Power rating procedure of hybrid concentrator/flat-plate photovoltaic bifacial modules

Juan F. Martínez | Marc Steiner | Maike Wiesenfarth | Gerald Siefer | Stefan W. Glunz | Frank Dimroth

Fraunhofer Institute for Solar Energy Systems ISE, Freiburg im Breisgau, 79110, Germany

Correspondence
Juan F. Martínez, Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, 79110 Freiburg im Breisgau, Germany.
Email: juan.francisco.martinez.sanchez@ise.fraunhofer.de

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Abstract
Hybrid concentrator/flat-plate photovoltaic (CPV/flat-plate PV) technology combines III–V multi-junction and flat-plate bifacial solar cells to convert direct, diffuse and rear irradiance into electricity. For the first time, this article presents a procedure to rate the power output of such modules at standard test and standard operating conditions. The reference conditions, data filtering criteria, and translation methods are taken, and in some parts adapted, from the CPV, flat-plate PV, and bifacial PV International Electrotechnical Commission (IEC) standards. The power rating is based on outdoor measurements performed on two hybrid modules (A = 1088 cm²) equipped with III–V triple- or four-junction solar cells mounted on bifacial positively doped passivated emitting rear contact (p-PERC) c-Si cells. The results show that the modules, named triple- and four-junction EyeCon, convert the reference AM1.5g spectrum with an efficiency of 32.6% and 34.2%, respectively. This exceeds by 1.4%abs and 3%abs the highest value reported so far for a terrestrial module that harvests global irradiance. Additionally, the modules generate 11.5 and 10.9 W/m² for every 100 W/m² of rear irradiance to surpass an output of 350 W/m². Finally, the influence of illumination mode, type of irradiance sensor, and filtering criteria were evaluated, and a simplified alternative with an acceptable power output underestimation of 0.5%rel is presented.

KEYWORDS
bifacial silicon, hybrid CPV/flat-plate PV module, III–V concentrator, power rating

1 | INTRODUCTION

In the search of new photovoltaic (PV) technologies capable of contributing to the renewable energy transition, several hybrid concentrator/flat-plate PV (CPV/flat-plate PV) architectures have developed over the last decade to reach highest conversion efficiencies under global illumination.1–4 These 4-terminal (4T) approaches combine highest efficiency III–V triple- or four-junction (3J or 4J) CPV cells with flat-plate monofacial or bifacial Si PV cells. The direct normal irradiance (DNI) is concentrated onto the CPV cells between 200x and 1000x using Fresnel, convex, and biconvex lenses. Besides CPV cells, flat-plate PV cells are integrated to absorb the diffuse and, in some cases, the rear side radiation. Thus, hybrid CPV/flat-plate PV modules have the potential to reach power outputs per unit area beyond 350 W/m² and surpass all other current PV technologies.5

Author to check the proofs: Juan F. Martínez.
For example, the hybrid CPV/flat-plate PV sub-module (A = 144 cm²) reported in Martínez et al. uses silicone on-glass Fresnel lenses to concentrate the DNI 226× onto 4J CPV cells that are mounted on an interdigitated back contact (IBC) Si cell. In this way, the sub-module converts up to 36.8% of the global normal irradiance (GNI). An example of a sub-module (A = 32.5 cm²) that uses 3J CPV cells in combination with polymethyl methacrylate (PMMA) convex lenses, reflective secondary optics, and a bifacial Si solar cell is reported in Yamada and Hirai. This sub-module reached a GNI conversion efficiency of 32.7% at a concentration of 203× for the CPV part. At the module level, a hybrid device (A = 0.264 m²) using glass convex lenses, refractive secondary optics, 3J micro-CPV cells (A = 0.36 mm²), and IBC Si cells yielded a 30.5% conversion efficiency of GNI at a concentration of 1000× for the CPV part. Another hybrid module (A = 0.1 m²) also using 3J micro-CPV cells (A = 1 mm²) is the one developed by the Swiss company Insolight. This hybrid module additionally applies PMMA biconvex lenses and monofacial Si cells to convert 24.5% of the available GNI at a concentration of 180× for the CPV part. However, this particular hybrid module is designed for fixed-tilt operation because it is equipped with embedded planar tracking. This technology is based on the idea of sliding the baseplate along the tilted plane in order to align the CPV cells with the focal spots. Therefore, the direct sunlight is not perpendicular to the optics. Nevertheless, all the efficiency values mentioned above are reported at normal incidence during outdoor operation and not at standard conditions.

In general, hybrid CPV/flat-plate PV technology is particularly suitable for locations where the annual average DNI/GNI ratio is between 60% and 85%. Under hazier conditions, the power generated by the high-efficiency CPV cells (η > 40%) is significantly reduced and undercompensated by the power output of the lower performance flat-plate PV cells (η < 20%). On the other hand, the performance of the latter under clearer sky conditions is not expected to justify its added cost. For these reasons, the non-rated efficiencies reported in the literature span between 24.5% and up to 36.8%. Notably, these values remain below those of conventional CPV modules (η < 38.9%) because their calculation is based on GNI instead of DNI. Nevertheless, it has been demonstrated that hybrid devices are able to generate between 3.5% and 30.6% more power, relative to their CPV part, when the DNI/GNI ratio is between 92% and 57%, respectively.

Despite all the experimental and theoretical knowledge available on hybrid CPV/flat-plate PV technology, nowadays the procedure to determine its efficiency and performance remains unstandardized. For the first time, this article presents a procedure to translate their power output measured outdoors to standard test conditions (STCs) and standard operating conditions (SOCs). Therefore, the approach first defines these reference conditions for hybrid CPV/flat-plate PV modules in Section 2. Hybrid STCs are taken from the common STCs of flat-plate PV modules defined in International Electrotechnical Commission (IEC) 61853-1, and hybrid SOCs are based on the concentrator SOCs defined in IEC 62670-1 to allow cross-technology comparisons. Figure 1 shows the flow chart of the entire power rating procedure using a color-coding scheme to reference the source from where each method was taken. From top to bottom, the algorithm described in Figure 1 is explained in detail throughout this article. For instance, in Section 3, we describe the measurement of the spectral and meteorological conditions, as well as the independent acquisition of the light I–V (LIV) characteristics of the CPV and PV arrays using a dual-axis solar tracker. Then, Section 4 presents the filtering criteria necessary to restrict the performance of both cell arrays to SOCs, and Section 5 follows the CPV, IEC

**FIGURE 1** Flow chart of the power rating procedure for hybrid concentrator/flat-plate photovoltaic (CPV/PV) bifacial or monofacial modules. The color of each block indicates the source of the methods used in the algorithm and the black feedback arrow denotes iterative calculations. The acronyms LIV, DIV, TC, and BiFi stand for light I–V, dark I–V, temperature coefficient, and bifacial gain. The Greek letters ε and γ represent the front irradiance response of the flat-plate PV array, ρ corresponds to its rear irradiance response, and ϕ accounts for its bifaciality factor [Colour figure can be viewed at wileyonlinelibrary.com]
62670-3,13 and flat-plate PV, IEC 60904-5,14 standards to calculate their temperature during outdoor operation and at SOC. As shown in Figure 1, the CPV (\(T_{CPV}\)) and flat-plate PV (\(T_{PV}\)) temperature calculation requires the use of the temperature coefficients (TCs) of the cells to iteratively obtain the reference ISC and VOC from a dark I–V curve (DIV) measured at 25°C. Section 6 demonstrates the application of IEC 62670-313 to perform the power rating of the CPV cell array at the STC and SOC defined for hybrid CPV/flat-plate PV modules in this work.

In Section 7, we present the power rating of the bifacial PV array following the guidelines of the flat-plate PV standards, IEC 6090415–17 and IEC 60891.18 Here, we adapted the current translation equation from IEC 60891 Procedure 118 to make it compatible with the newly developed methods that characterize the front (\(\varepsilon\) and \(\gamma\)) and rear (\(\rho\)) irradiance response of the flat-plate PV cells. Additionally, a method to separate the bifacial ISC of the PV array is used to calculate the bifacial gain (BiFi) and the bifaciality factor (\(\phi\)) as stipulated in the bifacial PV technical specification, IEC TS 60904-1-2.19 In Section 8, we combine the independently rated power outputs of the CPV and front side of the PV array (\(P_{FPH}\)) and report the STC and SOC hybrid efficiencies \(\eta_{hyb}\) along with the uncertainty of the fully IEC compliant procedure. Also, in the same section, we investigate and quantify the added uncertainty if the method is simplified.

The procedure is demonstrated with the power rating of the two 4T hybrid modules (A = 1088 cm²) shown in Figure 2. The module on top shows its rear side and is equipped with III–V metamorphic 3J (GaInP/GaInAs/Ge) CPV cells from AZUR Space20 (hereafter named 3J EyeCon), whereas the one below shows its front side and uses III–V wafer-bonded 4J (GaInP/GaAs/GaInAsP/GaInAs) CPV cells21 (hereafter named 4J EyeCon). Both modules concentrate DNI 321 times with a 4 × 12 array of silicone-on glass Fresnel lenses where a single lens has a size of 4.76 × 4.76 cm². Additionally, the 48 CPV cells are mounted with a dielectric adhesive onto the top surface of a flat-plate PV array of eight bifacial positively doped passivated emmitter rear contact (p-PERC) c-Si solar cells.8,22 This enables the flat-plate PV cells to act as heat distributors for the CPV cells. Moreover, the Si cells have a custom size of 91 × 141 mm² and a metallization layout optimized for absorption of diffuse and rear side irradiance. Further details about the module development and outdoor performance can be found in Martinez et al.8

As a last remark, it is important to note that the presented power rating procedure only applies to 4T hybrid bifacial or monofacial CPV/flat-plate PV modules, where the CPV and PV I–V curves can be measured independently while the module remains normal to the sun. This is noteworthy because the performance of state-of-the-art hybrid CPV/flat-plate PV modules has been demonstrated using conventional dual-axis solar tracking1,2,4 and novel module-embedded planar tracking.3 Therefore, we must mention that the optical losses associated with the angle of incidence when using planar-tracking are not addressed by the characterization methods developed in this work. Nevertheless, these methods apply to rate the optimum power output of such a hybrid module if it is mounted on a dual-axis solar tracker with the planar-tracking disabled. Additionally, 2-terminal (2T) hybrid CPV/flat-plate PV modules are also not addressed by this power rating procedure. Although there are no experimental demonstrations of such 2T devices in the literature, their promising performance (i.e., 0.995 < \(P_{2T}\) < \(P_{4T}\)), as projected using experimental data in Martinez et al., leaves the door open for their future development and for the need of methods to characterize them.

![FIGURE 2](image-url) Photograph of the rear side of the 3J (top) and of the front side of the 4J (bottom) bifacial EyeCon modules—Photo by Dirk Mahler. PV, photovoltaic [Colour figure can be viewed at wileyonlinelibrary.com]
### 2 | Reference Conditions for Hybrid CPV Modules (STC and SOC)

Defining a set of reference conditions to evaluate the performance of hybrid CPV/flat-plate PV modules is crucial to enable comparison of one hybrid architecture with another, as well as with conventional CPV and flat-plate PV technologies. In contrast to CPV modules, which only use direct irradiance as resource, hybrid CPV/flat-plate PV devices convert global irradiance as flat-plate PV modules do. Therefore, it is reasonable to use the existing flat-plate PV STC, as defined in IEC 61853-1, to rate the power output of hybrid CPV/flat-plate PV technology. In this manner, the STC for hybrid CPV/flat-plate PV modules are 25°C cell temperature and front side illumination of GNI = 1000 W/m² with reference AM1.5g spectral distribution, ASTM G-173-03 AM1.5g, as shown in Figure 3 (gray area). This corresponds to illuminating the CPV array with the direct part of the AM1.5g spectrum, that is the reference AM1.5d spectrum, ASTM G-173-03 AM1.5d, depicted as a red line in Figure 3, and the flat-plate PV array with the difference between both, that is, the reference diffuse irradiance shown as a blue line.

In addition to STC, we follow the approach of CPV module rating and define the SOC for hybrid CPV/flat-plate PV modules based on the concentrator SOC (CSOC), in order to establish a realistic scenario representative of outdoor operation. The goal is to reproduce the electrical and thermal behavior of the concentrator cells as in a CPV module because they contribute the largest fraction to the hybrid power output. These are ambient temperature of 20°C, wind speed of 2 m/s, and illumination with the AM1.5g spectrum scaled to 900 W/m². The latter is accomplished by illuminating the CPV array with the AM1.5d spectrum down-scaled 10% to 910 W/m² and the flat-plate PV array with the reference diffuse spectrum also down-scaled 10% to 90 W/m². In this manner, the GNI intensity matches that of DNI at CSOC, that is, 900 W/m², whereas the DNI/GNI ratio from STC is maintained, that is, 0.9. Table 1 summarizes the STC and SOC for hybrid CPV/flat-plate PV modules.

In the case of a bifacial hybrid module, the reference conditions defined in Table 1 apply for the rating of the front side, whereas for the rear side of the flat-plate PV cells, the technical specification for bifacial PV devices, IEC TS 60904-1-2, applies. This specification indicates that the rear power generation should be translated to rear intensities of 100 and 200 W/m² in order to obtain the bifacial power gain (BiFi) and the bifaciality factor ($\phi$), as is demonstrated in Section 7.

### 3 | Spectral, Meteorological, and I–V Data Acquisition

The outdoor measurement campaign was performed at Fraunhofer ISE in Freiburg, Germany, during the summer of 2019. The 3J and 4J EyeCon modules were mounted on a high-precision (<0.1') dual-axis solar tracker to enable optimum performance as shown in Figure 4. The I–V curves of the CPV and flat-plate PV arrays were recorded successively within 35 s of each other to ensure irradiance and temperature stability between measurements. As depicted in Figure 4, the tracker is equipped with several sensors to simultaneously record the spectral and meteorological conditions. The DNI is measured with three pyrheliometers (DNIpyr) to verify the precision is within 1%, although only one is shown in Figure 4. The GNI is measured with two pyranometers (GNIpyr) and with one Si reference cell (GNIrc), which is identical to the ones used in the modules, but with the rear side shaded. The spectral distribution of the DNI is assessed by means of three component cells mounted inside collimation tubes (GaInP 1.9 eV, GaInAs 1.4 eV, and Ge 0.7 eV) that generate photo-current (Iph) from the absorption of a particular band of the solar spectrum. Normalization with their response under the reference AM1.5d spectrum (Iph) and division between quotients yields the direct spectral matching ratios, SMR1 = $I_{1}/I_{1}\text{ref}$, SMR2 = $I_{2}/I_{2}\text{ref}$, and SMR3 = $I_{3}/I_{3}\text{ref}$, where the subscripts enumerate the component cells in descending order of band gap. As explained in Domínguez et al., the impact of the DNI spectral distribution on the power output of the multi-junction cell is equivalent to the one under the AM1.5d spectrum when the three SMR values are equal to 1.

The diffuse irradiance on the front-normal plane (DIF) was calculated as $\text{DIF}_{\text{pyr}} = \text{GNI}_{\text{pyr}} - \text{DNI}_{\text{pyr}}$ and alternatively for comparison as $\text{DIF}_{\text{rc}} = \text{GNI}_{\text{rc}}(1 - \text{DNI}_{\text{pyr}} / \text{GNI}_{\text{pyr}})$. We found that in average the DIFrc was 3.3 ± 1.2% lower than the DIFpyr, mainly because the spectral response of the thermopile pyranometer is significantly higher over the absorption range of the reference cell. The back normal irradiance (BNI) was measured with two rear-facing pyranometers and with two Si reference cells identical to the ones used in the modules and encapsulated in the same way, but with their front side shaded. The front and rear current responsivity of the reference cells and its
temperature dependence was calibrated using the differential spectral responsivity method at 25°C and 50°C. According to IEC 60904-10, both current responses were found linear within the outdoor measurement range (50–300 W/m²), because they deviated by less than 1.2%. Moreover, all BNI sensors were positioned nearly at the same height and as close as possible to the modules to minimize the influence of spatial nonuniformity. The calculation and measurement of the DIF and BNI with thermopile and reference cell sensors is intended to evaluate their impact on the power rating of the flat-plate PV array, as discussed in Section 8. Additionally, a thermometer and an anemometer were used to record T_{amb} and V_{wind} behind the tracker (not shown in the picture) [Colour figure can be viewed at wileyonlinelibrary.com]

### 4 RESTRICTIVE FILTERING CRITERIA OF FLUCTUATING OUTDOOR CONDITIONS

Given the dependence of multi-junction CPV technology on spectral (due to the series interconnection of sub-cells) and temperature variation (due to its effects on the cell and optics), we applied the filtering criteria defined in IEC 62670:2013 to constrain the performance of the CPV and flat-plate PV arrays to CSOC.

As shown in Table 2, the criteria not only restrict the allowed ranges of DNI, DNI/GNI, T_{amb}, and V_{wind} but also screen out sudden DNI fluctuations, thermal transients and sun tracking deviations. At the same time, a restriction of direct SMR values to be within ±3% of unity shall ensure that the impact of the DNI spectral distribution on the CPV cell power output is equivalent to the one under the reference AM1.5d spectrum.

In addition to that, we calculated the global SMR_{1-2} value from the measurement of the global spectral irradiance using a spectroradiometer and the external quantum efficiency data of the GaInP and GaInAs component cells, as explained in Section 3. This parameter quantifies the spectral equivalency of the GNI with the

### Table 1

| Reference conditions | Direct irradiance | Diffuse irradiance | Temperature | V_{wind} |
|----------------------|-------------------|-------------------|-------------|----------|
| STC                  | AM1.5d = 900      | AM1.5g-AM1.5d = 100 | T_{cell} = 25 | 0        |
| SOC                  | 0.9 AM1.5d = 810  | 0.9 (AM1.5g-AM1.5d) = 90 | T_{amb} = 20 | 2        |

Reference spectra: ASTM G173-03 AM1.5d and ASTM G173-03 AM1.5g

### Table 2

| Parameter                      | Data retaining criteria                                                                 |
|--------------------------------|-----------------------------------------------------------------------------------------|
| Direct irradiance              | 700 W/m² < DNI < 1100 W/m²                                                             |
|                                 | ΔDNI_{[t-30 minutes]} < 40%                                                             |
|                                 | ΔDNI_{[t-10 minutes]} < 10%                                                             |
|                                 | ΔDNI_{[IVsweep]} < 1%                                                                  |
|                                 | DNI/GNI > 0.8                                                                          |
| Direct Spectrum                | 0.97 < direct SMR_{x,y} < 1.03                                                          |
|                                 | (≥5 unity crossings) in (≥3 different days)                                             |
| Global Spectrum                | 0.97 < global SMR_{1-2} < 1.03                                                          |
| Ambient temperature            | 0°C < T_{amb} < 40°C                                                                   |
|                                 | ΔT_{amb} < 5°C                                                                         |
| Wind speed                     | 0.5 m/s < V_{wind} < 5 m/s                                                              |
| Sun-pointing error             | <0.2°                                                                                  |

Photograph of the rear plane of the dual-axis solar tracker used to characterize the 3J and 4J bifacial EyeCon modules. The tracker is equipped with several thermopile (pyr) and reference cell (rc) sensors to monitor front and rear irradiance (global normal irradiance [GNI], direct normal irradiance [DNI], back normal irradiance [BNI], collimated component cells), whereas V_{wind} and T_{amb} are measured by a weather station behind the tracker (not shown in the picture) [Colour figure can be viewed at wileyonlinelibrary.com]

![Figure 4](https://example.com/image.png)
reference AM1.5g spectrum in the response range of the flat-plate Si solar cells. Therefore, we also filtered out global SMR values beyond ±3% of unity to ensure spectral compliance between the DIF and the reference diffuse irradiance. Figure 5 shows the constraining effect of the filtering criteria in a plot of global versus direct SMR values. The amount of unfiltered data (gray) is reduced to 7% by the IEC 62670-3 criteria (red) and to 2% by additionally filtering for global SMR values (blue) between 0.97–1.03.

On the other hand, no BNI filtering criteria were applied because it depends on the already filtered GNI and the surroundings’ albedo. Besides, we measured the BNI with a calibrated reference cell sensor of nearly identical rear spectral response as the PV arrays under test. Thus, the power rating of the rear side can be considered as if it was performed under the AM1.5 g spectrum, but scaled to 10% and 20% as it is stipulated in the bifacial PV technical specification, IEC TS 60904-1-2. Besides filtering the experimental data and constraining the impact of spectral and meteorological conditions, the criteria summarized in Table 2 prevent potential mathematical errors and systematic deviations in the translation equations and in the intermediate calculations presented in this work.

5 | TRANSLATION OF CPV AND FLAT-PLATE PV ARRAY TEMPERATURES TO STANDARD CONDITIONS

Depending on the architecture of the hybrid module, the CPV and flat-plate PV arrays are thermally coupled to a greater or a lesser extent. In the EyeCon configuration where the cells are joined with a dielectric thermal adhesive, the flat-plate PV cells exhibit an inhomogeneous temperature profile with hotspots at the concentration foci. Also, a higher CPV cell temperature is expected compared with conventional concentrators because the thermal resistance of a Si heat spreader is larger than for a standard metal substrate. Such effects are explained in more detail in Martinez et al. An alternative to lower the mean operating temperature of both arrays is called micro-CPV and consists on reducing the concentrator cell (<1 mm²) and lens size (<5 cm²). This allows to decrease the heat input, which makes the CPV cell temperature less sensitive to the thermal conductance of the substrate.

Additionally, we found that the characterization of SOC performance of hybrid bifacial CPV-flat-plate PV modules requires simultaneous front and rear side illumination due to their dynamic thermal behavior. This means avoiding front shading of the module to characterize the rear side because the PV array temperature decreases at least 12 K when the GNI is blocked. The opposite should also be avoided because the CPV and PV array temperatures increase by more than 18 K when the rear convection and radiation are reduced. Even a short covering event (<10 s) can cause a thermal transient of up to ±8 K due to the small thermal mass of the arrays.

5.1 | Calculation of mean CPV and flat-plate PV array temperatures

In this sub-section we calculate the mean cell temperature of the CPV array as described in IEC 62607-3 and the equivalent cell temperature of the flat-plate PV array as described in IEC 60904-5. Both approaches rely on the short-circuit current (ISC_STC) and open-circuit voltage (VOC_STC) at STC, the absolute TCs α for ISC and β for VOC.

Dark I–V curves measured at 25°C and corrected for series resistance (R_s) were used to iteratively determine the VOC_STC from the on-sun measured ISC translated to STC (i.e., ISC_STC), as stipulated in IEC 62670-3 and explained in Muller et al. Based on the method, we extracted R_s values of 0.21 and 0.20 Ω for the CPV and PV arrays of the 3J EyeCon module, whereas for the 4J EyeCon, we obtained 1.54 and 0.19 Ω. LIV measurements under a sun simulator were not pursued because it is not trivial to accurately and uniformly reproduce the reference AM1.5d spectrum over the lens array, nor the angular and spectral distribution of the reference diffuse irradiance.

As defined in IEC 62670-3 and described in Muller et al., several thermal transient measurements (TTMs) were performed to determine the TCs α and β for the CPV and flat-plate PV arrays. A TTM consists on cooling the module close to Tamb and subsequently allow it to naturally heat up on-sun while recording its I–V characteristics as quick as possible. Table 3 summarizes the ISC_STC−VOC_STC pairs and the absolute α and β TCs of the 3J and 4J EyeCon modules.

The mean cell temperature of the CPV array, T_CPV, is calculated in degrees Celsius with Equation 1.
TABLE 3  Reference ISCE and TVOC pairs and absolute temperature coefficients of ISCE (a) and TVOC (β) of the concentrator photovoltaic (CPV) and photovoltaic (PV) arrays of the 3J and 4J EyeCon modules. Each temperature coefficient was averaged from five to seven outdoor thermal transient measurements

| Module       | Array | ISCE_STC A | TVOC_STC V | α μA m²/(W K) | β mV/K |
|--------------|-------|------------|------------|---------------|--------|
| EyeCon 3J    | CPV   | 1.058      | 36.428     | 0.30 ± 0.55   | −73.0 ± 8.2 |
|              | PV    | 0.512      | 4.625      | 5.32 ± 0.86   | −21.6 ± 2.0  |
| EyeCon 4J    | CPV   | 0.816      | 49.706     | 1.11 ± 0.77   | −83.0 ± 4.8  |
|              | PV    | 0.541      | 4.648      | 4.53 ± 2.1    | −18.8 ± 1.4  |

STC: AM1.5 (900 W/m²), DIF = 100 W/m², and TCPV = TPV = 25°C.

\[
T_{\text{CPV}} = \frac{V_{\text{OC}} - V_{\text{OC.STC}} + \beta \cdot 298.15 K}{N_e \cdot \left( \frac{k_b}{\theta} \right) \cdot \ln \left( \frac{I_{\text{SC}}}{I_{\text{SC.STC}}} \right) + \beta} - 273.15 K \quad (1)
\]

where \( N_e \) is the number of CPV strings in series (i.e., 12), \( n \) is the diode ideality factor (set equal to the number of junctions), \( k \) is the Boltzmann’s constant (1.38066 E-23 J/K) and \( q \) is the elementary charge (1.60218 E-19 C).

The equivalent cell temperature of the flat-plate PV array, \( T_{\text{PV}} \), is calculated also in degrees Celsius with Equation 2,\(^{14}\)

\[
T_{\text{PV}} = 25^\circ C + \frac{V_{\text{OC.STC}}}{\beta} \left[ \frac{V_{\text{OC}} - 1 - a \cdot \ln \left( \frac{I_{\text{SC}}}{I_{\text{SC.STC}}} \right)}{V_{\text{OC.STC}}} \right] \quad (2)
\]

where the parameter \( a \) corresponds to the normalized thermal diode voltage and is calculated from measurements with Equation A1 in the Appendix A. In Muller et al.,\(^{29}\) it is demonstrated that Equations 1 and 2 are equivalent; however, the first assumes that the diode ideality factor is equal to the number of junctions, whereas the second accounts for it in the parameter \( a \). Using Equation 1 to calculate \( T_{\text{PV}} \), with \( n = 1 \), results in a 2.5 K underestimation that would add to the uncertainty analysis. Hence, we used Equation 2 to stay as close as possible to the IEC standards.

Table 4 summarizes the calculated mean cell temperatures of the CPV and flat-plate PV arrays of the 3J and 4J EyeCon modules. During outdoor operation, their average temperatures were 69°C and 62°C for the CPV and PV arrays, respectively, and their standard deviations were below ±2 K.

Additionally, the cell array temperatures of the 4J EyeCon module were 4.3 K higher than those of the 3J EyeCon. This was expected because during manufacturing, the thermal resistance of the lamination layer increased due to large bubbles that unintentionally formed when the EVA of the 4J EyeCon module was curing.

### Table 4

| Module       | TPV   | TCPV   | TPV_SOC   | TCPV_SOC   |
|--------------|-------|--------|-----------|------------|
| EyeCon 3J    | 66.9 ± 1.2 | 46.5 ± 1.1 | 62.0 ± 2.5 | 43.0 ± 2.6 |
| EyeCon 4J    | 71.2 ± 1.8 | 50.7 ± 1.4 | 65.8 ± 2.6 | 46.8 ± 2.9 |

5.2 | Calculation of mean CPV and flat-plate PV array temperatures at SOC

Additionally, the CPV and flat-plate PV cell array temperatures need to be translated to SOC. The calculation was done according to IEC 62670-3\(^{13}\) using Equation 3. In this manner, the outdoor operating temperature of either cell array, \( T_{\text{array}} \), is translated to SOC, \( T_{\text{array_SOC}} \), by subtracting the \( T_{\text{amb}} \) deviation from 20°C and the temperature gradient due to GNI deviation from 900 W/m².

\[
T_{\text{array_SOC}} = T_{\text{array}} - (T_{\text{amb}} - 20^\circ C) - R_{\text{th_array}} \cdot (\text{GNI} - 900 \text{ W/m}^2) \quad (3)
\]

where the thermal resistance, \( R_{\text{th_array}} \), between each cell array and \( T_{\text{amb}} \) is calculated with Equation A2 in the appendix, as defined in IEC 62670-3\(^{13}\).

The mean cell temperatures translated to SOC are also shown in Table 4 above. In average the CPV and PV arrays operated at 64°C and 45°C, respectively.

6 | Power Rating of the CPV Array

The IEC 62670-3\(^{13}\) standard contains the linear equations, that is, Equations 4 and 5, necessary to translate the \( P_{\text{mpp}} \) of the CPV array to a fixed DNI level and cell temperature, for example, STC or SOC. Thus, after filtering the data according to Table 2 and subsequently calculating the mean cell temperature with Equations 1 and 3, we rated the DNI conversion efficiency at STC/SOC (\( \eta_{\text{CPV_STC/SOC_DNI}} \)) that is, STC (DNI = 900 W/m² and \( T_{\text{cell}} = 25^\circ C \)) or SOC (DNI = 810 W/m² and \( T_{\text{cell}} = T_{\text{SOC}} \)), using Equation 4.

\[
\eta_{\text{CPV_STC/SOC_DNI}} = \frac{1}{N} \sum_{i=1}^{N} f_{\text{VOC,i}} \cdot \left[ \eta_i - \delta \cdot (T_{\text{CPV,i}} - T_{\text{STC/SOC}}) \right] \quad (4)
\]

where \( N \) is the number of valid measurements after applying the filtering criteria from Table 2, \( \eta \) is the measured efficiency value, \( \delta \) is the absolute TC of efficiency extracted from five TTM (\( \delta_{3J} = -0.085\%_{\text{abs/K}} \) and \( \delta_{4J} = -0.070\%_{\text{abs/K}} \)), \( T_{\text{STC/SOC}} \) is the mean cell
temperature of the array at STC or SOC and \( f_{\text{Voc}} \) is the correction factor for the logarithmic dependence of \( V_{\text{OC}} \) on DNI, as calculated with Equation A3 in the appendix.

Figure 6 shows the STC (hollow bars) and SOC (solid bars) rated efficiencies of the 3J (blue) and 4J (red) CPV arrays as histograms. In average, the 4J CPV array achieved efficiencies of 36.1% and 33.2% at STC and SOC, respectively. This is 6\%rel higher than the 3J array due to the lower thermalization achieved with four rather than three p–n junctions.

Nevertheless, at SOC, both arrays decreased their performance by 3\%abs compared with STC due to the cell temperature being approximately 39 K higher. Subsequently, the rated power outputs \( P_{\text{CPV,STC|SOC}} \) are calculated with Equation 5 using the rated efficiencies \( \eta_{\text{CPV,STC|SOC}} \) and the reference DNI intensities \( DNI_{\text{STC|SOC}} \) at STC and SOC.

\[
P_{\text{CPV,STC|SOC}} = \eta_{\text{CPV,STC|SOC}} \times DNI_{\text{STC|SOC}}
\]

Figure 7 shows the power output as a function of DNI of the 3J (blue) and 4J (red) CPV arrays translated to a cell temperature of 25°C (solid circles) and \( T_{\text{SOC}} \) (solid triangles). Evidently, the correlation between power output and DNI is of a strong linear nature as supported by a \( R^2 > 0.97 \) and a normalized root-mean-square error (NRMSE) <0.4%. Additionally, the linear fits (solid and dashed lines) agree within ±3 W/m² with the rated power output at STC (dashes) and SOC (crosses).

It is important to note that the power output of the 3J and 4J CPV arrays at STC, that is, 310 and 325 W/m² under DNI = 900 W/m², would correspond to 346 and 363 W/m² at concentrator STC (CSTC), that is, under DNI = 1000 W/m², merely due to the 10% higher DNI. Also, at CSOC, that is, DNI = 900 W/m², the power output would correspond to 279 and 297 W/m² instead of the SOC-rated values of 253 and 269 W/m² under DNI = 810 W/m².

Nevertheless, a hybrid CPV/flat-plate PV bifacial module also converts the diffuse and rear side irradiance; thus, the front and rear power contributions of the flat-plate PV array need to be characterized and added to account for the total power output.

### 7 | Power Rating of the Bifacial Flat-Plate PV Array

The standard technical specification for bifacial PV devices, IEC TS 60904-1-2,\(^{19}\) describes the characterization procedure for flat-plate PV modules under simulated or natural sunlight applied single- (one side at a time) or double-sided (simultaneously on both sides). However, indoor measurements are not feasible to characterize the transmission of diffuse light through the primary optics of a hybrid CPV/flat-plate PV module because it requires calibration of the angular dispersion of the light emitted by the sun simulator. On the other hand, outdoor characterization under single-side illumination is not ideal because the thermal behavior of the module drastically deviates from operation under double-side illumination, as explained in Section 5. Therefore, we demonstrate the power rating of the bifacial PV array of a hybrid CPV/flat-plate PV module using outdoor double-side illumination and reference cell sensors, to measure GNI and BNI. Using reference cells of identical spectral response as the device
under test is recommended in IEC 60904-7-16 to avoid the need of spectral mismatch corrections.

In the following subsections, we present the procedures to separate the front and rear current contributions and the irradiance responses of the bifacial PV array. Nevertheless, the explained procedure will also work for hybrid CPV/flat-plate PV modules using monofacial instead of bifacial flat-plate PV cells.

Additionally, we show how to translate the I–V curves to STC and SOC based on the equations given in Procedure 1 of IEC 60891-118 with slight modifications.

7.1 Separation of bifacial I\(_\text{SC}\) into front and rear contributions

When the PV array is bifacially illuminated, the front and rear power contributions need to be independently translated to STC and SOC. Thus, the first step consists on splitting the bifacial I\(_\text{SC}\) of the PV array into front and rear components, that is, I\(_\text{SC}\) = I\(_\text{front}\) + I\(_\text{rear}\). Therefore, we correlated I\(_\text{rear}\) to the I\(_\text{SC}\) of a rear reference solar cell with identical spectral response (I\(_\text{SC,ref}\)) by calculating the mean ratio between the I\(_\text{SC}\) of the PV array with the front side shaded (I\(_\text{SC,rear}\)) and I\(_\text{SC,ref}\) corrected to the temperature of the flat-plate PV array, that is,

\[ I_{\text{SC,ratio}} = \text{mean} \left( \frac{I_{\text{SC,rear}}}{I_{\text{SC,ref}}} \right). \]

For the measurements investigated, the temperature correction is less than 2 K because both devices are only absorbing rear side irradiance.

Figure 8 depicts the I\(_\text{SC,rear}\) as a function of solar azimuth angle for the PV array (black circles) and for the reference cell sensor (gray triangles), which are both positioned in the northeast (NE) corner of the tracker as shown in Figure 4. As denoted by their ratio (hollow blue triangles), the I\(_\text{SC,rear}\) of the 4J EyeCon module has a mean value of \((0.907 \pm 0.008) \cdot I_{\text{SC,ref,NE}}\). Calculated in the same manner but using the northwest (NW) reference cell, the mean I\(_\text{SC,rear}\) of the 3J EyeCon module that is mounted on the NW corner of the tracker has a value of \((0.962 \pm 0.011) \cdot I_{\text{SC,ref,NW}}\) (not shown in Figure 8).

Moreover, the I\(_\text{SC}\) ratio between the northwest and the NE reference cell sensors (hollow red squares) oscillates between 0 and 12\% with a mean value of (3.5 \pm 3)\%. This shows the influence of the surroundings’ reflectivity on rear irradiance uniformity as the tracker’s background changes during the day. As depicted at the bottom of Figure 8, the NE reference cell has a better view factor of the southern (180°) metal sheets behind the tracker in the morning when the tracker points towards the East (90°). Thus, the \( I_{\text{SC,ref,NW}} / I_{\text{SC,ref,NE}} \) is below 1. However, as the day progresses and the tracker turns towards the west (270°), the view factor of the NW reference cell improves because it gets closer and more parallel to the metal...
sheets. Hence, \( I_{\text{SC,ref, NW}}/I_{\text{SC,ref, NE}} \) increases until it reaches 1 at 195°. Regardless of these effects, the \( I_{\text{SC-ratio}} \) of both EyeCon modules have low standard deviations (+1.1%) because the reference cell sensors were positioned right next to them. Thus, it is possible to split the \( I_{\text{SC}} \) of the PV array under bifacial illumination into \( I_{\text{front}} = I_{\text{SC}} - I_{\text{SC-ratio}} \cdot I_{\text{SC,ref}} \) and \( I_{\text{rear}} = I_{\text{SC-ratio}} \cdot I_{\text{SC,ref}} \), when \( I_{\text{SC,ref}} \) has been translated to the temperature of the PV array using the TC \( \alpha \) of the rear reference device, that is, +1.66 \( \mu \)A m\(^{-2}\)/(W K), according to Equation A4 in the appendix. The identical approach can be used for a monofacial PV array when setting \( I_{\text{front}} = I_{\text{SC}} \) and \( I_{\text{rear}} = 0 \).

7.2 | Bifacial PV array characterization of rear irradiance response

Once \( I_{\text{rear}} \) has been separated from the bifacial \( I_{\text{SC}} \), it should be translated to 25°C, using the TC \( \alpha \) of the PV array and Equation A4. Then, the rear irradiance response (\( \rho \)) is calculated as the mean ratio of \( I_{\text{rear, 25°C}} \) over BNI, that is, \( \rho = \text{mean}(I_{\text{rear, 25°C}}/\text{BNI}) \). In Figure 9, the rear irradiance response of the 4J EyeCon module at 25°C is shown as a function of solar azimuth angle. The unfiltered data (black circles) describes a parabolic trend that peaks around solar zenith (180°) and slightly drops towards dawn and dusk (<120° and >240°). The asymmetric trend is due to the different background view factors at the positions of the PV array and reference cell sensor.

Nevertheless, the filtered data (red circles) fall well within the plateau where 60% of the unfiltered data concentrates; thus, both data sets yield a mean value of 3.46 mA m\(^{-2}\)/W with a low standard deviation (<1.2%). Displaying similar behavior, the mean rear irradiance response of the 3J EyeCon module is 3.67 mA m\(^{-2}\)/W (not shown in Figure 8). That is 6% higher than the 4J EyeCon module due to the reflection losses caused by the bubbles in the lamination layer of the 4J EyeCon. Using these values, the \( I_{\text{rear, 25°C}} \) can be calculated at a BNI of 100 and 200 W/m\(^2\), as IEC TS 60904-1-2\(^19\) stipulates.

7.3 | Bifacial PV array characterization of front irradiance response

After subtracting \( I_{\text{rear}} \) from the bifacial \( I_{\text{SC}} \) to obtain \( I_{\text{front}} \), the latter should also be translated to 25°C using the TC \( \alpha \) of the PV array and Equation A4. For the characterization of the front irradiance response, we assume that \( I_{\text{front, 25°C}} \) is the result of absorbing the transmitted DIF plus the lens-scattered DNI. Because of this we postulate that \( I_{\text{front, 25°C}} = \epsilon \cdot \text{DIF} + \gamma \cdot \text{DNI} \), where \( \epsilon \) and \( \gamma \) are the independent irradiance responses to DIF and scattered DNI of the PV array. Normalizing the previous expression by GNI yields the univariate function of DNI/GNI given in Equation 6.

\[
I_{\text{front, 25°C}} \over \text{GNI} = \epsilon + (\gamma - \epsilon) \cdot \text{DNI} \over \text{GNI}
\]

Figure 10 shows the GNI irradiance response \( (I_{\text{front}}/\text{GNI}) \) as a function of DNI/GNI, where the GNI irradiance response at 25°C linearly decreases. According to Equation 6, the intercept of the linear trend described by the data represents \( \epsilon \), whereas \( \gamma \) corresponds to the sum of \( \epsilon \) and the slope. Moreover, the NRMSE of the linear fit applied to the unfiltered data (black circles) assuming \( \gamma = 0 \) (black line) decreased from 7% to 1% when the data was filtered (red circles), but increased to 13% when assuming \( \gamma = 0 \) (dashed line) for the unfiltered data. Note that \( \gamma = 0 \) would mean that lens-scattered DNI does not contribute to \( I_{\text{front}} \) of the PV array. Thus, it is important to consider the absorption of scattered DNI, particularly at the DNI/GNI where the power rating is performed, that is 0.9, because neglecting \( \gamma \) results in a 24% underestimation of \( I_{\text{front, 25°C}} \). As shown in the inset, the fits to the filtered (red line) and unfiltered (black line) data agree within 2% despite the narrow DNI/GNI range covered by the former.

In summary, the \( \epsilon \) and \( \gamma \) values of the PV array at 25°C are 3.38 and 0.23 mA m\(^{-2}\)/W for the 4J EyeCon module, whereas for the 3J EyeCon they are 3.93 and 0.13 mA m\(^{-2}\)/W. Using these values, \( I_{\text{front, 25°C}} \) can be calculated at any DIF and DNI intensity, for example, the \( I_{\text{SC,STC}} \) of the PV arrays reported in Table 3. Hence, the calculation of \( \epsilon \), \( \gamma \), \( I_{\text{SC,STC}} \), and \( T_{\text{PV}} \) requires Equations 2, A4, and 6 to be solved iteratively using \( I_{\text{SC,STC}} = \text{DIF}_{\text{STC}} \cdot \text{mean}(I_{\text{front}}/\text{DIF}) \) as initial guess until the RMSE of \( T_{\text{PV}} \) is below 0.1 K. This is due to the interdependence between the temperature and irradiance responses of the flat-plate PV cells that are very difficult to measure independently from each other in an outdoor setting.

Furthermore, \( \rho \), \( \epsilon \), and \( \gamma \) can be translated to \( T_{\text{SOC}} \) with Equation A4, using their values instead of current and an irradiance of \( G = 1 \) W/m\(^2\), because their temperature dependence is the same as for \( I_{\text{SC}} \). At \( T_{\text{SOC}} \), the \( \rho \), \( \epsilon \), and \( \gamma \) values of the 4J EyeCon module (i.e., 47°C) are 3.53, 3.45, and 0.23 mA m\(^{-2}\)/W, whereas for the 3J EyeCon (i.e., 43°C), they are 3.74, 4.00, and 0.13 mA m\(^{-2}\)/W.
\[
y = \varepsilon + (\gamma - \varepsilon) \cdot x
\]

7.4 | I–V curve translation to STC and SOC based on IEC 60891 and IEC TS 60904-1-2

The IEC 60891\textsuperscript{18} standard contains the linear equations required to translate the I–V curves of the PV array to STC and SOC. They correct the voltage and current deviation from a reference temperature using \(\alpha\), \(\beta\), and \(\kappa\) (the TCs of \(I_{SC}\), \(V_{OC}\), and \(R_s\)) and from a reference irradiance through the use of the current proportionally to the temperature change, while adjusting the voltage gradient caused by \(R_s\). Nevertheless, the current translation from a temperature and irradiance level \(T_2\) and \(G_2\) to \(T_2\) and \(G_2\) is proposed on the basis of shifting all current data points on the I–V curve by an amount \(I_{STC} = (G_2/G_1-1) + (\alpha(T_2 - T_1))\). However, this does not apply to the PV array of a hybrid CPV/flat-plate PV module because the transmitted irradiance through the lens is not measured to define the magnitude of the current shift. Alternatively, every current point on the measured I–V curve, \(I_j\), can be translated to STC or SOC, \(I_{STC(SOC)}\), using Equation 7

\[
I_{STC(SOC)} = I_j + [(\varepsilon \cdot \text{DIF}_{STC(SOC)} + \gamma \cdot \text{DNI}_{STC(SOC)} + \rho \cdot \text{BNI}) - I_{SC}]
\]

where the temperature corrected \(\varepsilon\), \(\gamma\), and \(\rho\) determine the reference short-circuit current and \(I_{SC}\) is the short-circuit current of the measured I–V curve. Here, it is important to note that the current temperature correction in Equation 7 is performed on \(\varepsilon\), \(\gamma\), and \(\rho\) as stated in the previous subsection, thus the \(\alpha(T_2 - T_1)\) term from the IEC 60891 Procedure\textsuperscript{18} is dropped. On the other hand, the voltage translation from the same standard applies without modification as given in Equation 8,

\[
V_{STC(SOC)} = V_j - R_s \cdot (I_{STC(SOC)} - I_0) + (\beta - \kappa) \cdot I_{STC(SOC)} \cdot (T_{STC(SOC)} - T_{PV})
\]

where \(V_j\) is any voltage point on the measured I–V curve and \(V_{STC(SOC)}\) is any voltage point on the I–V curve translated to STC or SOC.

The power output per unit area of the PV array at STC/SOC \(P_{PV,STC(SOC)}\) is the maximum value of the product between Equations 7 and 8 normalized with the aperture area of the module (1088 cm\(^2\)). As stipulated in the bifacial PV technical specification, IEC TS 60905-1-2\textsuperscript{19} the STC and SOC power output should be calculated at three BNI intensities (0, 100, and 200 W/m\(^2\)) using Equations 7 and 8. In Figure 11, we exemplarily show the power output of the PV array of the 4J EyeCon module translated to STC (blue triangles) and SOC (red circles) as a function of rear side illumination. The effect of the filtering criteria and the translating equations can be observed in the tight distributions of the 19 PMPP values that were translated to BNI = 0, 100, and 200 W/m\(^2\) (standard deviations <1% not stated in Figure 11).

Additionally, the mean \(P_{PV,STC(SOC)}\) at BNI = 0 W/m\(^2\) corresponds to the front power output rated at STC/SOC \(P_{PV,front-STC(SOC)}\) of the PV array of the hybrid CPV/flat-plate PV modules. Furthermore, the slopes of the linear fits applied to \(P_{PV,STC(SOC)}\), as shown in Figure 11, that pass through \(P_{PV,front-STC}\) (blue line) and \(P_{PV,front-SOC}\) (red line) represent the bifacial power gains (BiFi\textsubscript{STC(SOC)}) in absolute units. The bifaciality factor, \(\varphi\), defined as the ratio between the rear over the front power output, is then calculated as \(\varphi = 100 \text{ W/m}^2 \text{BiFi}_{STC}/P_{PV,front-STC}\), also in absolute units. As a summary, Table 5 compiles the STC and SOC results for \(P_{PV,front}\) BiFi, and \(\varphi\) of the PV arrays of the 3J and 4J EyeCon modules.
8 | POWER RATING OF A HYBRID CPV/FLAT-PLATE PV MODULE

The rated power output of a monofacial or bifacial hybrid CPV/flat-plate PV module results from adding the CPV and the front PV array contributions translated to STC|SOC, that is, $P_{\text{hyb,STC|SOC}} = P_{\text{CPV,STC|SOC}} + P_{\text{PV_front,STC|SOC}}$. Note that the presented procedure only works for 4T hybrid modules where the CPV and PV power contributions can be measured separately. For the EyeCon modules rated in this article, the $P_{\text{hyb,STC}}$ is equal to 326 W/m² for the 3J and 342 W/m² for the 4J module. These values correspond to conversion efficiencies of the AM1.5 global spectrum of 32.6% and 34.2%, calculated by dividing $P_{\text{hyb,STC}}$ with GNI = 1000 W/m². These results exceed the highest value reported in the solar cell efficiency tables for a terrestrial PV module capable of converting global irradiance. Furthermore, the 4J EyeCon module generates an additional power output of 10.9 W/m² for every 100 W/m² of rear irradiance due to the bifacial gain. This brings its power output beyond 350 W/m² and makes it the module with the highest power density in the world.

Table 6 summarizes the STC and SOC conversion efficiencies of the hybrid 3J and 4J EyeCon modules, that is, $\eta_{\text{hyb,STC|SOC}} = \frac{P_{\text{hyb,STC|SOC}}}{(DNI_{\text{STC|SOC}} + DIF_{\text{STC|SOC}})}$, in contrast with the lower efficiency of the 1J and 3J world record flat-plate PV modules. The values for $DNI_{\text{SOC}}$ and $DIF_{\text{SOC}}$ are given in Table 1. The reported uncertainties were calculated by propagating the error through the translation equations using random normal distributions (N = 10⁶) with mean and standard deviation derived from the data for each parameter. Additionally, we observed the guidelines described in Muller et al.²⁹ and Steiner et al.³¹ for $P_{\text{PV_front,STC|SOC}}$ and in Whitfield and Osterwald³² for $P_{\text{PV_front,STC|SOC}}$; and then calculated the uncertainty of $P_{\text{hyb,STC|SOC}}$ by adding both deviations in quadrature. Despite filtering and translating, the hybrid uncertainties are 400% and 60% larger than 1J and 3J flat-plate modules, respectively. This is due to the complex interaction of the optics with the sensitive performance of multi-junction cells under variable meteorological and spectral conditions, plus the flat-plate PV array uncertainty under low diffuse illumination.

It is important to note that the values listed in Table 6 were calculated with the procedure described in the previous sections based on measurements under double-side illumination using reference cell sensors, the filtering criteria from Table 2 and considering lens-scattered DNI absorption by the PV array. This way the results are compliant with the standard CPV, IEC 62670,¹²,¹³ flat-plate PV, IEC 60904-1-17 and 60891,¹⁸ and bifacial PV, IEC TS 60904-1-2,¹⁹ rating methods, but applied at the particular DNI and DIF intensities defined for hybrid modules in Table 1. In the following, we assess the impact of simplifying the power rating procedure in terms of alternatively using/assuming the following:

1. Single-side illumination: because it removes the need of a reference device, for example a BNI reference cell sensor, to split the bifacial ISC. However, shading the opposite side during outdoor characterization modifies the operating thermal behavior of the module.

### TABLE 6 Conversion efficiency of the reference AM1.5g spectrum for the 3J and 4J EyeCon modules at standard test condition (STC) and standard operating condition (SOC), in contrast with the world record efficiency of the flat-plate photovoltaic (flat-plate PV) 1J (c-Si) and 3J (InGaP/GaAs/InGaAs) modules at STC and comparison of the measurement uncertainties

| Module      | Type                  | STC $\eta$ (%) | SOC $\eta$ (%) |
|-------------|-----------------------|----------------|----------------|
| EyeCon 3J   | Hybrid CPV/flat-plate PV | 32.6 ± 1.7     | 29.5 ± 1.5     |
| EyeCon 4J   | Flat-plate PV          | 34.2 ± 1.9     | 31.3 ± 1.7     |
| Record 1J²⁹ | Flat-plate PV          | 24.4 ± 0.5     | —              |
| Record 3J²⁹ | Flat-plate PV          | 31.2 ± 1.2     | —              |

Abbreviation: CPV, concentrator photovoltaic.

### TABLE 5 Front power output, bifacial gain and bifaciality factor of the photovoltaic (PV) array of the 3J and 4J EyeCon modules at standard test condition (STC) and standard operating condition (SOC)

| Module      | Array | STC $P_{\text{PV_front}}$ (W/m²) | BiFi (abs.) | SOC $P_{\text{PV_front}}$ (W/m²) | BiFi (abs.) | $\phi$ (abs.) |
|-------------|-------|----------------------------------|-------------|----------------------------------|-------------|--------------|
| EyeCon 3J   | PV    | 16.5 ± 0.1                       | 0.115       | 13.8 ± 0.1                       | 0.111       | 0.697        |
| EyeCon 4J   |       | 16.9 ± 0.1                       | 0.109       | 14.0 ± 0.1                       | 0.105       | 0.645        |

Figure 11  Power output as a function of back normal irradiance (BNI) of the photovoltaic (PV) array of the 4J EyeCon module translated to standard test condition (STC) (blue triangles, N = 57) and standard operating condition (SOC) (red circles, N = 57). The intercept of the linear fit is fixed to the rated front power output ($P_{\text{PV_front,STC|SOC}}$), whereas the slope represents the bifacial power gain ($\text{BiFi}_{\text{SOC}}$) [Colour figure can be viewed at wileyonlinelibrary.com]

Table 5  Front power output, bifacial gain and bifaciality factor of the photovoltaic (PV) array of the 3J and 4J EyeCon modules at standard test condition (STC) and standard operating condition (SOC)
2. Pyranometers to measure GNI and BNI instead of reference cell sensors: because pyranometers are universal and more readily available than reference cells. 
3. All measured data: because they remove the need of component cells to calculate SMR values for the filtering criteria. 
4. No absorption of lens-scattered DNI by the PV array (γ = 0): because this simplifies the characterization of the front irradiance response, that is, ε = mean (I_{front,25}/DIF).

The comparison of these four alternative approaches with the one using double-side illumination, reference cell sensors, filtering criteria, and γ > 0 is presented in Figure 12, where the CPV (gray), front (red) and rear (blue) PV power contributions to the total hybrid output are shown for every case.

First, the hybrid bifacial power output is significantly underestimated by 3.4% at STC and 7.8% at SOC when single-side illumination is used. In this case, 95% of the loss comes from the CPV array and the rest from the bifacial PV part. This is expected because the concentrator cells generate 92% of the total power. Moreover, as explained in Section 5, the power deficit at SOC is correlated with the 18 K increase in T_{SOC} when the rear side of the module is shaded. However, the power loss at STC is not suppressed by the cell temperature correction to 25°C. This could be explained by larger chromatic aberration losses, derived from the higher lens temperature that are not corrected by the CPV TC of absolute efficiency.

Second, the influence of using pyranometers instead of reference cells still uses the latter to split the bifacial ISC of the PV array, but is based on the irradiance values measured by the former. Then, the underestimation of front and rear PV power output using pyranometers is only 0.5 and 0.2 W/m², respectively, because their GNI and BNI readings are higher: thus, the front and rear irradiance responses are lower than with reference cells. Nevertheless, that deviation is insignificant (<0.2%) for the hybrid front power rating because the front side of the bifacial PV array only contributes 5% to the total. In addition, the CPV power output is minimally reduced by 1 W/m² only at SOC, because the differences in the measured GNI and BNI only modify T_{SOC} by less than 1.4 K.

Third, the hybrid bifacial power output was significantly reduced up to 1.4% when all the measured data were used without filtering according to Table 2. The reason is the statistically decreased average of the CPV output due to the prevalent T_{amb} (23 ± 5°C), DNI intensity (791 ± 96 W/m²) and spectral distribution (direct SMR_{1-2} = 0.97 ± 0.08) in Freiburg. This underlines the importance of filtering the CPV data to eliminate the influence of local conditions depending on their frequency and interaction. On the contrary, the bifacial power output of the PV array was insignificantly overestimated by 0.2 W/m² due to unfiltered data.

Fourth, the front power output of the bifacial PV array is underestimated by up to 2.5% when the absorption of lens-scattered DNI is neglected (γ = 0) and the calculation of the front irradiance response is simplified to ε = mean (I_{front,25}/DIF). However, if γ = 0 is assumed for the unfiltered data set, the power underestimation raises significantly to 11.8% due to characterization under the prevalent spectral conditions in Freiburg (DNI/GNI = 0.84 ± 0.05), because the mean value of the front irradiance response is statistically decreased.

Based on this analysis, we believe that a simplified hybrid bifacial power rating procedure is acceptable when the CPV array is measured without rear shading, the PV array is characterized under single-side illumination (if no reference rear device is available to split the bifacial ISC) using pyranometers as GNI and BNI sensors while assuming the absorption of lens-scattered DNI (γ > 0) and at least filtering the CPV data according to the CPV standard, IEC 62670-3. In this case, the hybrid bifacial power output is only 0.5% lower and within the uncertainty of the fully compliant procedure, but the complexity and hardware requirements are significantly reduced.

9 | SUMMARY AND CONCLUSION

For the first time, the article presents a power rating procedure for hybrid bifacial CPV/flat-plate PV modules based on the CPV, IEC 62670,12,13 flat-plate PV, IEC 6090414-17 and IEC 60891,18 and bifacial PV, IEC TS 60904-1-219 standards. This includes the proposed standard test and operating conditions (STC and SOC) for the terrestrial conversion of the reference AM1.5g spectrum and the filtering criteria required to do so. The procedure is demonstrated with two modules, of a technology type named EyeCon. Two modules are equipped with triple- or four-junction CPV solar cells mounted on flat-plate bifacial Si cells.

The thermal behavior of the CPV and PV arrays is presented and discussed on the basis of their calculated temperatures according to

FIGURE 12 Concentrator photovoltaic (CPV) (gray), front PV (red), and rear PV (blue) power output of the 4J EyeCon module at standard test condition (STC) and standard operating condition (SOC), rated under double- or single-side illumination, using reference cells (ref cell) or pyranometers (pyran) as global normal irradiance (GNI) and back normal irradiance (BNI) sensors, taking into account all measured data or only filtered data according to Table 2 and with (γ > 0) or without (γ = 0) considering absorption of lens-scattered global normal irradiance (DNI) by the flat-plate PV array [Colour figure can be viewed at wileyonlinelibrary.com]
IEC 62670-3\textsuperscript{13} and IEC 60904-5.\textsuperscript{14} At SOC, the average temperatures of the concentrator and flat-plate PV cells were found to be 64°C and 45°C, respectively.

The CPV part of the hybrid modules has been rated according to IEC 62670-3,\textsuperscript{13} but using STC and SOC conditions rather than CSTC and CSOC. The power output of the 3J and 4J CPV arrays corresponds to a DNI conversion efficiency of 34.4% and 36.1% at STC and 31.2% and 33.2% at SOC.

For the power rating of the PV array, the bifacial $I_{SC}$ is split into front and rear contributions using a rear reference solar cell to subsequently characterize the irradiance response of each side independently. Then, the I–V curves of the PV array are translated to STC and SOC using procedure 1 in IEC 60891\textsuperscript{18} with a slight modification of the current translation equation. It was found that the front side of the flat-plate array contributes 16.9 W/m$^2$ at STC and 14.0 W/m$^2$ at SOC. Furthermore, the developed rating procedure considers the lens-scattered DNI that reaches the PV array in addition to the diffuse sunlight.

Adding the power output of the CPV and PV arrays resulted in a conversion efficiency of the reference AM1.5g spectrum of 32.1% and 34.2% for the 3J and 4J EyeCon modules, respectively. This exceeds the highest value reported in the solar cell efficiency tables for the conversion of global irradiance by a terrestrial PV module.\textsuperscript{30} According to the technical specification of bifacial PV devices, IEC TS 60904-1-2,\textsuperscript{19} the 4J EyeCon module generated 10.9 W/m$^2$ for every 100 W/m$^2$ of rear irradiance due to its bifacial gain. This brings the power output of the bifacial EyeCon module beyond 350 W/m$^2$ and shows the significant benefit of the hybrid CPV/flat-plate PV technology to deliver highest power per module area.

Finally, we found that a simplified power rating procedure, using single-side illumination to characterize the bifacial PV array and pyranometers to measure the GNI and BNI, yielded acceptable results (power underestimation <0.5\textsuperscript{\%}rel) as long as the CPV array data were measured without rear shading and filtered according to IEC 62670-3.\textsuperscript{13}

Future work shall focus on the energy yield calculation of hybrid CPV/flat-plate PV modules to assess their potential worldwide.

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**ORCID**

Juan F. Martínez https://orcid.org/0000-0001-5137-8896
Marc Steiner https://orcid.org/0000-0003-4870-9396
Maike Wiesenfarth https://orcid.org/0000-0002-8741-2272
Stefan W. Glunz https://orcid.org/0000-0002-9877-2097
Frank Dimroth https://orcid.org/0000-0002-3615-4437

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In IEC 60904-5, the parameter \( a \) represents the normalized thermal diode voltage of the flat-plate PV array and is calculated with Equation A1 from two I–V measurements at the same temperature but different intensities. Typical values for the dimensionless parameter \( a \) are around 0.06 according to IEC 60891. For the PV array of the 3J EyeCon module, it has a value of 0.0662, whereas for the 4J EyeCon, it is equal to 0.0693. The calculation was performed with two \( I_{SC} - V_{OC} \) pairs measured at 43.9°C for the former and 49.4°C for the latter in the DIF + BNI range between 150 and 580 W/m².

\[
a = \frac{V_{OC1} - V_{OC2}}{V_{OC2} \ln \left( \frac{I_{SC1}}{I_{SC2}} \right)}
\]  

The thermal resistance \( R_{th, array} \) of the CPV and PV cell arrays \( (T_{array}) \) against ambient temperature \( (T_{amb}) \) is calculated with Equation A2.

\[
R_{th, array} = \frac{1}{a} \left( \frac{T_{array} - T_{amb}}{GNI + BNI} \right)
\]

The mean \( R_{th} \) for the CPV and flat-plate PV arrays of the 3J EyeCon module are 0.044 and 0.023 K/m²/W, whereas for the 4J EyeCon, they are 0.048 and 0.027 K/m²/W. In the case of hybrid monofacial modules, only the GNI influences the calculation; hence, the BNI should be set to 0 W/m².

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\[ f_{\text{Vac}} = 1 - \frac{N_e \cdot n \cdot k \cdot T_{ceV}}{q \cdot V_{ac}} \cdot \ln \left( \frac{\text{DNI}}{\text{DNI}_{STC50C}} \right) \]  \hspace{1cm} (A3)

Relying on the verified \( I_{sc} \) linearity with respect to temperature, Equation A4 translates a measured \( I_{sc1} \) from a temperature \( T_1 \) and irradiance \( G \), to \( I_{sc2} \) at a temperature \( T_2 \). The calculation uses the absolute TC of short-circuit current of the device, \( \alpha \), which is given in units of \( \mu\text{A}\cdot\text{m}^2/(\text{W} \cdot \text{K}) \) and is valid in the investigated range (25°C–50°C).

\[ I_{sc2} = I_{sc1} - \alpha \cdot G \cdot (T_1 - T_2) \]  \hspace{1cm} (A4)