell into reverse bias and activates the bypass diode, leading to a short-circuited parallel substring in which a shaded solar cell then represents to worst case scenario. Hence, in a hotspot endurance test “the maximum internal power dissipation of the diode occurs when the circuit element protected by the bypass diode is short circuited” as noted in the IEC 61215–2:202119 MQT 09. For the worst-case scenario, the operating point of the shaded solar cell can be constructed graphically by applying Kirchhoff’s mesh rule. As the voltage of the shaded solar cell is equal to the voltage of the remaining unshaded solar cells in a substring plus the forward voltage of the bypass diode, plotting both IV curves individually and mirroring one of the IV curves along the current axis gives the operating point of the shaded solar cell as the intersection of both curves [44–47]. It is worth mentioning, that even when the bypass diode is active with current flowing through it, a significant part of the current is still flowing through the substring with the shaded solar cell as the substring is not decoupled from the circuit. In this case, the solar cell is not a generator anymore, but is operated as a consumer and dissipates power. In a similar manner, the operating point of a shaded solar cell in parallel-connected substrings can be constructed graphically by mirroring the IV curve of the shaded solar cell along the voltage axis [44–46]. Combining series-connected substrings with parallel-connected substring allows the graphical construction of the operating point of shaded solar cells in various module designs, taking into account each individual i) solar cell, ii) substring with shaded or unshaded solar cells, iii) parallel substring with shaded or unshaded solar cells, iv) block with shaded or unshaded substrings connected in series or in parallel and which are protected by an antiparallel-connected bypass diode and v) the module consisting of several blocks usually connected in series [36,44,48]. Fig. 1c illustrates the construction of the operating point of a shaded M6 PERC solar cell in a typical 144 half-cut solar cell module for a hotspot test under short-circuit conditions. The module comprises by two parallel substrings featuring 24 solar cells per substring, whereby two of these substrings and a bypass diode forma block and three of these blocks are connected in series, see Fig. 1a and b. The IV curves of the shaded solar cell, the remaining unshaded solar cells in the string, subtracted by the voltage of the bypass diode, the bypass diode itself, the parallel substring of the block consisting of the two substrings and the bypass diode and

Table 1

IV parameters of the PERC, TOPCon, HJT and PVST solar cells.

Parameters	PERC	TOPCon	HJT	PVST
I_{sc} (A)	5.52	5.65	5.6	2.39
V_{oc} (V)	0.678	0.698	0.719	1.754
FF (%)	81.2	81.4	80.7	79.8
η (%)	22.1	23.2	23.5	24.2



(caption on next column)

Fig. 1. Illustration of the modeling framework: a) equivalent circuit model and b) same but other equivalent circuit model of the 144 half-cut solar cell module with a shaded M6 PERC solar cell (grey) in a string (orange) - two parallel substrings feature 24 solar cells per substring, two of these substrings and a bypass diode, BPD, from a block and three of these blocks are connected in series -, c) IV curves and graphical construction of the operating point of the shaded solar cell (blue) in the module during in a hotspot test under short-circuit (SC) conditions and a shading ratio (SR) of 40 %, including the remaining unshaded solar cells in the string (orange, solid), subtracted by the voltage of the bypass diode (orange, dashed), of the bypass diode (red) of the block consisting of the two substrings and the bypass diode (green), and of the module (black), as well as the dissipated power of the solar cell (blue area), the power of the bypass diode (red area), the string with the shaded solar cell (orange area) and the parallel substring (grey area) - the IV curve of the module (black) and the block (green) is shown in an unshaded scenario, the IV curve of the shaded solar cell (blue) is the only one that is not mirrored (*) along the voltage axis, the IV curve of the BPD (red, dotted and solid) is shifted to indicate the shares of the current that flows through the string, the substring and the BPD and to align it with the areas, indicating the power of the string, the substring and the BPD -, and d) temperature distribution of the module with the shaded solar cells in the bottom left corner, modeled numerically using the dissipated power of the solar cell as an input parameter. V_{rev} and I_{rev} indicate the reverse voltage and current and P_{diss} indicated the dissipated power of the shaded solar cell.

the module are shown in Fig. 1c. The solar cell is shaded by about 40 % and is operated in reverse bias regime. Hence it is dissipating power. The dissipated power (P_{diss}) can be subdivided into a part that is related to the irradiated area of the solar cell (P_{light}) and a part that is related to the whole area which is induced by additional leakage currents in the solar cell (P_{leak}) [47,49,50]. While P_{light} is relatively homogenous and induced by the photocurrent in the illuminated area of the solar cell, P_{leak} can be non-homogenous and is mostly correlated to the quality of the silicon wafer and the solar cell. In the considered shading scenario the bypass diode is “active” already, however, with a low current flowing through it (Fig. 1c, red area) whereas a significant part of the current is flowing through the string with the shaded solar cell (Fig. 1c, orange area) as well as the parallel substring (grey area). Hence, the dissipated power of the string with the shaded solar cell as well as the power of the parallel substring is quite low as both operate at voltages determined by the bypass diode. Noteworthy, it should be pointed out that the solar cells in the module are assumed to be nominal identical. Thus differences in the characteristics of the solar cells in the forward and reverse bias region that are usually observed in reality [51,52] are not considered in the modelling of the studied modules designs.

It is worth mentioning that there are some constraints in the model. Firstly, the IV curves of the shaded solar cells in the mini-modules are measured at room temperature, but in case of uniform or partial shading of the solar cell heating occurs which in turn influences the reverse IV characteristics of the solar cells. Clement et al. observed a positive temperature coefficient, leading to a shift to lower voltages, hence high breakdown voltages, with an increase in the temperature [5]. This effect is not included in the current model and requires measurements of the shaded solar cells at different temperatures, especially at high temperatures in the range from 100 °C to 200 °C. Secondly, the IV curves of the unshaded solar cells are also measured at room temperature although in a module these solar cells usually have a higher temperature due to illumination at one sun. At high temperatures the voltage of the solar cells decreases which in turn affects the operating point in reverse bias regime and thus the dissipated power of the shaded solar cells. This effect is not included in the model and requires measurements of the unshaded solar cells at higher temperatures. Thirdly, the IV curves are measured for M6 half-cut solar cells only as larger solar cells for the different solar cell architectures were not available. Hence, for module designs with G12 solar cells, the parameters of the measured M6-half-cut solar cells were scaled according to the increase in the area, ignoring possible changes in the reverse IV characteristic due to differences in the

fabrication process of the larger solar cells.

In addition to the determination of the dissipated power of the shaded solar cell with the model mentioned above, a three-dimensional model of the module is created to obtain the hotspot temperature of the shaded solar cell. This model is based on numerical simulation with the finite-element simulations software package COMSOL Multiphysics, solving the steady-state heat equation and using P_{diss} as an input parameter and as a source for Joule heating. P_{diss} is divided into P_{light} and P_{leak} whereas P_{light} is used for the irradiated area of the solar cell and P_{leak} is equally distributed over the total area of the solar cell. The module consists of a glass on the top, an encapsulation at the top and bottom of the solar cells as well as in between the solar cells and a backsheet at the bottom. The thickness of the glass, encapsulation material, solar cells and backsheet is 2.8 mm, 600 μm , 180 μm and 340 μm , respectively. Typical distances between the solar cells in a string and the distance between strings are assumed to be 2 mm and 4 mm, respectively. The distance of the solar cells to the edge is assumed to be 20 mm. The material properties used in the simulations are taken from literature [53]. The thermal conductivity of glass, encapsulation material, solar cells and backsheet is 1, 0.3, 163 and 0.2 W/(m K), respectively. The density of glass, encapsulation material, solar cells and backsheet is 2200, 935, 2329 and 1200 kg/m³, respectively. Radiative heat transfer to the environment is also accounted for at the glass and backsheet of the module. The emissivity of the glass and the backsheet is assumed to be 0.9 and 0.84, respectively. The simulation takes into account free and forced convection at the boundaries due to wind and ambient temperature, assuming a convective heat transfer coefficient of 10 W/(m² K) [54].

3. Results and discussion

3.1. Reverse bias characteristics of PERC, TOPCon, HJT and PVST solar cells

Fig. 2 shows the IV characteristics of the mini-modules with the PERC, TOPCon, HJT and PVST solar cells in reverse and forward bias region for different shading ratios, applying various illuminations to imitate homogeneous shading. The fitted parameters for the split-cell model are shown in Table 2.

It is observed that PERC, TOPCon, HJT and PVST solar cell show very different characteristics in reverse bias direction for various shading ratios. The different reverse bias characteristics are believed to be specific for the technology and related to the properties of the pn-junction, i. e. the doping profiles for silicon solar cells with diffused junctions [55,56], but also the bulk doping concentration in case of silicon heterojunctions [57]. In addition, it was reported that the edge regions play an important role for the reverse bias characteristics of silicon solar cells with diffused junctions as local shunts can occur [58]. In accordance with recent observations, PERC solar cells are strongly affected by the shading ratio due to an illumination-dependent leakage current that has a significant impact on the shape of the reverse IV curves [5]. The leakage current is increasing with higher illumination and it can be attributed to avalanche breakdown [59] or impact ionization that might be further multiplied through the photogenerated minority charge carriers crossing the space-charge region [5]. It can be seen that for a shading ratio of 100 % a hard breakdown at about -20 V occurs while for a shading ratio of 0 % a soft breakdown in the range from -5 V to -20 V occurs. In contrast, TOPCon, HJT and PVST solar cells are less affected by an illumination-dependent leakage current as for different shading ratios the shape of the reverse IV curves is quite similar (not shown). Clement et al. also reported for TOPCon solar cells that reverse IV curves were not affected by the illumination-dependent leakage current [5]. While for HJT and PVST solar cells a soft breakdown in the range from -20 V to -27 V or -32 V, respectively, occurs, the TOPCon solar cells exhibit a soft breakdown at much lower reverse voltages in the range from -20 V to well below -40 V. Interestingly, the PVST solar cells could be

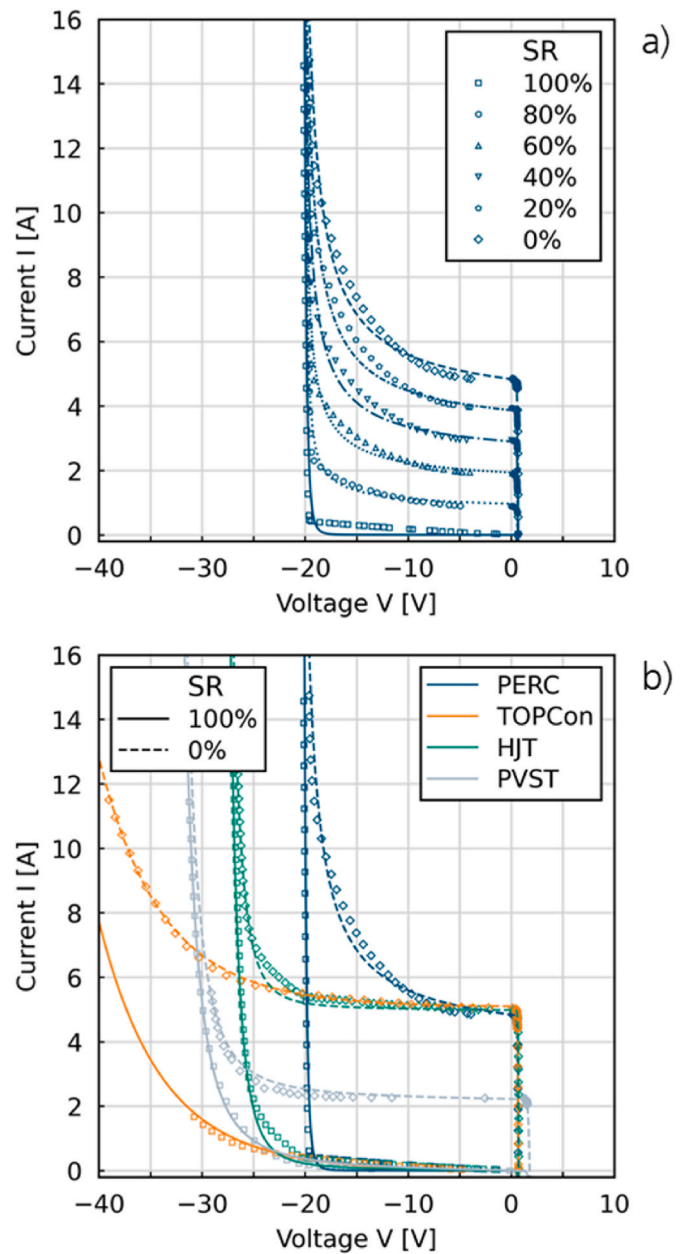


Fig. 2. Measured and fitted IV curves of the a) PERC solar cell (blue) for different homogeneous shading ratios from 0 to 100 % in 20 % steps and of the b) PERC (blue), TOPCon (orange), HJT (green) and PVST (grey) solar cell for shading ratios of 0 % (dotted line) and 100 % (solid line). The IV curves of the solar cells were fitted with the split-cell model which takes into account the contribution of the leakage current in dependence of the illumination.

measured a couple of times in the reverse bias region without any significant change in the shape of the IV curve for different shading ratios from 0 to 100 % in 20 % steps. The voltage sweep duration was only a few of seconds to avoid excessive heating of the solar cells, but in reality a hotspot could occur for much a longer time which might significantly change the shape of the IV curve due to the higher temperature [42]. Furthermore, it is worth mentioning that the IV curves are similar for uniform shading as well as for partial shading of PERC, TOPCon, HJT and PVST solar cells using an opaque cover (not shown). Clement et al. also reported for PERC solar cells that both uniform and partial shading produce similar effects on the illumination-dependent leakage current [5]. It was also reported that the leakage current for PERC solar cells can be assumed to depend on the photogeneration only and not on the

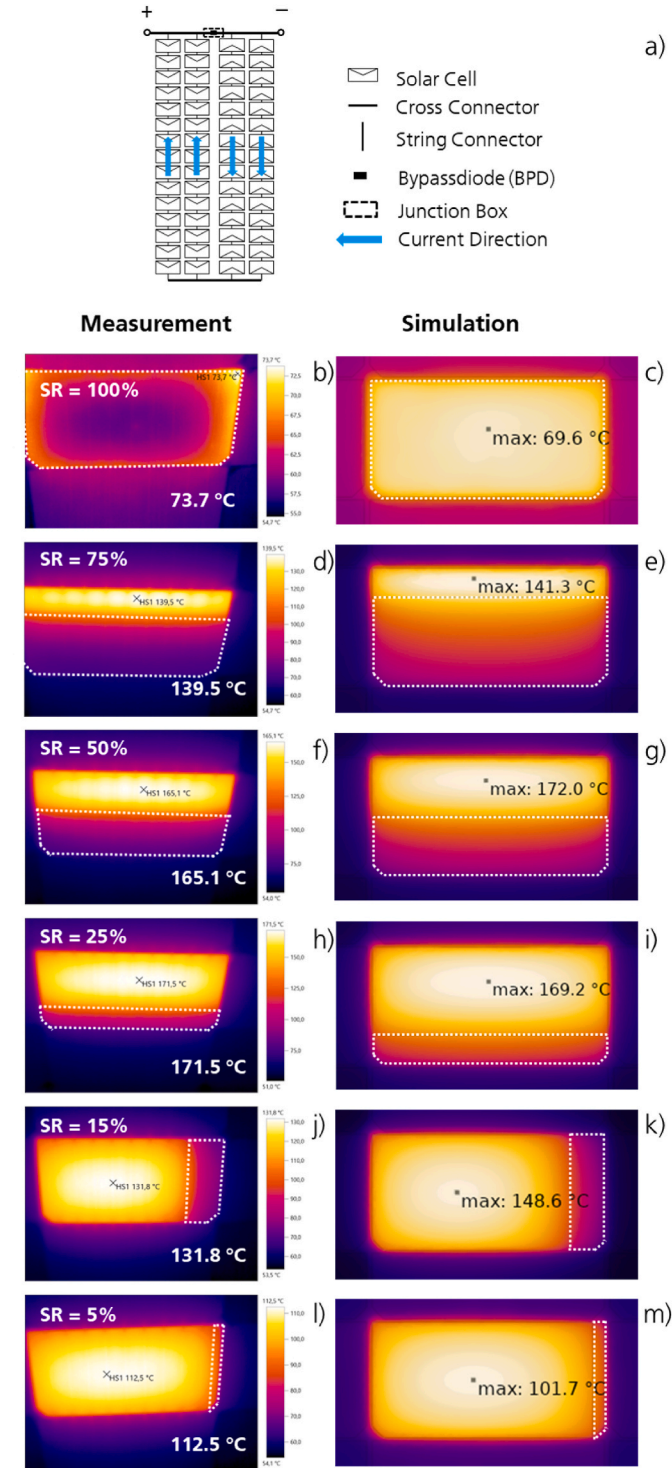


Fig. 3. a) Illustration of the equivalent circuit model of the test module with 60 half-cut M6 PERC solar cells, measurement (left) of the hotspot temperature of PERC solar cells with an infrared camera from the backsheet side of the test module after 1 h of the hotspot endurance test and simulation (right) of the hotspot temperature for different shading ratios of 100 % (b,c), 75 % (d,e), 50 % (f,g), 25 % (h,i), 15 % (j,k) and 5 % (l,m), using the modeled dissipated power of the shaded solar. The dashed lines represent the shaded area of the solar cell. For shading ratios of 15 % (i,j) and 5 % (k,l) the shading was along the short side of the solar cell because the shading ratio could be realized much more precisely in the experiment than shading along the long side of the solar cell. The temperature scale for the measured and simulated temperature is the same and only shown once for the measured temperature.

Table 2

Parameters fitted by the split-cell model for PERC, TOPCon, HJT and PVST solar cells.

Parameters	PERC	TOPCon	HJT	PVST
1 Sun				
I_{ph} (A)	5.52	5.65	5.60	2.39
I_{01} (A)	1.3×10^{-11}	4.2×10^{-12}	5.0×10^{-12}	1.5×10^{-30}
n_1 (.)	1.02	0.97	1.01	1.17
I_{02} (A)	1.1×10^{-6}	6.1×10^{-7}	1.4×10^{-6}	3.4×10^{-16}
n_2 (.)	1.97	1.88	2.04	1.81
R_s (Ω)	2.6×10^{-3}	1.2×10^{-3}	1.5×10^{-3}	4.5×10^{-2}
R_{sh} (Ω)	1.6×10^3	1.1×10^4	2.6×10^2	2.1×10^2
V_{br} (V)	-20.8	-86.6	-29.5	-33.2
α (.)	65.2	32.5	5.7×10^{-2}	3.5×10^{-1}
m (.)	9.3×10^{-1}	6.7	3.1	1.99
0 Suns				
I_{ph} (A)	0	0	0	0
I_{01} (A/cm ²)	1.1×10^{-11}	2.3×10^{-12}	3.1×10^{-12}	4.5×10^{-31}
n_1 (.)	1.05	1.13	1.01	1.15
I_{02} (A/cm ²)	1.4×10^{-6}	4.5×10^{-7}	1.2×10^{-6}	1.4×10^{-16}
n_2 (.)	1.88	1.78	1.98	1.84
R_s (Ω cm [2])	2.6×10^{-3}	9.8×10^{-3}	1.5×10^{-3}	2.9×10^{-2}
R_{sh} (Ω cm [2])	1.6×10^3	2.6×10^4	2.6×10^2	2.1×10^2
V_{br} (V)	-20.8	-86.6	-29.5	-33.2
α (.)	1.2×10^{-3}	32.5	5.7×10^{-2}	3.5×10^{-1}
m (.)	4.4	6.6	3.1	1.99

spatial distribution of incident light [5].

3.2. Validation of modeled hotspot temperatures

The model described in the previous section was validated by experimental data obtained from measurements of the hotspot temperature of a partially shaded solar cell in the test module with M6 PERC solar cells during the hotspot endurance test. To this end, the solar cell is subjected to different shading scenarios with shading ratios of 100 %, 75 %, 50 %, 25 %, 15 % and 5 % and the hotspot temperature was measured after about 1 h when an equilibrium temperature was reached. Then, the dissipated power of the shaded solar cell is modeled for the realized shading scenarios and the hotspot temperature is simulated. Fig. 3 displays the comparison of the measurements and the simulations in terms of the hotspot temperature of the shaded solar cell.

It can be observed that different shading ratios lead to different hotspot temperatures and that in the illuminated (unshaded) area of the solar cell the highest temperatures prevails. It can be seen by the images of the infrared camera that a homogeneous heating of the solar cell is present when partially shading occurs. The hotspot temperature is the lowest with 73.7 °C when the solar cell is completely shaded with a shading ratio of 100 % and gradually increases to a maximum hotspot temperature of 171.5 °C for a shading ratio of 25 %. For smaller shading ratios of 15 % and 5 % along the short side of the solar cell the hotspot temperature is decreasing significantly to 131.8 °C and 112.5 °C, respectively. The simulations show a similar trend in the hotspot temperature for the different shading scenarios, although the maximum hotspot temperature of 172.0 °C is obtained for a shading ratio of 50 %. However, the simulated hotspot temperature of 169.2 °C for a shading ratio of 25 % is quite close to the measured hotspot temperature of 171.5 °C. For smaller shading ratios of 15 % and 5 % along the short side of the solar cell the simulated hotspot temperature with 148.6 °C and 101.7 °C deviates substantially from the measured hotspot temperature by -16.8 K and 10.8 K, respectively. Furthermore, the simulations could reproduce the spatial temperature distribution observed for the shaded solar cell from the middle to the edges quite well and even the temperature increase in adjacent solar cells in the test module due to heat transfer from the shaded solar cell to the adjacent illuminated (unshaded) solar cells can be seen. Possible reasons for the temperature differences between the measurements and the simulations could be that i) the reverse bias characteristics of the solar cells in the module differ to

reverse bias characteristics of the solar cell in the mini-module which was used for the simulation and ii) that the reverse bias characteristics of the shaded solar cells in the mini-modules are measured at room temperature, but excessive heating of the solar cell occurs due to the partial shading, leading to a shift in the reverse bias to higher breakdown voltages.

3.3. Dissipated power and hotspot temperature for different shading ratios

Fig. 4 illustrates the construction of the operating point of a shaded M6 PERC solar cell with a variation of the shading ratio from 100 % to 10 % in a typical 144 half-cut solar cell module for a hotspot test under short-circuit conditions. The module is characterized by two parallel substrings featuring 24 solar cells per substring, whereas two of these substrings and a bypass diode are combined in a block and three of these blocks are connected in series.

In general, it can be observed that for different shading ratios of the solar cell different operating points and hence different dissipated powers exist. For a completely shaded solar cell with a shading ratio of 100 % almost no current is flowing through the shaded solar cell and the string with the shaded solar cell. In this case, the short-circuit current of the module (9.7 A) is divided and almost half of the current (4.8 A) flows through the “active” bypass diode (red area) and almost the other half of it (4.5 A) flows through the parallel substring (grey area). In contrast, for the shading ratio of 80 %, 60 % and 40 % a significant current is flowing through the solar cell, so that the shaded solar cell operates in reverse bias and dissipates power (blue area). In these cases, the bypass diode is “active” too, but less current flows through it (red area), whereas a significant part of the current now flows through the shaded solar cells and the string with the shaded solar cell (orange area) as well as the parallel substring (grey area). The highest dissipated power of the shaded solar cell occurs at a shading ratio of 20 % as the bypass diode is almost “inactive” and only a small current flows through it. Half of the current

(4.7 A) now flows through the shaded solar cell and the string with the shaded solar cell and the other half of it (4.6 A) flows through the parallel substring (grey area).

Fig. 5 shows the dissipated power (P_{diss}), the power in the irradiated area of the shaded solar cell (P_{light}) and the power that is related to the additional leakage currents in the solar cell (P_{leak}) in more detail. Furthermore, the hotspot temperature of the shaded solar cell in the 144 half-cut solar cell module is depicted for a hotspot test under short-circuit conditions, varying the shading ratio from 0 % to 100 % for M6 PERC solar cells and also for TOPCon, HJT and PVST solar cells. The dissipated power was modeled by the graphical construction of the operating point of the shaded solar cell and the hotspot temperature was simulated numerically as described above.

The influence of the shading ratio on P_{diss} , P_{light} and P_{leak} is very different among the PERC (blue), TOPCon (orange), HJT (green) and PVST (grey) solar cells. Taking a closer look at the PERC solar cells, it can be seen that P_{diss} is the highest with 56.4 W at a shading ratio of 28 % while P_{light} and P_{leak} are the highest with 45.2 W and 13.0 W at a shading ratio of 24 % and 40 %, respectively. Interestingly, the maximum hotspot temperature of 164.5 °C occurs at a shading ratio of 32 % and is thus shifted by 4 % towards a higher shading ratio compared to the maximum P_{diss} at a shading ratio of 28 %. The reason for this shift can be ascribed to the heat transport inside the shaded solar cell from the unshaded to the shaded region of the solar cells and from the unshaded solar cell region to the adjacent solar cells in the module. Similar observations were also shown in literature [54]. Hence, shading along the short side of the solar cell is leading to even higher hotspot temperatures of 175.8 °C and a further shift towards a high shading ratio of 40 % compared to a shading along the long side of the solar cells as the heat transport is impeded to a certain extent (not shown). For TOPCon and HJT solar cells a shading ratio of 8 % leads to the highest P_{light} of 61.1 W and 66.0 W, respectively, while the maximum hotspot temperature with 173.4 °C and 180.6 °C, respectively, occurs at a shading ratio of 18 %.

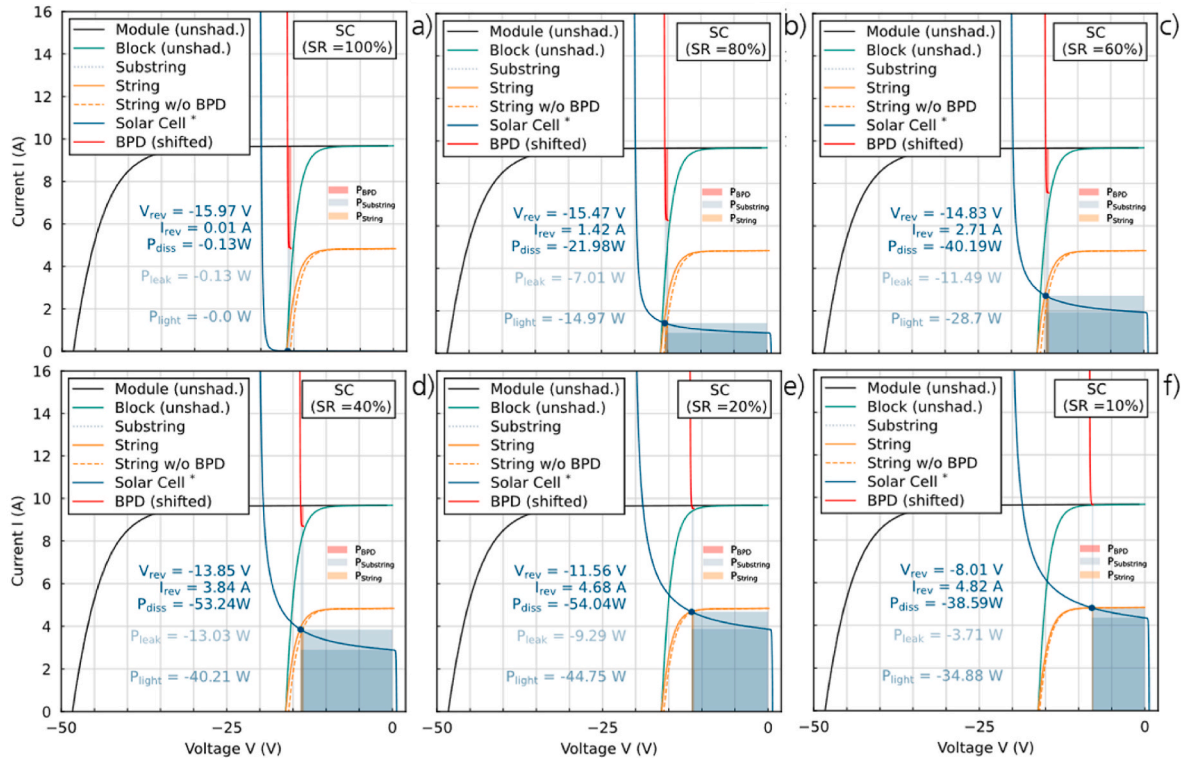


Fig. 4. IV curves and graphical construction of the operating point of the shaded solar cell (blue) in a hotspot test of the 144 half-cut solar cell module with M6 PERC solar cells under short-circuit (SC) conditions with the dissipated power of the solar cell (blue area) for shading ratios (SR) of a) 100 %, b) 80 %, c) 60 %, d) 40 %, e) 20 % and f) 10 %.

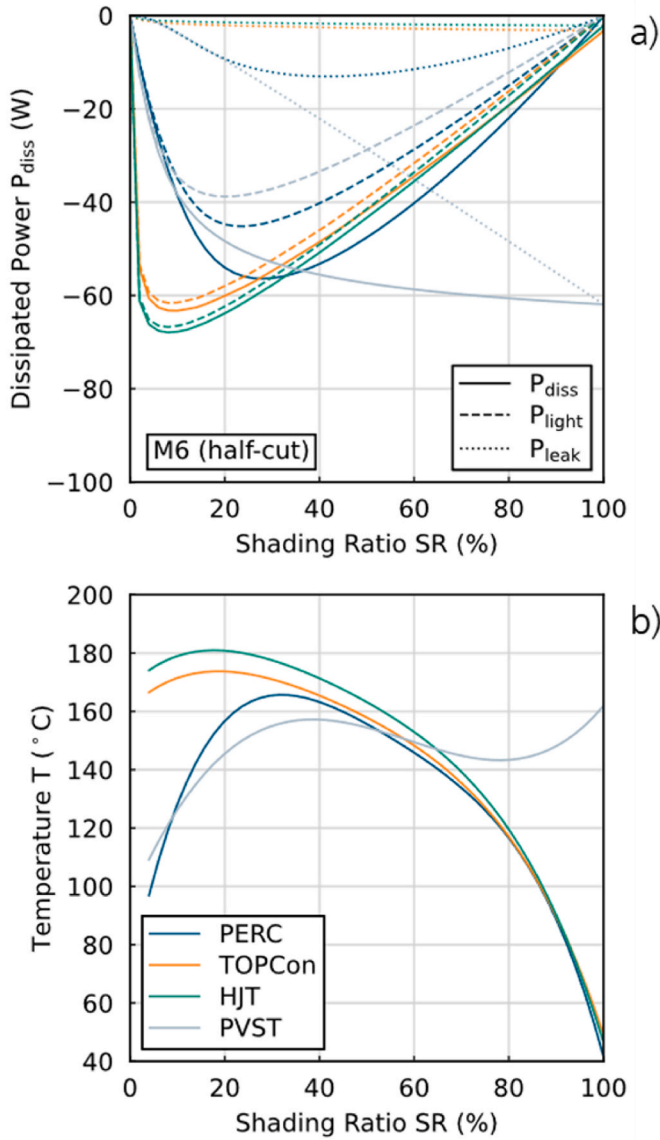


Fig. 5. a) Modeled dissipated power (P_{diss}), power in the irradiated area of the shaded solar cell (P_{light}) and power that is related to the additional leakage currents in the solar cell (P_{leak}) of a 144 half-cut solar cell module with M6 PERC solar cells (blue), TOPCon (orange), HJT (green) and PVST (grey) solar cells under short-circuit conditions and corresponding b) modeled hotspot temperature for different shading ratios. The shading was assumed to occur along the long side of the solar cell.

marginal for both TOPCon and HJT solar cells over the whole range of the different shading ratios. Interestingly, for the PVST solar cell P_{diss} is the highest with 62.3 W at a shading ratio of 100 %. In this case P_{diss} is governed by P_{leak} as P_{light} is very small. In contrast, P_{light} is the highest with 38.8 W at a shading ratio of 20 %. PVST solar cells exhibit almost three times higher voltages and almost half the current of PERC, TOPCon and HJT solar cells. Therefore, a high P_{leak} prevails at high shading ratios for the module design. In terms of temperature, it can further be seen that two distinct maximum hotspot temperatures exist. On the one hand, the maximum hotspot temperature is 155.9 °C at a shading ratio of 40 % while, on the other hand, 162.4 °C is reached at a shading ratio of 100 %. The rise of the hotspot temperature at shading ratios higher than 80 % is originated by another interesting phenomena. Below 80 % the maximum hotspot temperature occurs in the irradiated area of the solar cell while above 80 % it occurs in the shaded area of the solar cell due to the high P_{leak} (not shown). The results emphasize that, for the module

design under consideration, there is a strong correlation between the solar cell architecture and dissipated powers and hotspot temperatures of a shaded solar cell in the worst-case scenario of a hotspot endurance test.

Fig. 6 shows the hotspot temperature for different shading ratios and the maximum hotspot temperature of a shaded solar cell in a half-cut solar cell module with different number of solar cells per string, using M6 and M12 PERC, TOPCon, HJT and PVST solar cells.

It can be seen that the hotspot temperature increase for higher number of solar cells per module, corresponding to a higher number of solar cells per string, for M6 PERC (blue), TOPCon (orange) and HJT (green) solar cells while it is almost constant for PVST (grey) solar cells. Increasing the number of PERC solar cells per module (per string) from 120 (20) to 180 (30) increases the maximum hotspot temperature of the shaded solar cell from 148.7 °C to 186.2 °C, respectively. The trend of an increase in the hotspot temperature is comparable to reported values from literature [4,6]. However, the hotspot temperature was about 20 K lower for a similar module and increased from 145.2 °C for a module with a similar power of 445 W featuring M6 PERC solar cells to 148.7 °C for a module with similar power of 535 W featuring M10 PERC solar cells [4]. In this case, the shading ratio at which the maximum hotspot temperature occurs is shifted from 29.6 % to 40.3 % for 20 to 30 solar cells per string, respectively. TOPCon and HJT solar cells exhibit a similar trend. The hotspot temperature increases for TOPCon solar cells from 154.6 °C to 200.0 °C for 20 to 30 solar cells per string, respectively, while for HJT solar cells the hotspot temperature increases from 160.8 °C to 208.5 °C for 20 to 30 solar cells per string, respectively. In contrast, the hotspot temperature of PVST solar cells is almost constant with around 157.0 °C, independent of the number of solar cells per string. This is caused by the high voltage of the PVST solar cells, leading to a higher voltage of the string with PVST solar cells compared to PERC, TOPCon and HJT solar cells. The high voltage of the string is larger than the breakdown voltage of the PVST solar cell, so that the voltage at the operating point of the PVST solar cells in the reverse bias regime is not increasing anymore with a larger number of solar cells per string. Therefore, the dissipated power and the hotspot temperature is constant. Noteworthy, if the number of PERC, TOPCon and HJT solar cells is increased, the dissipated power and the hotspot temperature are becoming constant as well (not shown). Furthermore, increasing the wafer size from M6 to M12 leads to different trends in the hotspot temperature for PERC, TOPCon, HJT and PVST solar cells. The hotspot temperature increase by 8–12 K for PERC solar cells when changing from M6 to M12 which is similar to the reported values from literature [4], while for TOPCon solar cells the hotspot temperature decrease by 2–6 K. The hotspot temperature increase can be described by the larger distance of the heat that has to be transported in lateral direction to the colder neighboring solar cell, resulting in a higher hotspot temperature for larger wafer sizes [4]. In contrast, for TOPCon solar cells the shape of the reverse bias characteristics with the higher breakdown voltage leads to an operating point in the reverse bias region at which the dissipated power of the large size solar cells is slightly lower compared to the smaller solar cell. For HJT solar cell the hotspot temperature increase by 8–10 K and, similarly, for PVST solar cells the hotspot temperature increases by 9–10 K when changing from M6 to M12, respectively.

3.4. Minimizing the hotspot temperature by using alternative module designs

In general, the predicted hotspot temperatures are in some cases above usual lamination temperatures of around 140 °C [60,61] and clearly above the known material parameters like the thermal index (TI), relative thermal index (RTI) and relative thermal endurance index (RTE) of typically 90–110 °C [16,62]. The TI/RTI/RTE values are metrics for determining the long-term thermal suitability of polymers for photovoltaic modules in different climates and for different mounting configurations, taking a minimum testing duration of 20,000 h into account.

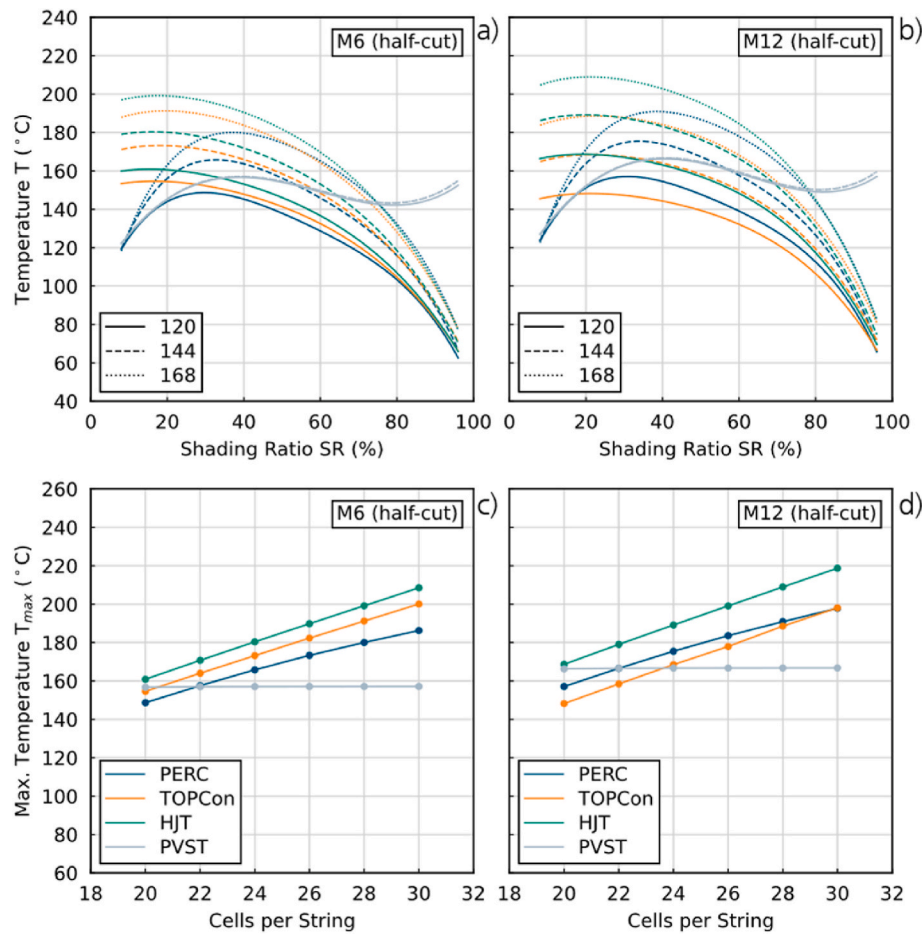


Fig. 6. a,b) Modeled hotspot temperature for different shading ratios of a solar cell in a half-cut solar cell module with different number of solar cells per the module, 120 (solid), 144 (dashed) and 168 (dotted), corresponding to different number of solar cells per the string, 20, 24 and 28, respectively, and c,d) modeled maximum hotspot temperature of a shaded solar cell for different number of solar cells per the string, using M6 (a,c) and M12 (b,d) PERC (blue), TOPCon (orange), HJT (green) and PVST (grey) solar cells. The shading was assumed to be along the long side of the solar cell.

In this way, the limits of a material can be determined at a certain temperature for their permanent or frequent use. Usually, polymer materials are not designed for continuous operation at temperatures in the range of typical hotspot temperature and the duration of 1 h in a hotspot endurance test already corresponds to a period of one summer days. Hence, alternative module designs with a low number of solar cells per string and more bypass diodes are required to minimize the hotspot temperature [2,10,63], especially for PVST solar cells which are more susceptible and prone to degradation at high temperatures [29]. In this respect, another important aspect are the electrical output parameters of the module. The 144 half-cut solar cell module with M6 PERC solar cells has a modeled V_{mpp} of 41.6 V, an I_{mpp} of 10.5 A and a P_{mpp} of 436.8 W while the same module with M6 PVST solar cells exhibits a V_{mpp} of 111.3 V, an I_{mpp} of 4.3 A and a P_{mpp} of 478.3 W, which is almost three times the voltage and half the current of the module with PERC solar cells. Therefore, the module design needs to be adapted for PVST solar cells to obtain similar electrical output parameters as for modules with PERC, TOPCon and HJT solar cells.

Fig. 7 presents the hotspot temperature of a shaded solar cell following a module design similar to a module from BP Solar from 2011 [64] and from Mitsubishi Electric from 2012 [65], and shown in literature [2,66] featuring 144 half-cut solar cells using M6 PERC, TOPCon, HJT and PVST solar cells with a reduced number of solar cells per string and more bypass diodes, allowing typical electrical output parameters of the module for PERC, TOPCon and HJT solar cells.

It can be seen that all versions of the module design feature 6 instead of the usual 3 bypass diodes. Hence, the number of solar cells per the

string is reduced by a factor of two, leading to much lower hotspot temperature for different shading ratios of the M6 PERC (blue), TOPCon (orange), HJT (green) and PVST (grey) solar cells compared to the module with 3 bypass diodes, see Fig. 6. The PERC solar cell shows a maximum hotspot temperature ranging from 100.0 °C to 124.9 °C when the solar cell per module (per string) are increased from 120 (10) to 180 (15), respectively. In this case, the shading ratio at which the maximum hotspot temperature occurs is shifted from 22.4 % to 25.9 % for an increase from 10 to 15 solar cells per string. TOPCon and HJT solar cells exhibit hotspot temperatures of 104.5 °C and 130.2 °C, respectively, or 107.9 °C and 135.2 °C, respectively, when the number of solar cells per string is increased from 10 to 15. The hotspot temperature of PVST solar cells is the highest with 111.4 °C and 143.5 °C when the number of solar cell per module (per string) are increased from 120 (10) to 180 (15), respectively. In this case, the shading ratio at which the maximum hotspot temperature occurs is shifted from 18.8 % to 29.6 % for an increase from 10 to 15 solar cells per string. In contrast to the module with 3 bypass diodes, it can also be seen that for the module design with the reduced number of solar cells per string and 6 bypass diodes the temperature for the PVST solar cell has only one distinct maximum hotspot temperature. It is worth mentioning that with a smaller number of PVST solar cells per string a significant reduction in the voltage of the string occurs. In this case, the voltage of the string is smaller than the breakdown voltage of the PVST solar cell, so that the voltage at the operating point of the PVST solar cells in the reverse bias regime is lower compared to the case in which the number of solar cells per string is larger, see Figs. 5 and 6. Hence, the hotspot temperature is not constant anymore,

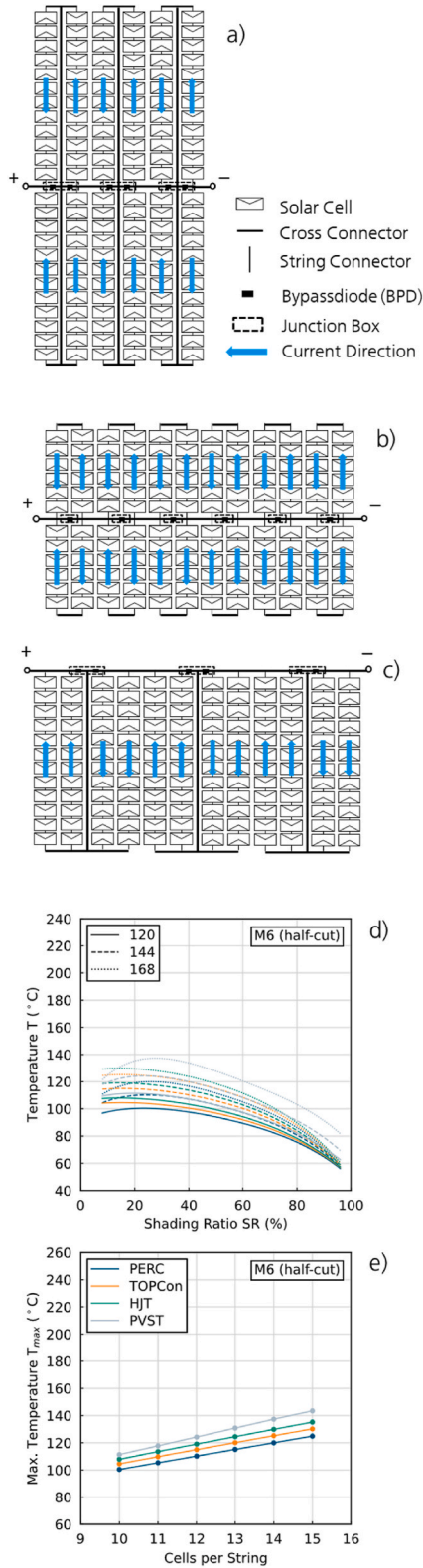


Fig. 7. a-c) Illustration of the equivalent circuit model of the 144 half-cut solar cell module with a reduced number of solar cells per string, d) modeled hotspot temperature of a shaded solar cell for different shading ratios with different number of solar cells per the module, 120 (solid), 144 (dashed) and 168 (dotted), and e) modeled maximum hotspot temperature of a shaded solar cell for different number of solar cells per the string, assuming PERC (blue), TOPCon (orange), HJT (green) and PVST (grey) solar cells. The shading was assumed to be out along the long side of the solar cell.

but strongly depends on the number of PVST solar cells per string.

Fig. 8 presents the hotspot temperature of a shaded solar cell for a module design featuring 144 half-cut solar cells corresponding to a module design for shingled solar cells [67] as well as for additional module designs featuring 72 full-size solar cells using M6 PVST solar cells [66,68,69] resembling a module from BP Solar from 2001 [70]. The module designs enable similar electrical output parameters as for the previously considered modules with PERC, TOPCon and HJT solar cells.

The results show that the maximum hotspot temperature of the PVST solar cells is substantially influenced by the module design. PVST solar cells in a 144 half-cut solar cell module features a maximum hotspot temperature of 98.6 °C at a shading ratio of 17.0 % due to the fact that only 8 solar cells per string exist. The 144 half-cut solar cell module with M6 PVST solar cells has a modeled V_{mpp} of 37.1 V, an I_{mpp} of 12.9 A and a P_{mpp} of 478.6 W. In contrast, PVST solar cells in a 72 full-size solar cell module shows a maximum hotspot temperature of 124.3 °C and 85.5 °C for the modules design with 12 and 6 solar cells per string, respectively. In this case, the shading ratio at which the maximum hotspot temperature occurs is 24.1 % and 13.4 % for 12 and 6 solar cells per string, respectively. The 72 full-size solar cell module with M6 PVST solar cells exhibits a V_{mpp} of 55.7 V, an I_{mpp} of 8.6 A and a P_{mpp} of 478.6 W.

4. Conclusion

In this work, a model for evaluating modern high-performance modules with different solar cell architectures like PERC, TOPCon, HJT and PVST solar cells is established to determine the operating point of a solar cell at different shading ratios in a hotspot endurance test and to correlate the dissipated power to the hotspot temperature. Therefore, the current-voltage characteristics of mini-modules featuring a single PERC, TOPCon, HJT and PVST solar cell are measured in forward and reverse bias direction at different shading ratios.

It is shown that a strong correlation between the solar cell architecture and the module design exists. PERC, TOPCon, HJT and PVST solar cells show very different reverse bias behaviors among each other, leading to different hotspot temperatures under various shading ratios whereas HJT and TOPCon solar cell exhibit higher hotspot temperatures than PERC solar cells. Increasing the number of PERC solar cells per module (per string) from 120 (20) to 180 (30) increases the maximum hotspot temperature of the shaded solar cell from 148.7 °C to 186.2 °C, respectively. The hotspot temperature increases for TOPCon solar cells from 154.6 °C to 200.0 °C for an increase from 20 to 30 solar cells per string, while for HJT solar cells the hotspot temperature increases from 160.8 °C to 208.5 °C. Besides, it is shown that increasing of the wafer size leads to different trends in the hotspot temperature for PERC, TOPCon, HJT and PVST solar cells. For PERC and HJT solar cells the hotspot temperature increase by a maximum of 12 K–10 K when changing from M6 to M12, respectively, while for TOPCon solar cells the hotspot temperature decrease by a maximum of 6 K. For PVST solar cells the hotspot temperature increases by a maximum of 10 K when changing from M6 to M12.

Furthermore, it is shown that alternative module designs with a reduced number of solar cells per string and more bypass diodes, but also with more parallel substrings, are beneficial in terms of minimizing the hotspot temperature, especially for PVST solar cells which are more susceptible and prone to degradation at high temperatures. For PVST solar cells in a half-cut solar cell module a maximum hotspot temperature of 98.6 °C was obtained, using only 8 solar cells per string. In contrast, PVST solar cells in a full-size solar cell module shows a maximum hotspot temperature of 124.3 °C and 85.5 °C for two different modules design with 12 and 6 solar cells per string, respectively. The results emphasizes that there is a strong correlation between the solar cell architecture and the module design, leading to different dissipated powers and hotspot temperatures of a shaded solar cell in the worst-case scenario of a hotspot endurance test.

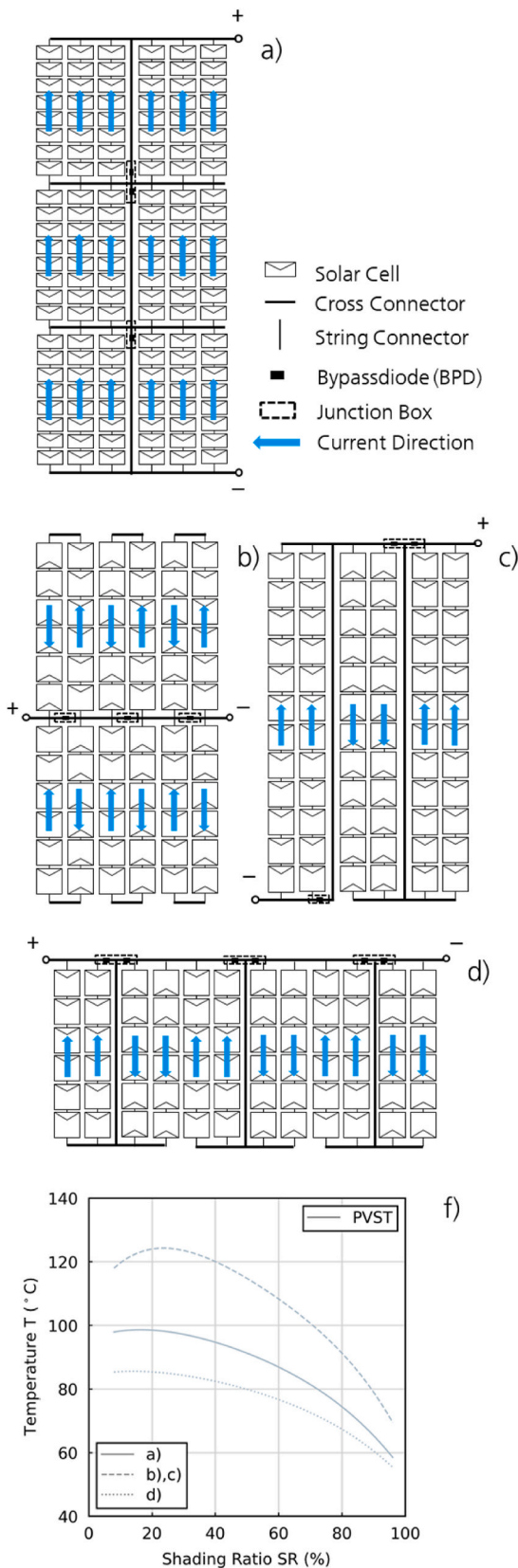


Fig. 8. Illustration of the equivalent circuit model of the different module designs: a) 144 half-cut solar cell module and additional modules featuring b-d) 72 full-size solar cell module using M6 PVST solar, and f) modeled hotspot temperature for different shading ratios of a solar cell with a) 8 (half-cut), b,c) 12 (full-size) and d) 6 (full-size) of solar cells per the string. The shading was assumed to be along the long side of the solar cell.

CRediT authorship contribution statement

Christian Reichel: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Jacob Forster:** Writing – review & editing, Validation, Methodology, Investigation, Data curation, Conceptualization. **Benedictus Artha:** Writing – review & editing, Software, Validation, Methodology, Investigation, Data curation. **Kaare Ingwersen:** Writing – review & editing, Software, Validation, Methodology, Investigation, Data curation. **Ammar Tummali:** Writing – review & editing, Software, Validation, Methodology, Investigation. **Julian Weber:** Writing – review & editing, Validation, Methodology, Investigation. **Esther Fokuhl:** Writing – review & editing, Validation, Methodology, Investigation, Data curation. **Li Carlos Rendler:** Writing – review & editing, Validation, Methodology, Investigation. **Dirk Holger Neuhaus:** Validation, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The authors would like to thank Nils Klasen, Andreas Beinert and Daniel Philipp for fruitful discussions. Ronny Köhler from Heckert Solar is gratefully acknowledged for organizing the manufacturing of the test module for the validation of the solar cell temperature in the hotspot endurance test. This work was funded by the German Ministry of Economic Affairs and Energy under Grant No. 03EE1095B “KoMoGER”.

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