Power rating and qualification of bifacial PV modules

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Abstract

The extra energy gain offered by bifacial PV modules has helped make them an increasingly popular choice in the global PV industry. But the question of how to define, measure and rate the electrical output from bifacial modules is a hotly debated topic, given the extent to which the rear-side contribution is dependent on a range of variable factors relating to local environmental conditions and system configurations. Drawing on in-house modelling and simulation software developed at TÜV Rheinland, this paper explores the power rating issue for bifacial devices, examining the definitions of rear irradiance, measurement test method, power stabilization and verification for type approval. Relevant reliability and safety tests are discussed, with additional modifications and suggestions for bifacial PV modules.

Introduction

The global PV industry is experiencing a boom in bifacial PV modules. Coming with extra energy gain from the rear side, bifacial PV modules are finding themselves with versatile and promising application possibilities in many fields, from building-integrated photovoltaics to utility-scale power plants. These application advantages are reflected in the forecasts of bifacial technology development in the market: according to the recently released international technology roadmap for photovoltaics (ITRPV) 2017 results [1], the world market share of bifacial PV modules will steadily increase to about 35% by 2028. Compared with monofacial PV modules, energy yields of around 10% higher (or even more) from bifacial modules in the field have been consistently reported by various parties [2,3]. Such increases in yield can considerably reduce the levelized cost of energy.

Bifacial PV technology is not a new concept in the PV community. As early as 1966, a US patent regarding an n-type bifacial solar cell with a p^+np^+ structure was granted to a Japanese researcher [4]. Nowadays, passivated emitter rear totally diffused (PERT), passivated emitter rear cell (PERC) and heterojunction (HJT) are the three mainstream technologies for bifacial PV devices [5]. It is feasible to increase the competitiveness of PV manufacturers through a transformation from the production of traditional monofacial PV modules to bifacial ones with little additional cost.

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The most important reference in setting the price of PV modules is still the power rating under *standard test conditions* (STC), defined as follows: a device temperature of 25°C, and an incident irradiance of 1,000W/m^2 with the spectral distribution AM1.5G. This leads to the first technology-related problem of how to define, measure and rate the electrical output power of bifacial PV modules, taking into consideration the rear-side power contribution. These tasks also stir up heated arguments in the PV industry, because the rear-side irradiance is highly dependent on environmental factors and installation configurations. The fact is that the ground albedo, installation location, tilt angle, ground clearance, shading (including self-shading) and other elements can all affect the rear-side irradiance and energy yield of a bifacial PV module.

In response to the strong demand for an appropriate power rating method for bifacial PV modules, the international standard IEC 60904-1-2 has been proposed, which describes the test methods and additional requirements for the *I–V* characterization. Since there is still no standard definition of rear irradiance under AM1.5G conditions, it is proposed that the measurement results for the bifacial device under test with a front irradiance of 1,000W/m^2, along with different levels of rear irradiance (namely 100W/m^2, 200W/m^2 and a third undefined level), be reported in accordance with the IEC standard [6]. Much as the standard is trying to give a solution for *I–V* measurement, the power rating issue for bifacial PV modules remains unresolved. The manufacturers and PV product buyers are confused by so many power results, and cannot find common ground on which the bifacial devices can be priced and on how the quality of different bifacial products can be evaluated and compared. To look into the power rating problem associated with bifacial PV devices, it helps to break it down into the following issues: 1) definition of rear irradiance; 2) test method of measurement; 3) power stabilization; and 4) verification for type approval.

The reliability and safety issues with bifacial PV modules come next in line. Because of the rear contribution to energy generation, bifacial PV modules in the field often operate at higher currents, which may impact the reliability of PV systems. In addition, to maximize the bifacial gain, special mounting designs for bifacial PV modules are often used to reduce the shading caused by racks. The test conditions for IEC 61215-2 and IEC 61730-2 may need to be modified accordingly in order to encompass the potential reliability and safety issues.

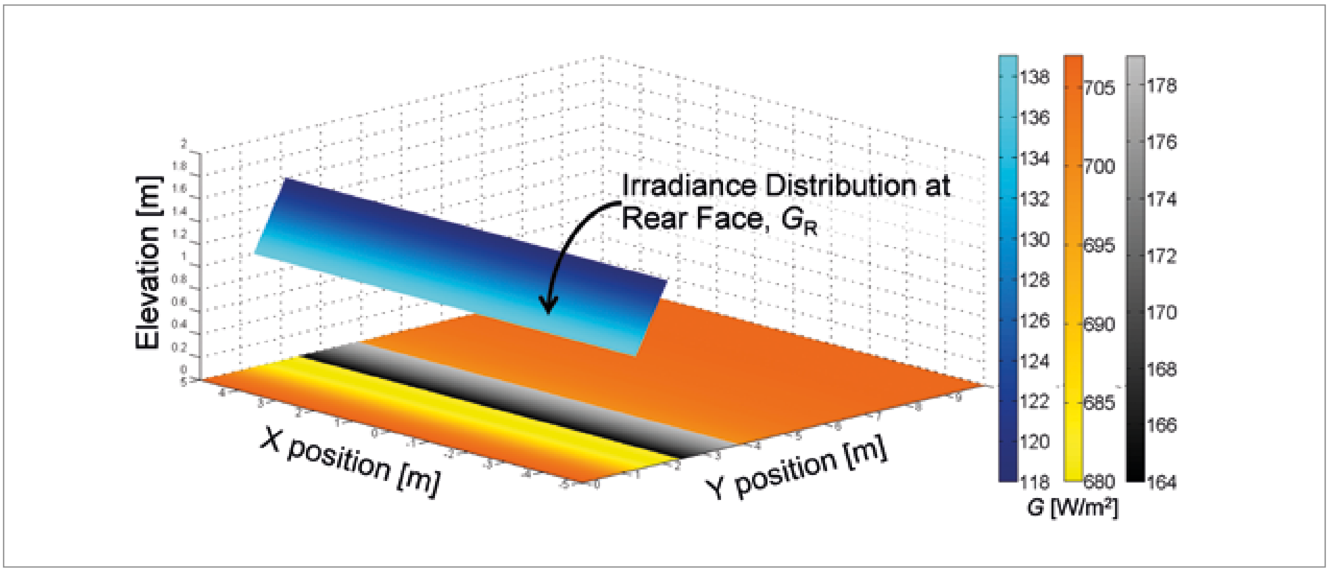

Figure 1. Irradiance distribution for a single-row bifacial PV array simulated in the conditions shown in Table 1, without taking into consideration the influence of the racks. The blue bar represents the distribution of irradiance G_R at the module's rear face (shown here facing the front). The orange and black bars represent horizontal ground irradiance: black signifies the area shaded by the modules, and orange the area which is not shaded.

Definition of rear irradiance

From an objective standpoint, in-house computer coding has been developed by TÜV Rheinland to model and simulate the expected rear irradiance under the environmental conditions defined in IEC 60904-3, with additional ground clearance of the PV module (details in Table 1) [7]; the simulation results are presented in Fig. 1. The higher end of the PV array receives slightly less irradiance than the lower end when the bifacial modules are installed at a tilted angle of 37 degrees and with a ground clearance of 1m. According to TÜV Rheinland's simulation, the rear irradiance on the PV array varies in the range 118–138W/m^2 with a spatial non-uniformity of 7.8%, which is in good agreement with other published research [8]. This theoretical work has laid a solid

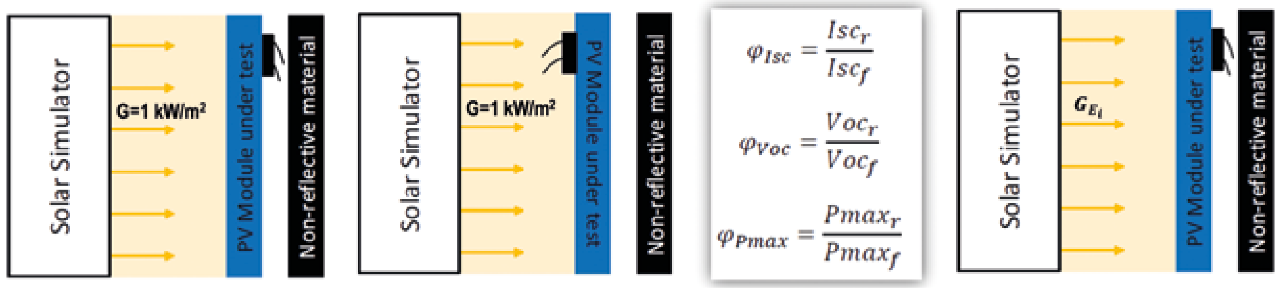

Figure 2. Schematic of the single-side illumination test method for bifacial PV modules.

foundation for bifacial standard test conditions and the TÜV Rheinland internal standard 2PfG 2645/11.17, which defines requirements for supplementary power rating and label verification of bifacial PV modules.

Bifacial standard test conditions (BSTC) are defined by a rear irradiance of 135W/m^2, corresponding to the 1m ground clearance of a bifacial module in the same environment as that specified in IEC 60904-3. The equivalent irradiance for bifacial PV devices can therefore be calculated using the formula (as shown in Table 2):

$$G_E = (1{,}000 + \varphi \cdot 135)\text{W/m}^2 \qquad (1)$$

where φ is the smaller of the two values of the bifaciality coefficients φ_{Isc} and φ_{Pmax} for I_{sc} and P_{max}. The benefits of BSTC are not only the compatibility with STC and IEC 60904-3, but also the direct comparability of the PV performance between bifacial and monofacial PV modules under the same conditions. Furthermore, the photovoltaic performance data under BSTC could provide useful information for PV installation and power plant design.

Test method of measurement

The TÜV Rheinland internal standard 2PfG 2645/11.17 allows both single-side illumination and double-side illumination test methods as defined in IEC 60904-1-2, although the single-side version is currently used in the TÜV Rheinland laboratories. Regardless of the stipulation of BSTC, the *I–V* measurement results with a rear irradiance (G_{ri}) of 100W/m^2 and 200W/m^2 can also be provided as supplementary information in the test report. As shown in Fig. 2, the bifaciality is determined first by measuring the front and rear sides of a bifacial PV module separately under STC. Next, the bifacial module is measured again on just the front side with an equivalent irradiance (G_{Ei}), which is calculated using the equation:

$$G_{Ei} = 1{,}000\text{W/m}^2 + \varphi \cdot G_{ri} \qquad (2)$$

where $\varphi = \text{Min}(\varphi_{Isc}, \varphi_{Pmax})$ and G_{ri} = 135W/m^2, 100W/m^2, 200W/m^2, ...

Modelled parameter	Bifacial reference condition
Air mass	1.5G
Beam and circumsolar irradiance	As defined in IEC 60904-3
Diffuse irradiance	As defined in IEC 60904-3 Isotropic diffuse
Ground albedo	Lambertian diffuse reflector Light sandy soil with spectral albedo as given in SMART
Inclination angle	37 degrees
Shading	PV array self-shading on the ground No near-object shading
Module transmittance	Spectral transmittance data for glass/EVA/glass and glass/POE/glass structures of bifacial modules

Table 1. Summary of the parameters used in the simulation.

Front irradiance	1,000W/m^2
Rear irradiance	135W/m^2
Equivalent irradiance	1,000W/m^2 + φ·135W/m^2
Module temperature	25°C
Angle of incidence	0 degrees
Irradiance spectrum	AM1.5G

Table 2. Parameter definitions for BSTC.

Power stabilization

In accordance with IEC 61215-1,-1-1,-2 standards, PV modules should be electrically stabilized before any further measurement. As bifacial PV devices are mostly PERT, PERC and HJT technology based, issues such as light-induced degradation (LID) exist and should not be neglected.

LID is a phenomenon whereby PV modules undergo a performance and power degradation as a result of illumination exposure; this deterioration is related to various factors such as the cell technology, wafer quality and manufacturing processes [9].

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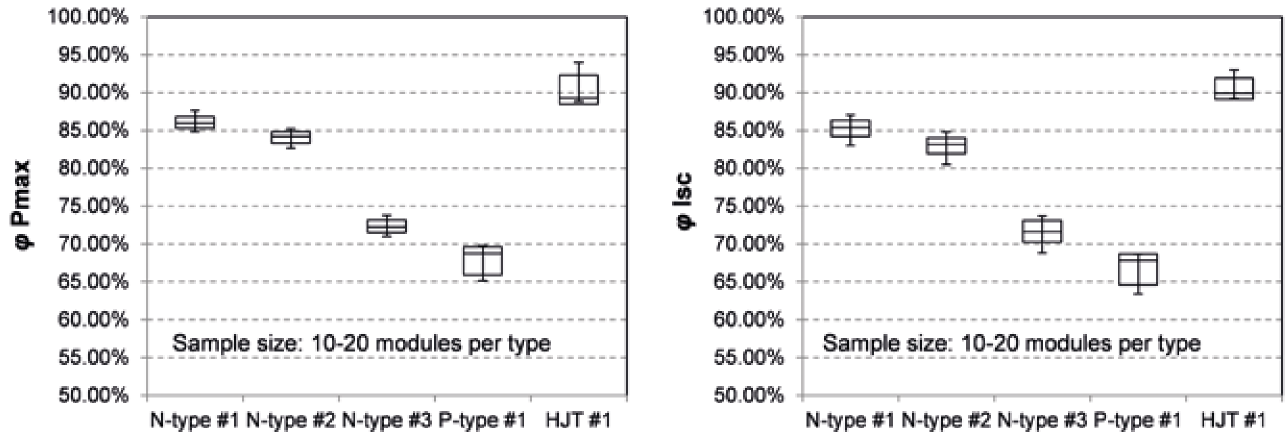

Figure 3. Variations in bifaciality coefficients (φ) of P_{max} and I_{sc}, evaluated by measuring modules in production from different manufacturers.

Test	Monofacial PV	Bifacial PV
I_{mpp} applied → $I_{mpp}@G_E$		
MST 21 – Temperature	Near I_{mpp} applied during the test	Near $I_{mpp}@G_E$ applied during the test
MQT 11 / MST 51 – Thermal cycling	I_{mpp} applied in sequences	$I_{mpp}@G_E$ applied in sequences
MQT 09 / MST 22 – Hot-spot endurance	I_{mpp} applied while finding the hot-spot-sensitive cells and the shading rate	$I_{mpp}@G_E$ applied while finding the hot-spot-sensitive cells and the shading rate
I_{sc} applied → $I_{sc}@G_E$		
MQT 18 / MST 25 – Bypass diode	Applied current: • I_{sc} for first hour • I_{sc} × 1.25 for second hour	Applied current: • $I_{sc}@G_E$ for first hour • $I_{sc}@G_E$ × 1.25 for second hour
Relevant test		
MST 26 – Reverse-current overload	Declared I_R by manufacturer × 1.35	To consider: $(n-1) \times I_{sc}@G_E \times 1.25 \times 1.35$ (if this value is higher), where n is the maximum allowable number of strings in parallel

Table 3. Supplementary test conditions on relevant test items in IEC 61215-2 and IEC 61730-2 for bifacial PV modules (G_E = 1,000W/m^2 + φ·300W/m^2). (As specified in IEC 61730-2, the applied reverse current shall be equal to 135% of the PV module's over-current rating, hence the factor 1.35.)

Several degradation mechanisms have been reported: boron–oxygen complex activation (B-LID), for example, is the most commonly known LID mechanism in boron-doped Czochralski-grown c-Si devices, and has been under investigation since the 1970s [10]. Recently, light- and elevated-temperature-induced degradation (LeTID) was reported initially in rear-passivated mc-Si solar cells; it is more severe in PERC devices and can lead to an efficiency loss of up to 10% [11].

Most industrial crystalline silicon solar cells and modules suffer from some type of LID. A drop in power of even 1% could result in considerable energy and capital losses; an initial stabilization is therefore essential in order to accurately specify the power rating for a bifacial PV device. However, whether both sides of a bifacial module need to fulfil the requirement of initial electrical stabilization is still under investigation.

Verification for type approval

Variations in the bifaciality coefficients have been observed on the production lines of different bifacial PV technologies (see Fig. 3); therefore, the verification of rated values is necessary for the labelling of modules under BSTC. The TÜV Rheinland 2PfG 2645/11.17 standard establishes a label verification system for photovoltaic data under BSTC, with the same requirements for measured P_{max}, mean P_{max}, V_{oc} and I_{sc} as defined in IEC 61215-1:2016 [12]. An additional requirement of P_{max} under BSTC for the minimum power class is particularly enforced in order to guarantee the quality of PV modules, even at the lower end power class:

$$P_{\max(\mathrm{BSTC})}(\mathrm{Lab}) \cdot \left(1-\frac{|m_{1(\mathrm{BSTC})}|[\%]}{100}\right) \leq P_{\max(\mathrm{BSTC})}(\mathrm{NP}) \cdot \left(1+\frac{|t_{1(\mathrm{BSTC})}|[\%]}{100}\right) \quad (3)$$

where $m_{1(BSTC)}$ and $t_{1(BSTC)}$ are respectively the measurement uncertainty of the laboratory and the manufacturer's rated upper production tolerance for $P_{max(BSTC)}$ in per cent (NP = name plate).

Module reliability and qualification

Bifacial PV modules in the field are observed to continuously operate at higher currents than their monofacial counterparts because of the power contribution from the rear side. Higher currents can cause higher localized temperatures in PV modules, especially in areas where current crowding might occur; this may impact the reliability of PV systems, in particular with regard to solder bond fatigue and bypass diode endurance. Thus, the relevant test conditions in IEC 61215-2 and IEC 61730-2 should be modified in order to reflect the higher current flows observed for bifacial modules in the field.

Bifacial modules experience significantly higher total irradiances at higher albedos compared with monofacial samples, as highlighted in the modelling results (Fig. 4), under the conditions given in IEC 60904-3. The current stringency definition used in this work derives from irradiances corresponding to reflective ground conditions (1,300W/m^2 at 0.51 albedo). A rear irradiance of 300W/m^2 is considered to be a typical irradiance which represents the worst scenario in field operation. Thus, the affected test items in IEC 61215-2 and IEC 61730-2 are updated with additional requirements to account for the higher equivalent irradiance G_E = 1,000W/m^2 + φ·300W/m^2.

Table 3 lists the revised test conditions for bifacial PV modules, based on the original procedures for monofacial PV modules in the IEC standards. The applied currents, I_{mpp} or I_{sc}, are enhanced to their corresponding I_{mpp} or I_{sc} values under an irradiance of (1,000 + φ·300)W/m^2 in the temperature test (MST 21), thermal-cycling test (MQT 11/MST 51), hot-spot endurance test (MQT 09/MST 22) and bypass diode test (MQT 18/MST 25). As regards the current for the reverse-current overload test, it is recommended to use in the calculation the higher of:

- the module's overcurrent protection rating provided by the manufacturer;
- the maximum reverse current that could be reached ((n–1) × I_{sc}@G_E ×1.25, where n is the maximum allowable string number in parallel, and 1.25 is the safety factor).

The adapted test sequences for bifacial PV modules are undergoing a verification process in the laboratory at TÜV Rheinland to prepare the 2PfG standard regarding the reliability test for bifacial PV modules. Several module types from different manufacturers are being tested under the new test sequences; so far, no bifacial module failures in the above-mentioned tests have been encountered. The preliminary test results, however, have shown that module components, especially bypass diodes, can

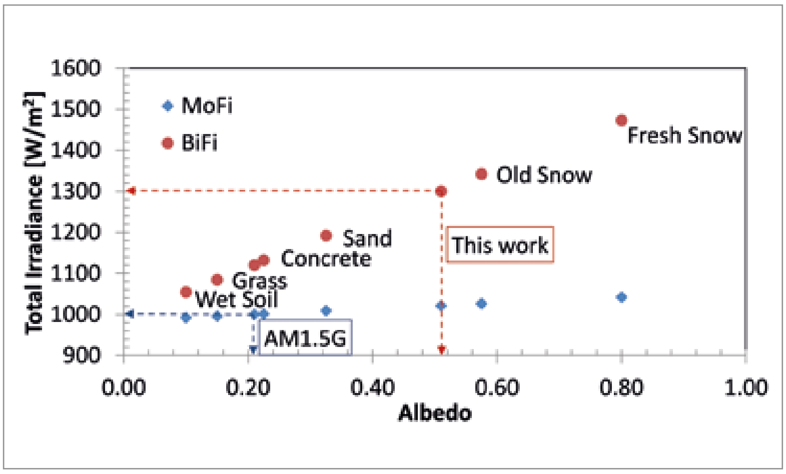

Figure 4. Analysis of the albedo sensitivity of total irradiance received by bifacial and monofacial PV modules. The simulation was carried out using the environmental conditions as defined in IEC 60904-3.

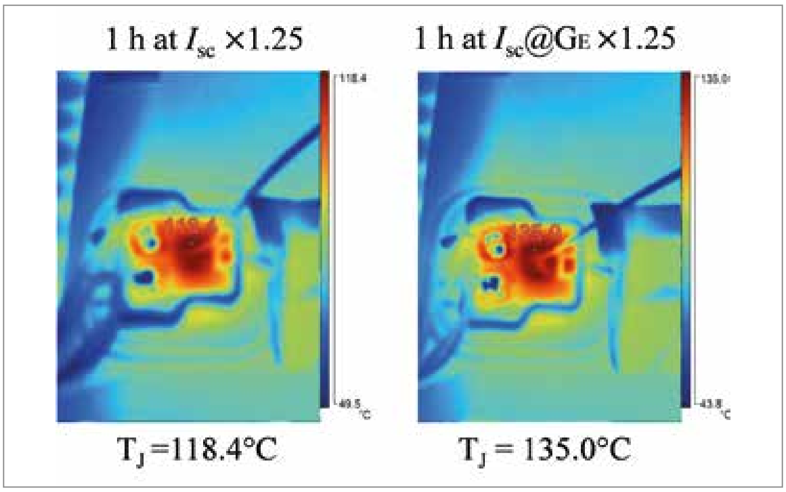

Figure 5. Example of elevated diode junction temperature observed by the TÜV Rheinland laboratory during the bypass diode thermal test with enhanced test current.

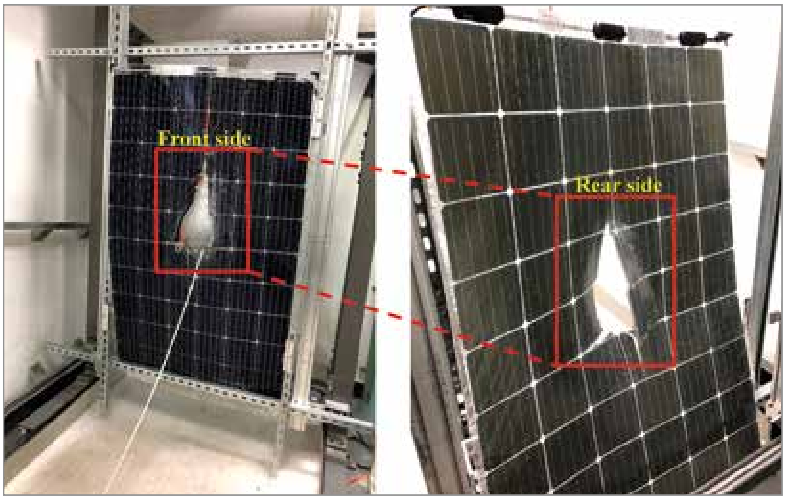

Figure 6. Examples of module breakage test failures of bifacial PV modules observed at the TÜV Rheinland laboratory.

"Module components, especially bypass diodes, can operate at 10–30°C higher temperatures with the enhanced test currents, which could critically test the endurance of the materials involved."

operate at 10–30°C higher temperatures with the enhanced test currents (Fig. 5), which could critically test the endurance of the materials involved. Other bifacial PV module failures in tests such as the module breakage test (MST 32) have been observed; these failures were mainly caused by the particular mounting design without supporting bars at the back (see Fig. 6). For safety reasons, this type of failure warrants more attention from constructors and end-users.

Another issue regarding the reliability of bifacial PV modules is potential-induced degradation (PID). In the field, PV modules are connected together in the form of a string to achieve a certain high voltage; at the same time, this string needs to be grounded for safety reasons. As a consequence, modules at either end of a string suffer from large electrical potential stresses between the frame and the solar cells, which can lead to severe performance degradation, referred to as *PID*. For crystalline silicon PV modules, there are two common PID mechanisms. The first of these is known as *Na^+ migration* in the high electric field between the glass and the solar cell, which results in significant shunts; these *PID* shunts are often observed in p-type c-Si technologies. As regards n-type c-Si PV technologies, *surface polarization*, the second PID mechanism, can be mainly responsible for the increased surface recombination and power drop [13].

IEC TS 62804-1:2015 provides indoor test methods for the detection of PID. The modules can be tested with a high voltage, either in damp heat using a climate chamber for 96h, or by contacting the surfaces with a conductive electrode for 168h. The test requires four representative and identical samples, two for the positive voltage bias test and two for the negative voltage bias test [14]. Thus, IEC TS 62804-1:2015 is currently capable of handling the PID test for bifacial PV modules.

Summary

Driven by the strong demand for reducing the levelized cost of energy, the market share of bifacial PV modules has increased rapidly in recent years because of the extra energy gain contributed by the rear side. The complexity of the technical problems with bifacial PV modules requires modifications and updates in respect of the current power rating and qualification standards. TÜV Rheinland has published its internal standard 2PfG 2645/11.17, which addresses the power rating issue for bifacial modules; it defines BSTC with a front-side irradiance of 1,000W/m^2 and a rear-side irradiance of 135W/m^2 in accordance with the 1m ground clearance for bifacial modules in the same environment as defined in IEC 60904-3. Supplementary reliability tests are proposed, with enhanced test conditions reflecting the worst scenario in field operation, for which a rear irradiance of 300W/m² is chosen. Laboratory verification is ongoing at TÜV Rheinland; the internal standard 2PfG concerning the reliability and safety tests in liaison with IEC 61215-2 and IEC 61730-2 will soon be published to assure the quality of bifacial PV modules for better and safer operation.

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About the Authors

Dr. Xiaoyu Zhang studied highly efficient dye-sensitized solar cells with liquid-state electrolyte and solid-state hole-transporting material at East China University of Science and Technology (ECUST), with a major in applied chemistry. In 2016 she obtained her Ph.D. in engineering from ECUST and then joined TÜV Rheinland (Shanghai) Co., Ltd, where she now works as a senior project engineer in R&D in the solar/fuel-cell technology department. Her interests lie in the accurate measurement and energy rating of PV modules, as well as in the power rating and qualification of bifacial PV modules.

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