Development and outdoor characterization of a hybrid bifacial HCPV module

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Funding information
Mexican Secretary of Energy: National Council of Science and Technology

Abstract
Conversion of direct, diffuse, and albedo irradiance into electricity is demonstrated with a new kind of hybrid bifacial high-concentration photovoltaic module named bifacial EyeCon. It consists of Fresnel lenses that concentrate the direct sunlight 321x onto III-V triple-junction solar cells that are mounted on the front surface of p-PERC bifacial c-Si cells. Thus, the Si absorbs the front and rear diffuse irradiance. Because III-V and Si cells are electrically isolated (hence a 4-terminal device) but thermally coupled by a dielectric adhesive, Si also acts as a heat distributing substrate. To accommodate the concentrator cells, we adapted the metallization layout and also optimized it for low intensity, ie, 200 W/m² on the front and 100 W/m² on the rear, using finite element network simulation. Additionally, when the concentrator cells are mounted on a bifacial Si cell instead of a metal heat distributor, their operating temperature is 16 K higher. However, we demonstrate with outdoor measurements that the power output of the bifacial EyeCon module reaches up to 326 W/m² when the direct to global irradiance ratio is 92%. At a lower fraction of 70% the bifacial Si cells augment the power output of the III-V string by 19%rel.

KEYWORDS
III-V concentrator, bifacial silicon, direct plus diffuse irradiance, hybrid PV module

1 | INTRODUCTION
Promoting the energy transition from its current fossil fuel-based status towards a renewable and sustainable future is the goal of new and conventional photovoltaic technologies. Nowadays, fixed tilt flat-plate c-Si modules reach up to 24.4% efficiency 1 while decreasing their cost to unprecedented prices, ie, $0.25/Wp at the end of 2018 2. On the other hand, dual-axis tracked concentrator photovoltaic (CPV) modules equipped with four-junction (4J) solar cells convert up to 38.9% of the direct spectrum 3 but fail to exploit the diffuse component. These strengths and weaknesses have motivated several research groups to hybridize both technologies. The purpose behind this approach is energy yield maximization at acceptable electricity generation costs, particularly in locations with an average direct irradiance component between 60% and 80%.

Such hybrid modules use lenses and multijunction cells to concentrate and convert direct normal irradiance (DNI) while absorbing diffuse and scattered sunlight with an integrated Si solar cell. Different architectures and configurations have been proposed in the literature, including two patents 4,5. Efficiencies for such hybrid modules are calculated with the global energy resource and are typically lower than those reported for CPV modules, which only take into account the direct light. But of course the power output per area of hybrid CPV modules can still be significantly higher than standard CPV.

For instance, Lee et al 6 reported a hybrid micro-CPV module with triple-junction (3J) and interdigitated-back-contact (IBC) c-Si solar
cells mounted on a dual-axis tracker ($A=2640$ cm$^2$, $C_{geo}=1000x$). The module converted 30.5% of the global normal irradiance (GNI) because the Si cells boosted CPV power output by 3.5%rel when the DNI/GNI was 92%. Askins et al.\textsuperscript{7} presented another hybrid CPV module ($A=1000$ cm$^2$, $C_{geo}=180x$) that reached an efficiency of 24.5% when the DNI/GNI was 83%. In this case, the c-Si cells increased the 3J CPV string power generation by 6.3%rel.

At the submodule level, Yamada et al.\textsuperscript{8} applied 3J cells, PMMA primary optics, reflective secondary elements, and a c-Si solar cell in a hybrid CPV prototype ($A=16$ cm$^2$, $C_{geo}=100x$) that reached an efficiency of 29.4% when DNI/GNI was 81%. After optimization to improve diffuse light transmission, the efficiency was raised to 30.7%. Additionally, the improved hybrid submodule generates 10% more power if the c-Si cell is operated bifacially instead of only mono-facially.\textsuperscript{9} In the same size category, we built a hybrid CPV submodule ($A=144$ cm$^2$, $C_{geo}=226x$), which we named EyeCon \textsuperscript{10}, using silicone-on-glass (SoG) Fresnel lenses and 4J solar cells mechanically stacked on the surface of an IBC c-Si cell that also acts as the heat distributor. We showed that at a high DNI/GNI of 90%, efficiencies as high as 36.8% are possible, and that at an average DNI/GNI of 57%, the Si cell increases the CPV output by up to 30.6%rel.

These examples demonstrate that it is possible to harvest over 30% of GNI under real outdoor operating conditions using commercially available solar cells. On top of this, the hybrid monofacial energy yield could be improved between 10% and 30%, depending on the diffuse component, when bifacial Si cells are applied.\textsuperscript{9}

In the following, we present the design, development, and characterization steps followed to upscale and transform our hybrid monofacial CPV submodule into an enhanced hybrid bifacial HCPV module ($A=1088$ cm$^2$, $C_{geo}=321x$). It is important to note that we followed the manufacturing processes of the FLATCON\textsuperscript{8} module, a proven CPV technology capable of converting up to 36.7% of DNI.\textsuperscript{12}

2 | MODULE DESIGN

2.1 | Geometrical constraints

Our bifacial hybrid HCPV module uses a primary SoG Fresnel lens with an aperture of 47.6 mm $\times$ 47.6 mm in a 4 $\times$ 12 lens array. The lens together with a 3J cell of 3 mm in diameter yields a geometric concentration of 321x. Maximization of diffuse irradiance absorption requires that the bifacial Si cells cover an area of 1088 cm$^2$ (190 mm $\times$ 571 mm) as depicted at the bottom of Figure 1. Given these dimensions and taking a cell size upper limit of 156 mm $\times$ 156 mm, the required size of the bifacial cell is 94 mm $\times$ 141 mm. This equates to eight cells arranged in a 2 $\times$ 4 array with a 2-mm separation to cover 97.4% of the full aperture. In this configuration, each Si cell hosts six 3J CPV cells as shown at the top of Figure 1. No metallization was applied to the front surface of the bifacial Si cell at the positions of the concentrator cells. The nonmetallized areas were designed to leave isolated pads of 8 mm $\times$ 17 mm in size.

2.2 | Metallization layout optimization of bifacial Si cell

Once we fixed the dimensions of the Si cell and the positions of the nonmetallized pads, we began the optimization process for our p-PERC bifacial Si cell. The main operating differences of the Si cell in our hybrid module compared with a conventional flat-plate module are the higher and inhomogeneous temperature profile and the low irradiance it receives. The intensity levels for optimization were defined after measuring outdoors the diffuse irradiance on the front (DIF; 171 ± 93 W/m$^2$) and back (85 ± 18 W/m$^2$) plane of our dual-axis solar tracker at the test site during April 2018. Thus, we set the target irradiance to 200 W/m$^2$ on the front and 100 W/m$^2$ on the rear.

A finite element network simulation using Griddler\textsuperscript{13} was performed to balance the optical and resistive losses in terms of the number of bus bars (BB), their width, and the finger pitch of the front and rear sides. The CAD drawings of the 1BB, 2BB, and 3BB configurations investigated are shown at the top of Figure 2. Additionally, the required parameters of the precursor and metallization as measured in the laboratory or as reported by the manufacturer are given in Table 1. Typical values achieved in our screen-printing process were used for the height and width of front and rear fingers.
The simulations were performed at a cell temperature of 25°C with a shaded area of 3.5 mm × 11 mm inside the nonmetallized pads to reproduce the presence of the CPV cells on the front surface. In order to assess the impact of the different BB configurations, we fixed their width so that their sum remained constant (1 × 1.5 mm, 2 × 0.7 mm, and 3 × 0.5 mm) and simultaneously varied the front and rear finger pitch. At the bottom of Figure 2, we observe that efficiency and optimum pitch increase with BB number from 17.8 to 18.2% and 18.3% as well as from 1.5 to 2 mm and 2.2 mm, respectively (open triangles). Based on this, we chose the 2BB configuration since the efficiency gain and potential paste savings are marginal in a 3BB scheme.

Another advantage of this design is that the cell can be measured with the same chuck used for commercially available 4BB cells. Further optimization was performed by fixing the front pitch at 2 mm (previous optimum) and varying the rear pitch (blue circles). A significant improvement from 18.2 to 18.8% is observed when the rear pitch increases from 2 to 3 mm. Therefore, we increased the rear pitch to 3 mm and varied the front one to confirm that 2 mm is indeed the optimum (red circles). Finally, a variation of the BB width shows that 0.7 mm was already the optimum; however, its impact is nearly insignificant (green circles).

Once the metallization layout was defined, we manufactured 87 cells in the 2BB configuration with a width of 0.7 mm, a 2 mm front pitch, and a 3 mm rear pitch. Batch processing and characterization were done at the Fraunhofer ISE PV-TEC. The cells were measured monofacially on front and rear at 200 W/m². Table 2 provides a summary of their I-V characteristics and bifaciality factors, where the latter are calculated as the ratio of the rear over the front value.

Assuming superposition, the weighted average efficiency for 200 W/m² on the front and 100 W/m² on the rear is 17.7%. Notably, this value is considerably lower than the best bifacial one-sun Si solar cells (~24%) despite the optimization. The main reason is the logarithmic voltage loss due to the significantly lower irradiance level. However, it should be mentioned that this Si cell design leads to a reduced consumption of Ag paste in the order of 33% compared with state-of-the-art Si 5 BB cells. This may lead to some cost advantages.

### Table 1: Precursor and metallization parameters used in the finite element network simulation of the bifacial p-PERC c-Si cell

| Parameter          | Unit   | Precursor | Front | Rear |
|--------------------|--------|-----------|-------|------|
| $R_{\text{sheet, emitter}}$ | Ω/sq   | 95        |       |      |
| $R_{\text{sheet, bulk}}$ | Ω/sq   | 64.5      |       |      |
| $R_{\text{internal}}$ | mΩ·cm² | 15.5      |       |      |
| $R_{\text{sh internal}}$ | MΩ·cm² | 0.1       |       |      |
| $J_{\text{Ph}}$ | mA/cm² | 41.5      | 39    |      |
| $J_{\text{01, passivation}}$ | fA/cm² | 80        | 30    |      |
| $J_{\text{01, metallization}}$ | fA/cm² | 800       | 1200  |      |
| $J_{\text{02, passivation}}$ | nA/cm² | 6         | 0     |      |
| $J_{\text{02, metallization}}$ | nA/cm² | 15        | 0     |      |
| $\rho_{\text{paste}}$ | mΩ·μm  | 31.5      | 31.5  |      |
| $R_{\text{c paste}}$ | mΩ·cm² | 2.5       | 2.5   |      |
| Finger height     | μm     | 10        | 2.3   |      |
| Finger width      | μm     | 45        | 150   |      |

### Table 2: Mean I-V characteristics measured monofacially at 200 W/m² with standard deviation and bifaciality factor of the 87 p-PERC bifacial c-Si cells fabricated

| Cell Side | $I_{\text{SC}}$, mA | $V_{\text{OC}}$, mV | FF, % | $\eta$, % |
|-----------|---------------------|---------------------|-------|-----------|
| Front     | 1059 ± 5            | 617 ± 4             | 76.3 ± 0.6 | 18.8 ± 0.2 |
| Rear      | 862 ± 17            | 612 ± 3             | 77.2 ± 0.5 | 15.4 ± 0.4 |
| Bifaciality | 81.4%              | 99.2%               | 101.2% | 81.9%     |
2.3 Thermal effect of lens size and bifacial absorption

In Martinez et al.,\textsuperscript{14} we presented the thermal behaviour of a hybrid EyeCon CPV module that couples 4J CPV cells on a monofacial Si cell with a dielectric adhesive of moderate thermal resistance (150 mm\(^2\) K/W). We measured that the CPV cells operate at 77°C (ie, 16 K higher than an equivalent FLATCON\textsuperscript{®} module with Cu heat distributors) and the Si cell at 56°C for a geometric concentration of 226x. This corresponds to 900 W/m\(^2\) focused onto a 3-mm CPV cell with a 40 mm x 40 mm lens (\(\eta_{opt}=87.4\%\)), while the Si cell absorbs 100 W/m\(^2\) of diffuse irradiance at an ambient temperature of 25°C.

In the present bifacial EyeCon design, the concentration ratio (321x) was not only raised by using a 47.6 mm x 47.6 mm lens but also the absorption of diffuse radiation was increased by enabling the rear side of the Si cell to absorb light hitting the glass baseplate of the module. In this paper, the expected power increase and losses relative to a conventional CPV module that uses a metal heat distributor for the concentrator cells are quantified. The investigation is performed using thermal simulations with our validated finite element model. The model description and material parameters can be found in Martínez et al.\textsuperscript{14}

At the top of Figure 3, we present the simulated mean CPV cell temperature as a function of lens aperture (or geometric concentration as depicted by the top x-axis assuming a 7.07 mm\(^2\) cell) for three cases: Sim1, 2, and 3. In all scenarios, the ambient temperature is fixed to 25°C and 900 W/m\(^2\) are concentrated onto the CPV cells. The Gaussian intensity profile on the CPV cell was measured and implemented into the model as 12 concentric rings with decreasing intensity towards the edge.

Sim1 (black circles) represents a conventional CPV module where the cell is soldered onto a Cu heat distributor that covers 53% of the lens aperture and has a thickness of 0.3 mm. According to Jaus,\textsuperscript{15} these dimensions are the optimum compromise between cost and performance for a 16-cm\(^2\) lens.

Sim2 (blue triangles) corresponds to our hybrid bifacial CPV module design where the SCA is attached to the bifacial Si cell with a dielectric adhesive of low thermal resistance (83 mm\(^2\) K/W). Here, the absorption of diffuse irradiance is neglected.

Sim3 (red triangles) is identical to Sim2 with the difference that diffuse irradiance is applied on the front and rear as a homogeneous heat flux of 100 W/m\(^2\) on each side.

The first trend observed is that in all three cases, the CPV cell temperature increases linearly with lens aperture, ie, heat input. As expected, the CPV cell mounted on a metal heat distributor increases at a lower rate (0.5 K/cm\(^2\)) than those mounted on a Si cell (1.2 K/cm\(^2\)). Additionally, absorption of diffuse irradiance from both sides does not affect the heating rate because the heat flux is constant, but instead, it introduces an offset of 5.4 K. As a consequence, at our current lens size (47.6 mm x 47.6 mm) and under bifacial operation, we can expect the CPV cell temperature to reach 88.6°C, while the Si cell operates at an average of 65.2°C. Although these temperatures remain within safe operating regimes, higher performance would be expected for smaller lenses, whereas higher concentration may favour economics. Both could be reached with micro-CPV approaches such as the one described in Domínguez et al.\textsuperscript{16}

As an example, we have calculated the relative power loss (green circles) of the hybrid bifacial EyeCon design against a conventional CPV module (FLATCON\textsuperscript{®}) using the temperature gradient between Sim3 and Sim1 and the temperature coefficient of relative power (0.106 %rel/°C) provided by the cell manufacturer. As the plot reflects at 321x, the penalty in power for operating at 16 K higher cell temperature is −1.7%rel.

**FIGURE 3** Top: Thermal simulation of the concentrator photovoltaic (CPV) cell temperature as a function of lens aperture and the relative power loss (green) due to ΔT comparing a bifacial hybrid CPV module using Si as a heat distributor (Sim3) and a conventional CPV module that uses a Cu substrate (Sim1). The indoor measurement (magenta) compares with Sim2, where a Si cell distributes the heat without absorbing diffuse irradiance on either side. Bottom: Assembly of bifacial Si cell on glass with six chip resistors (1.5 Ω) mounted on its surface with a dielectric adhesive (\(R_d=83\) mm\(^2\)K/W) in order to emulate concentrated irradiance (321 x 900 W/m\(^2\)) by applying 1.6 W/resistor [Colour figure can be viewed at wileyonlinelibrary.com]
Finally, to test the validity of our simulations, we assembled the cell stack shown at the bottom of Figure 3. The assembly consists of a glass base and one bifacial Si cell with six chip resistors (1.5 Ω) glued to its surface using the same dielectric adhesive as used in the hybrid CPV module. An electric power of 1.6 W/resistor was applied in order to emulate concentrated irradiance (321 × 900 W/m²). In the experiment, we measured by contact probe a steady-state temperature on the resistor surface of 81.9°C (magenta circle). This measurement supports our modelling results since it agrees within 1 K with its equivalent simulation (Sim2) at a lens aperture of 22.7 cm².

3 | MODULE DEVELOPMENT

3.1 | Electrical interconnection of bifacial Si circuit

The manufacturing process of the EyeCon baseplate begins with the contacting of the bifacial Si cells. The PV ribbons were glued along the full length of the BB with an electrically conductive adhesive, and the cells were spaced 2 mm. Two strings of four cells interconnected in series were joined at one end to yield a single circuit of eight cells. Moreover, the cells are aligned with a tolerance of ±300 μm in order to avoid a significant offset between the nonmetallized pads and the positions of the lens focal spots.

3.2 | Lamination of bifacial Si cells onto baseplate

After the eight Si cells have been contacted and strung together, they are centred and laminated only from their rear side onto a glass baseplate (220 mm × 601 mm × 3 mm). The lamination process is performed using standard ethylene-vinyl acetate at 150°C and 200 mbar. Contacting, stringing, and lamination of the Si cells onto the glass baseplate were performed in the Module Technology Evaluation Center at Fraunhofer ISE.

3.3 | Fabrication of the concentrator solar cell assembly

In parallel to the manufacturing of the Si baseplate, we fabricated several concentrator solar cell assemblies (SCAs). They consist of a metamorphic 3J solar cell from AZUR Space Solar Power in Heilbronn, Germany, and a bypass diode soldered onto a Cu substrate barely large enough (3.5 mm × 11 mm × 0.3 mm) to accommodate them and to allow electrical interconnection. A bypass diode is interconnected in parallel and with opposite polarity to the 3J cell using ultrasonic thin-wire bonding (50 μm Au wire) on the front contact, while the back is connected by the Cu substrate. After fabrication, all SCAs were I-V tested at an effective concentration of 280x to assess their performance and only the best 48 were selected to build the hybrid module.

3.4 | Mechanical stacking of 3J on bifacial Si solar cells

Mounting of the 3J solar cells at the focal spot inside the nonmetallized pads of the Si solar cells is a process that requires high accuracy. To achieve this, we measured the centre position of the 48 Fresnel lenses within the parquet using a coordinate measuring machine. The coordinates were then fed to a pick-and-place process, and each SCA was picked by vacuum-suction and brought to the target destination. Before placement, we dispensed a 10-mm line of dielectric adhesive to fix the SCA in position. The bond line achieved after pressing the SCA onto the glue was (50 ± 10) μm; therefore, we estimated its thermal resistance to be (83 ± 17) mm²K/W according to the reported thermal conductivity by the manufacturer, ie, (0.6 ± 0.1) W/mK. Additionally, we tested and confirmed the dielectric strength of the adhesive up to 100 V. Hence, the electrical isolation between 3J and Si cells is guaranteed since the largest potential difference within the module at the interface between the cells is below 36 V. After curing the epoxy for 24 hours at room temperature, we measured the X-Y coordinates of the 3J cells and found an offset of (44 ± 20) μm to the intended lenses foci points. This deviation is insignificant for the 3J cells, which were 3 mm in diameter.

3.5 | Electrical interconnection of CPV 3J circuit

Interconnection of the mounted 3J solar cells was done with ultrasonic heavy-wire bonding (500-μm Al wire). Along the short dimension of the baseplate, four cells within a row were strung in parallel and then these 12 strings were interconnected in series. As described in Steiner et al[17, the interconnection scheme was chosen to minimize power losses due to inhomogeneous current generation and temperature distribution within the module. Figure 4 shows a picture of the heavy-wire bonding process on the nearly finished EyeCon baseplate.

3.6 | Module assembly

Once the 3J and Si interconnections were electrically tested, the finished EyeCon baseplate is attached to a stainless steel frame where both circuits are soldered to their independent external terminals. Also, the lens plate is mounted and accurately fixed to the frame at a focal length of 77 mm. Finally, the module is sealed and ready for outdoor characterization. Fabrication of the SCAs, mechanical stacking onto the bifacial Si cells, interconnection, and final module assembly were performed in the ConTEC laboratory at Fraunhofer ISE.
Hybrid baseplate
8 bifacial Si cells
48 CPV 3J cells

4 | MODULE OUTDOOR CHARACTERIZATION

Outdoor characterization of the bifacial EyeCon module is ongoing since May 2019 on our dual-axis solar tracker in Freiburg, Germany. The tracker is equipped with several sensors to measure spectral and meteorological parameters. For instance, it has a front-facing pyranometer and pyrheliometer that measure GNI and DNI, respectively. From these two quantities, we calculated the DIF as the difference GNI-DNI. Additionally, we installed a rear-facing pyranometer to measure the back normal irradiance (BNI) that is composed of rear sky-diffuse and albedo radiation. On the rooftop, the tracker sits on a wooden floor of low reflectivity and has an inhomogeneous background with buildings and structures that project shadows and partially block the horizon. Therefore, we expect the BNI to be similar in a plane-field of dry soil with multiple solar trackers. For the control algorithm, a tracking accuracy sensor provides the azimuth and elevation sun pointing angles. Ambient temperature and wind speed are logged by a weather station mounted behind the tracker. On-sun I-V characterization is performed by sweeping voltage with a bipolar power supply and measuring the module response using digital multimeters while simultaneously recording data from all the sensors.

4.1 | Acceptance angle of the hybrid HCPV module

It is well known that the tolerance to tracking misalignment of a CPV module mainly depends on the design of the primary optics and the size of the receiver. Typically, the half acceptance angle ($\alpha_{1/2}$) of a CPV module is defined as the misalignment angle where the power output drops to 90% of its maximum capacity.

In order to obtain $\alpha_{1/2}$ of our hybrid module, we deliberately misaligned the tracker and measured the maximum power output of the CPV and bifacial Si cells. The plots in Figure 5 show the normalized power output of the 3J CPV cells (red), the bifacial Si cells (blue), and the hybrid sum CPV + Si (black) for azimuth (top) and elevation (bottom) angle variations.

FIGURE 4 Photograph of the bifacial EyeCon baseplate made of 8 bifacial Si cells and 48 triple-junction solar cells during the concentrator photovoltaic circuit interconnection by ultrasonic heavy-wire bonding in the ConTEC laboratory at Fraunhofer ISE [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 5 Normalized power output of the 3J concentrator photovoltaic (CPV) cells (red), bifacial Si cells (blue) and the hybrid bifacial EyeCon module CPV + Si (black) as a function of azimuth (top) and elevation (bottom) sun pointing angle measured during clear-sky conditions. Note the change in scale of the y-axis for the CPV and Si strings [Colour figure can be viewed at wileyonlinelibrary.com]
In both cases the maximum CPV power contribution (89%) occurs at 0° and then decreases in a parabolic manner, while the opposite occurs for the Si cell string. This is expected because the focal spot moves away from the CPV cells and onto the Si cells as the sun pointing angle deviates from 0°. Nevertheless, the $\alpha_{1/2}$ of the CPV cells is 0.44° in azimuth and 0.63° in elevation. The higher tolerance in elevation misalignment is expected because the parallel strings are oriented in the direction of tilt; therefore, current fluctuations are balanced within the strings and power output is maintained over a 0.2° higher range of misalignment.

The hybrid $\alpha_{1/2}$ increases less than 0.05° relative to the value for the CPV part alone when the DNI/GNI ratio is 80%. The increase is marginal because the bifacial Si cells barely increase their power contribution under misalignment even if the focus starts hitting the Si cell surface (see also next section). In conclusion, Si does not improve significantly the tolerance to tracking misalignment of our hybrid HCPV, but it is capable of boosting its power output by 11% when properly aligned.

### 4.2 Concentrated sunlight effect on bifacial Si cells

The misalignment of the concentrator lens to the sun results in light being first reflected by the SCA, and for larger misalignment angles, focused light is also hitting the silicon surface. We have investigated the effect of misaligning up to 5° in a prototype sub-module made up of one bifacial Si cell and six CPV SCAs. This allows the focal spot to partially or completely impinge onto the Si cell.

As shown at the top of Figure 6 when the module is misaligned 2°, the concentrated irradiance fully falls onto the Si cell hitting partly the ribbon or metallized square around the CPV cells. At 5° misalignment, the distorted focus completely falls onto the Si cell.

The effects of concentrated sunlight on the I-V characteristics of the Si cell are depicted at the bottom of Figure 6. Here we observe that the concentrated irradiance increases the $I_{SC}$ of the aligned submodule (black line) by 87% in the 2° case (blue line) and 137% in the 5° scenario (red line). At the same time, the $V_{OC}$ also increases 5% in both cases due to the higher carrier generation. However, the FF drops by 22%$_{rel}$ and 31%$_{rel}$ respectively, and limits the increase in maximum power MPP (magenta circles) to 53%$_{rel}$ and 74%$_{rel}$. The reduction in FF is a result of distributed series resistance in the Si cell, which limits the flow of current from the focus point to the BB.

The results show that the Si cell cannot significantly compensate for losses due to misalignment because it only increases the hybrid output power up to 8.1% at 5°, while the CPV losses exceed 50% beyond 1°. It should be noted that after 30 minutes of exposure to concentrated sunlight, the Si cell did not degrade in performance. Also, no other problems with the reliability of the hybrid CPV module have been experienced during three months under full sunlight operation outdoors.

![FIGURE 6](image-url)
available resource, but the Si string adds an additional 7.6% rel to the CPV power output.

At the bottom of Figure 7, we also show the response of the bifacial EyeCon module under nonideal conditions for CPV, ie, average DNI/GNI = 70%. Although the 3J cell string efficiency stays nearly unaffected (30.7%), its power contribution significantly decreases from 303 to 217 W/m². This fits to the DNI drop from 974 to 705 W/m². Under these conditions, hybridization is crucial to harvest the available 429 W/m² of diffuse irradiance. Overall the hybrid power output was boosted by 19% rel compared with the CPV part alone. This is a major improvement, increasing the potential to introduce CPV as a hybrid technology in locations where the annual DNI/GNI ratio falls below 80%.

5 | SUMMARY AND CONCLUSION

A hybrid bifacial HCPV module using metamorphic 3J solar cells (3 mm) and bifacial p-PERC c-Si cells (94 mm × 141 mm) has been designed, fabricated, and characterized outdoors. The Si cell metallization was adapted to accommodate the concentrator cells on its surface and optimized to operate under irradiance of 200 W/m² on the front and 100 W/m² on the rear. A finite element network simulation yielded a bifacial efficiency of 18.8% for the Si cells, and the measured average efficiency of the batch was 17.7% using only industrial manufacturing processes. Besides absorbing diffuse, scattered, and backside radiation, the Si cells acted also as a heat distributor for the 3J CPV cells. The CPV cell temperature remained in a safe operating regime and was found to be approximately 16 K higher (at DNI = 900 W/m², DIF = 100 W/m², BNI = 100 W/m², and Tamb = 25°C) compared with a standard CPV module with metal heat distributor and identical dimensions. This was leading to a small power loss for the CPV cell string of 1.7% rel, which was overcompensated by the additional power generated by the Si string. A power increase of 7.6% rel and 19% rel was measured under clear-sky conditions with DNI/GNI = 92% and hazy conditions of DNI/GNI = 70%, respectively. This corresponds to power outputs of 326 and 259 W/m² for the hybrid bifacial EyeCon module. Further characterization to rate the power output at standard test and standard operating conditions, as well as the analysis of the expected annual energy yield of hybrid CPV modules, is ongoing and will be published elsewhere.

ACKNOWLEDGEMENT

The authors want to acknowledge the support of all colleagues in the "III-V Photovoltaics and Concentrator Technology," the "Module Technology," and "PV-TEC" departments at Fraunhofer ISE for helping with the cell and module fabrications as well as characterization. The work of Juan F. Martínez was partly supported by the National Council of Science and Technology (CONACYT) and by the Mexican Secretary of Energy (SENER) through a PhD scholarship. The authors are responsible for the contents of this paper.

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How to cite this article: Martínez JF, Steiner M, Wiesenfarth M, et al. Development and outdoor characterization of a hybrid bifacial HCPV module. Prog Photovolt Res Appl. 2020;28:349–357. https://doi.org/10.1002/pip.3239