Presented at the 15th International Conference on Concentrating Photovoltaic Systems, 25 – 27 March 2019, Fes, Morocco
AIP Conference Proceedings 2149, 060006 (2019); https://doi.org/10.1063/1.5124199

Pushing Energy Yield with Concentrating Photovoltaics

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Abstract. A 4J CPV module achieving 41.4 % efficiency at CSTC is presented in this paper. The high efficiency is enabled through the combination of high quality achromatic full-glass lenses with high efficiency 4J solar cells. This module has been built to demonstrate the potential of CPV module technology when improving the efficiency of the optical elements as well as the solar cell performance by integrating more junctions. The characteristics of the full-glass lens module are compared to a conventional Fresnel lens module. High efficiency is one of the keys to increase the energy yield of CPV power plants and to make the technology more competitive. Another aspect is the use of diffuse, scattered and albedo light resources which is typically not converted in high-concentration PV modules. Hybrid CPV modules combine high concentration PV with a flat-plate technology like silicon to push the energy yield even further. In this work, we present latest developments of our EyeCon hybrid module technology at Fraunhofer ISE and demonstrate the potential of a bifacial submodule (136 cm^2) consisting of one silicon solar cell on which six concentrator cells are mounted. The technology has significant potential to extend the application area where CPV technology can compete with conventional flat plate PV.

INTRODUCTION

The CPV community has been successful in demonstrating concentrator photovoltaic modules with efficiencies well beyond other solar technologies [1],[2]. The increase in efficiency over time was in the past enabled by improvements in concentrator solar cell performance moving from 2- to 3- and more recently 4-junction devices. This has led to commercial module efficiencies peaking at 38.9 % under concentrator standard test conditions (CSTC) for a SOITEC module with 4-junction cells [3]. Cell efficiencies are already high but future progress in module performance can also result from improved optics. In this paper, we present a CPV module which has achieved a CSTC efficiency of 41.4 %. The result was included into the PIP efficiency tables [3]. The module combines high efficiency 4J solar cells [5] with high efficiency achromatic full-glass lenses.

Another strategy followed for the development of improved CPV technology is to focus on increasing the energy yield through the use of diffuse, scattered and backside radiation. Indirect radiation is especially important if CPV is applied in regions with medium direct normal irradiance (DNI) where population density and energy consumption are often high. As land area is scarce and expensive, these regions are especially attractive for high efficiency PV (like CPV) technology. We are developing a concentrator-flat plate hybrid technology with optimized energy yield and low environmental footprint to address these markets. We expect that up to 40 % of GNI can be directly converted into electricity using this hybrid module, more than by any other foreseeable PV technology.

4J MODULE WITH ACHROMATIC FULL-GLASS LENSES

At Fraunhofer ISE, we are working on high performance CPV modules for more than two decades and we have developed FLATCON® modules with 3- and 4-junction solar cells reaching up to 36.7 % CSTC module efficiency [9]. These modules use silicone-on-glass lenses with an optical efficiency of approximately 86 % [1],[4]. Higher optical efficiencies are reached with full-glass lenses which avoid scattering of light at the draft angles of the facets of the Fresnel structure and with achromatic lenses which avoid losses due to chromatic aberration. This allows reaching optical efficiencies above 90 % and consequently increases module efficiencies. Compared to SoG Fresnel lenses, these full-glass lenses are higher in weight and also in production cost. But we believe that full-glass lenses can become a viable solution if scaled down in size to a point where the structure can be formed directly in glass by a rolling or embossing process.

As a demonstration of the potential of such an approach, a CPV module using achromatic full-glass lenses with an aperture area of 122 cm² has been developed. The module is shown in Figure 1, left. It consists of 10 high efficiency 4J cells mounted and electrically interconnected to metal heat distributors. The cells achieve efficiencies of up to 46 % [3],[5]. The sunlight is focused on the 10 cells by 10 achromatic full-glass lenses. These glass lenses have an optical efficiency of around 96 % [4]. This is a much higher optical efficiency compared to conventional silicone-on-glass (SoG) Fresnel lenses (80 – 90 % [1]).

To emphasize the different characteristics of the achromatic full-glass lens compared to the regular Fresnel lens, two 4J cells named A & B have been electrically characterized outdoors while being illuminated by an achromatic full-glass lens and by a regular Fresnel lens. The designated area of cell A is 5.3 mm² and 7.1 mm² for cell B. The aperture area of the full-glass lens is 12.2 cm² and 22.7 cm² for the Fresnel lens. This gives geometrical concentration factors of 230x for the cell A under the full-glass lens and 320x for the cell B under the Fresnel lens. Figure 1 (right) shows the measured electrical solar cell efficiency of both cell/lens combinations as a function of relative cell to lens distance. First, Figure 1 shows that the maximum measured efficiency values are 15 $\%_{rel.}$ higher with the full-glass lens. Additionally, the efficiency values are much more stable to changes in the cell to lens distance for the full-glass lens.

The main reason for the higher efficiency values when using the full-glass lens is its around 10 $\%_{rel.}$ higher optical efficiency compared to the SoG Fresnel lens. The second reason is that the 4J cell (cell A) which has been used with the full-glass lens has a lower front contact grid shading [4]. This results in around 3 $\%_{rel.}$ higher current. The lower front contact grid shading could be realized because of the more homogenous distribution of the irradiation by the full-glass lens compared to the SoG Fresnel lens. Using a solar cell with the same front contact grid of cell A together with the SoG Fresnel lens, the gain in current would be over compensated by the decrease in fill factor due to series resistances losses. Finally, the main reason for the less pronounced dependency of efficiency as a function of cell to lens distance is the much lower chromatic aberration of the full-glass lens [4].

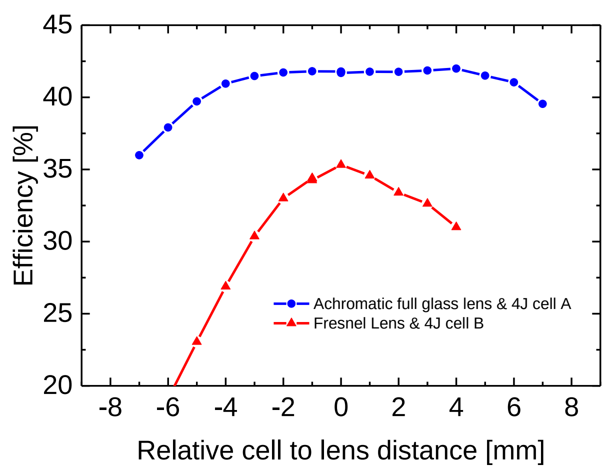

FIGURE 1. Left: 4J CPV module consisting of 10 achromatic full-glass lenses which focus the sunlight onto ten high efficiency 4J solar cells. Right: cell efficiency as a function of relative cell to lens distance. This dependency was measured for one achromatic full-glass lens together with the 4J cell A and for one conventional Fresnel lens together with the 4J cell B. The 4J cell A with designated area of 5.3 mm² has a 3 $\%_{abs.}$ lower front contact grid shading compared to cell B. Cell B has a designated area of 7.1 mm².

The efficiency of the 4J module shown in Figure 1 left has been rated according to the standard IEC 62670-3. The rating procedure is described in [6]. The measurements were recorded at the outdoor test setup at Fraunhofer ISE in Freiburg, Germany. The IEC 62670-3 rating procedure includes outdoor measurements at concentrator standard operating conditions (CSOC). Furthermore, module temperature coefficients have been determined using thermal transient measurements [6]. These temperature coefficients have been used to translate the CSOC efficiency values to CSTC. The measured CSOC and CSTC efficiency in this measurement campaign are shown in the histogram in Figure 2 left. The mean value of these efficiency values is the efficiency of the 4J module rated at CSOC (39.5 %) and CSTC (41.4 %). Figure 2 right shows exemplarily one of the current-voltage characteristics measured at CSOC without correcting the temperature. The 41.4 % module efficiency rated at CSTC of the 4J module is the highest reported efficiency value for a CPV module of this size [3].

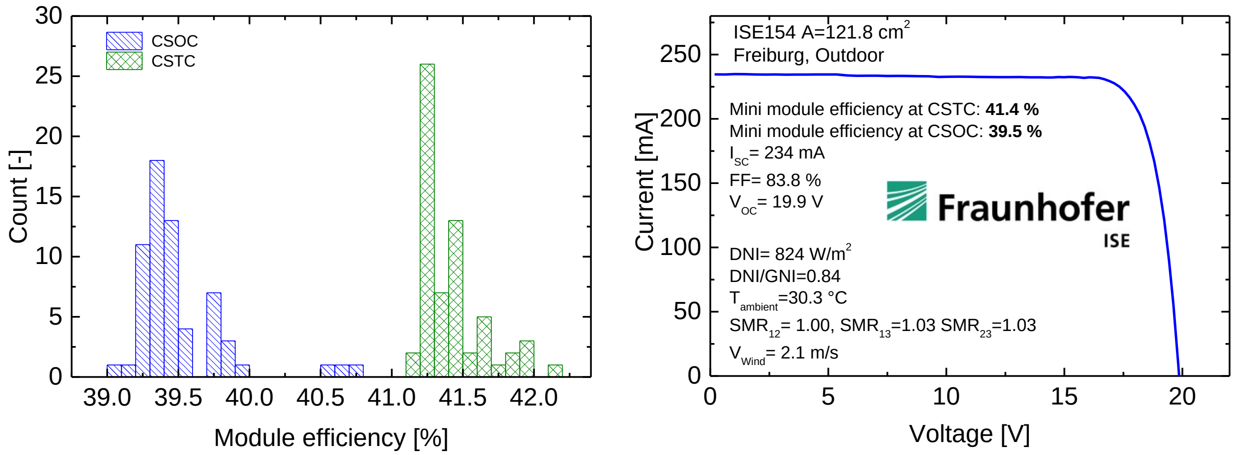

FIGURE 2. Left: Histogram of 4J CPV module efficiencies rated at CSOC and CSTC according to IEC 62670-3. The mean values are 39.5 % at CSOC and 41.4 % at CSTC. Right: exemplary I-V curve at CSOC without correcting for ambient temperature.

INCREASING THE ENERGY YIELD

Another approach to increase the energy yield of the CPV module technology is to capture and convert diffuse, scattered and backside radiation. For this reason, Fraunhofer ISE has developed a hybrid module called EyeCon which uses flat plate PV cells (silicon or thin film). The EyeCon module technology uses the silicon cell not only to capture the diffuse sunlight but also to act as the heat distributor for the concentrator cells [7]. Details of the thermal design which allows keeping the CPV cell temperatures below 80 °C for a lens area of 16 cm^2 and geometrical concentration of 226 are published in [8]. First results of outdoor measurements for a monofacial EyeCon submodule (144 cm^2) were presented during the CPV-14 conference [7]. Now the bifacial EyeCon submodule (136 cm^2) with increased geometrical concentration (321x), is presented in Figure 3 left, using a bifacial Si cell, specifically designed for the application in the hybrid module. The grid layout was adapted to the low irradiance level (front 200 W/m^2 and back 100 W/m^2) and contact pads were foreseen for mounting the III-V CPV cells and bypass diodes. The cell captures radiation from the front and backside and therefore increases the useful annual solar resource by up to 50 % in a country like Germany.

Additionally Figure 3 right depicts the improvement of using a bifacial (red line) rather than a monofacial (blue line) Si cell to increase the power output of conventional CPV. The power boost is between 4 and 5 % for DNI/GNI values between 0.5 and 1, where the average conversion efficiency of the CPV array is 2.8 times that of the Si cell. The bifaciality, ß, obtained from the ratio between the rear and front efficiency measured indoors is 0.83 and the average ratio of the albedo (background reflected + rear sky irradiance) and global normal irradiance is 0.16 according to the multi-linear regression (R^2_{bif} = 0.75) applied to the outdoor data measured in Freiburg, Germany during February 2019.

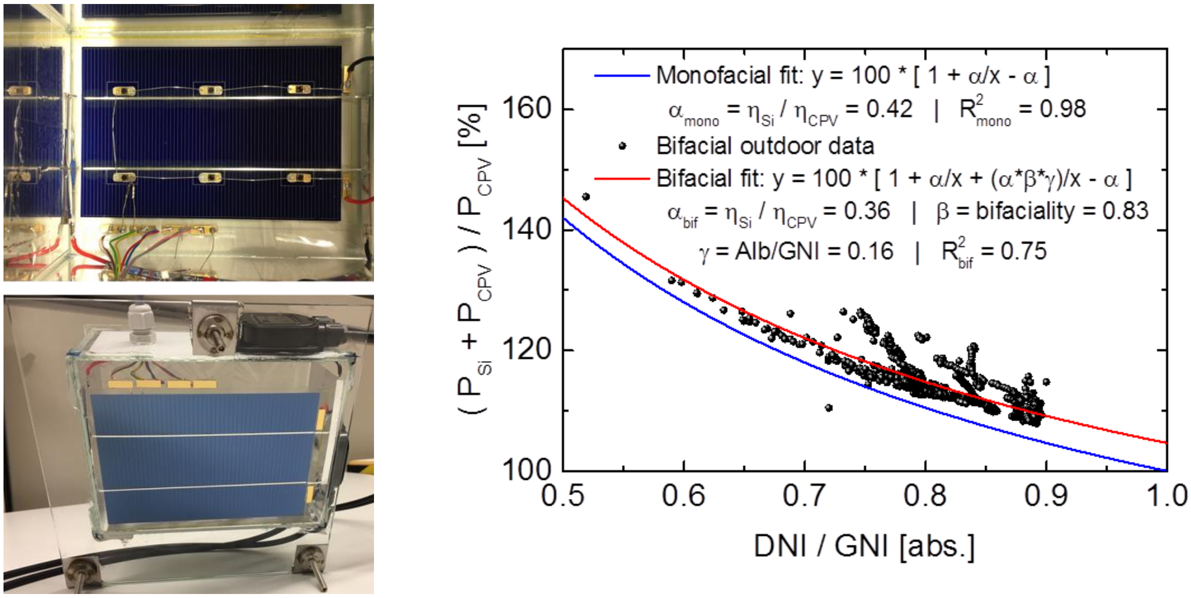

FIGURE 3. Left: Bifacial EyeCon submodule built with one bifacial p-PERC silicon solar cell and six III-V 4J CPV cells that use SoG Fresnel lenses to achieve a geometrical concentration of 321x. The picture shows the front (top) and rear (bottom) views of the EyeCon submodule. Right: Comparison of the CPV power increase by the integrated Si cell between the monofacial (blue) and bifacial (red) cases. The blue line has been extracted from measurement data of a monofacial module. This measurement data is not shown in the graph but can be found in [7]. Bifaciality (ß = 0.83) was derived from indoor measurements whereas the average efficiencies ratio (α_{mono} = 0.42 and α_{bif} = 0.36) and the average albedo per GNI ratio (γ = 0.16) were obtained by multi-linear regression (R^2_{mono} = 0.98 and R^2_{bif} = 0.75).

Enabling the EyeCon module technology to harvest the diffuse, scattered and albedo irradiance expands the world wide areas where CPV module technology could be cost competitive. As shown in Table 1, the bifacial power gain in locations where CPV has already been installed ranges from 9 to 20 %, while in regions where it has not yet been deployed the potential benefit well exceeds 30 %.

TABLE 1. Exemplary Summary of Monofacial and Bifacial Power Gains per Region and DNI/GNI Ratio

Region	$P_{Gain\_monofacial}$	$P_{Gain\_bifacial}$	$DNI_{yearly}/GNI_{yearly}$
Calama, Chile	5 %	9 %	0.91
Guarda, Portugal	10 %	14 %	0.82
Badgaon, India	15 %	20 %	0.73
Regions with yearly DNI below 2 MWh/m^2*a	30 %	34 %	0.58

CONCLUSION

Two options to push the energy yield with concentrator photovoltaics have been presented in this work. The first option is to increase the module efficiency by using high efficient optics and 4J cells. The second option is to increase the amount of useable solar resource by building hybrid CPV modules.

Option one is demonstrated with a CPV module that has been built using achromatic full-glass lenses and 4J solar cells. The optical efficiency of the full-glass lenses is about 96 % [4] and the 4J solar cell efficiency is about 46 % [3],[5]. The 4J module efficiency has been rated at concentrator standard operating (CSOC) and test conditions (CSTC) according to the standard IEC 62670-3. The outcome of the rating procedure is an efficiency values of 39.5 % at CSOC and 41.4 % at CSTC [3]. The main reason for the high efficiency values is the high optical efficiency of the full-glass lens which is about 10 $\%_{rel.}$ higher compared to conventional SoG Fresnel lenses.

Furthermore, the more homogenous illumination of the full-glass lenses compared to Fresnel lenses allowed a reduction of the front contact grid shading which led to 3 $\%_{rel.}$ increase in cell efficiency compared to cells which would be appropriate for a conventional Fresnel lens array.

Besides the increase of module efficiency, it is important to increase the energy yield. This is accomplished in the hybrid approach where the available solar resource for a conventional CPV module is increased by the use of bifacial silicon cells that capture diffuse, scattered and albedo irradiance in order to boost power generation while also acting as heat distributor for the concentrator solar cells. The key of this concept is to maximize the energy yield of CPV power plants by the integration of flat plate PV cells that absorb irradiance from the front and backside, while minimizing the additional cost of the hybrid approach. In this way the market where CPV technology becomes cost competitive is expected to increase towards populated areas where flat plate PV technology is currently dominant.

ACKNOWLEDGMENTS

This work was partly funded by the European Union’s Horizon 2020 research and innovation program under grant agreement No 640873 (CPV-Match). The authors want to thank all members of the department “III-V Photovoltaics and Concentrator Technology” at Fraunhofer ISE for their support and especially to Alexander Wekkeli for the photo of the full-glass lens module and Dr. Andreas Bett for many important discussions. We thank our partners, SOITEC and CEA-LETI for contributing part of the 4J solar cell development. Finally Juan F. Martínez wishes to acknowledge the support of the National Council of Science and Technology (CONACyT) and the Mexican Secretary of Energy (SENER) through a Ph.D. scholarship.

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