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Towards Industrialization of Planar Microtracking Photovoltaic Panels

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Abstract. Planar micro-tracking concentrator photovoltaic modules hold great promises, as they enable the combination of efficiencies greater than 30% with the form factor of conventional rooftop panels operating at fixed tilt. Over the past three years, Insolight has been developing a fixed-tilt system, combining a biconvex silicone lens array, high efficiency multi-junction cells and integrated micro-tracking. A first prototype built in 2016 was validated with a peak conversion efficiency of 36.4 %. On the path towards industrialization of the systems, we present the evolution from the first lab prototype to fully automated panels featuring several thousands cells, installed on a rooftop pilot site. Continuous operation and data logging of the outdoor installation over a year enable us to validate a simple and robust integrated micro-tracking scheme. Recent measurements showed a module efficiency of 29% at concentrated standard test conditions. Different hybrid PV-CPV architectures are under evaluation for the capture of global irradiance.

INTRODUCTION

While Concentrated Photovoltaics (CPV) is capable of record efficiencies (recently 41.4% achieved by a high concentration CPV module [1]), the economical viability of the approach suffers from high installation and operation costs compared to standard silicon-based PV. Indeed, conventional CPV generally relies on the concentration of sunlight using lenses with acceptance angles of less than a few degrees [2]. The consequence is that conventional CPV modules always have to face the sun, implying the need of precise dual-axis trackers and a large module footprint, incompatible with the constraints of rooftop installations.

In contrast, planar micro-tracking concentrators enable the combination of concentrator efficiencies with the form factor of conventional panels operating at fixed tilt [3, 4, 5, 6]. In this approach, the absence of dual-axis trackers enables simpler systems with reduction of installation, operation and maintenance cost overheads, and can also provide an efficiency boost in space-constrained applications where electricity production has the most value, such as zero-energy buildings [7].

INSOLIGHT'S LAB PROTOTYPE (2016)

Over the past three years, Insolight has been developing a fixed-tilt system, combining a biconvex silicone lens array, commercial high-efficiency multi-junction (MJ) cells and integrated micro-tracking (Fig 1 a). The micro-tracking actuation is integrated within the module frame and translates the cell array with respect to the lens array.

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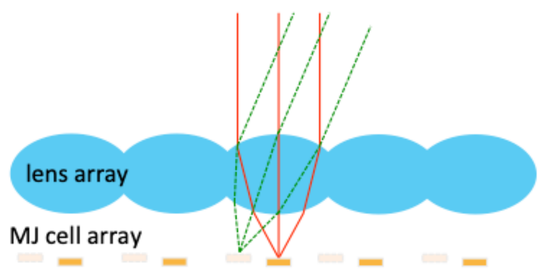
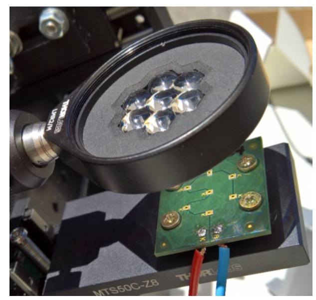
Translations of a few millimeters over the course of a day are used to keep the solar cells under the focal spots as the sun moves. Two-axis actuation enables tracking over an optimized curved trajectory. Due to the varying angles of incidence (AOIs), planar tracking concentrator design is based on guidelines that are different than conventional CPV [8]. In particular, Fresnel lenses are not an option due to their unfavorable off-axis performance.

Insolight produced a first laboratory prototype in 2016, featuring a seven-lens hexagonal array and a concentrating factor ~180. The laboratory prototype was combined with an array of seven 0.6x0.6 mm^2 InGaP/GaAs/InGaAsNSb triple-junction cells (Fig 1 b) to achieve 36.4% peak efficiency vs direct sunlight in outdoor measurements (Fig 2 a). The angular acceptance was validated over AOIs of +/- 40° (limited by mechanical constraints that have been lifted since then) with optical efficiencies > 80% of the cosine law (Fig 2b-c). As an application example, the device was used to power an off-grid chloralkali electro-chemical reactor, taking advantage of the MJ cell's large V_{oc} > 3V [9]. Recently, Ito *et al.* published a detailed analysis of a very similar design, demonstrating efficient focusing up to 55° AOI, nearly 30% module efficiency vs direct irradiance, and a 32% increase of power generation with respect to conventional Si cells on a sunny day [10].

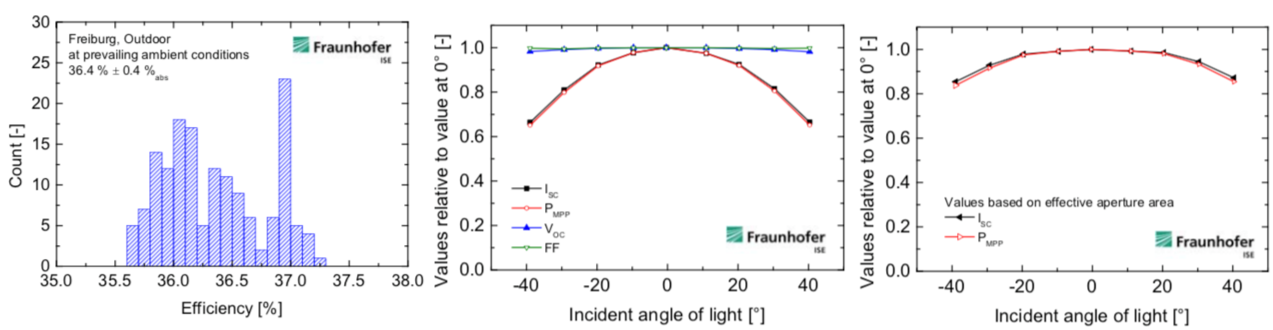


(a)



(b)

FIGURE 1. (a) Schematics (simplified) of Insolight system. The multi-junction (MJ) cell array is translated with respect to the lens array to accommodate for different AOIs. (b) Photograph of the first lab prototype (2016).



(a) (b) (c)

FIGURE 2. (a) Histogram of the 2016 lab prototype efficiency, for measurements performed on August 11, 2016 under prevailing ambient conditions at the sun tracking unit of Fraunhofer ISE in Freiburg, Germany. The amount of measured current-voltage characteristics used for the histogram is 157. The mean values and the standard deviations are given in the inset. (b) Short-circuit current I_{SC}, open-circuit voltage V_{OC}, fill factor FF and maximum power P_{MPP} of the mini-module as a function of incident angle of light. The values are presented as a ratio to the respective values at 0°. In (b) the values are plotted without additional correction. In (c), P_{MPP} and I_{SC} are given as a fraction of cosine projection.

FROM LAB TO PILOT SITE

From 2016 to 2019, Insolight has been working on assembly, reliability and scalability aspects, evolving from laboratory prototypes to fully automated 0.5 m^2 panels featuring several thousand 1mm^2 GaInP/GaInAs/Ge MJ cells

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(maintaining the concentration factor to ~180). Design guidelines are chosen to take into account constraints and opportunities of high-volume manufacturing, leveraging on standard components and industrialization processes. Materials and components are also selected in regard of reliability and qualification norms. Reliability of module architecture is currently being tested according to norm IEC-62108. Insolight modules feature a regular protection glass and are fitted within standard PV module frames. A rooftop installation located on the EPFL campus in Lausanne, Switzerland (Fig. 3) has been operated and monitored for more than a year. This fixed-tilt, southward facing installation, connected to the grid, has enabled us to validate a robust integrated micro-tracking scheme, as well as reliability in outdoor conditions (including two Swiss winters). Continuous operation and data logging for over a year provide us feedback on design choices. An example of data subset for a single panel during 30 consecutive days in Aug-Sep 2018 is shown in Fig. 4. This data demonstrates a reliable conversion of Direct Inclined Irradiance (DII) into current over this period. Another subset for three consecutive days going from cloudy to clear day, is shown in Fig. 5.

FIGURE 3. Photographs of the Insolight pilot site on a rooftop of the EPFL campus in Lausanne, Switzerland

Data from the pilot site is currently being exploited to analyze the module performance under different weather conditions and optimize its architecture.

Very recently, one of the Insolight modules was tested by the Instituto de Energía Solar at the Universidad Politécnica de Madrid (UPM-IES), and a conversion of 29% according to Concentrator Standard Test Conditions (C-STC) was measured (Fig 6) [11]. The dominant loss factors from the 7-lens prototype to the rooftop modules are (1) the addition of protection glass, (2) additional absorption due to thicker concentrating optics, (3) alignment losses. Points (2) and (3) are due to technical factors that can be overcome, still leaving an interesting margin for improvement.

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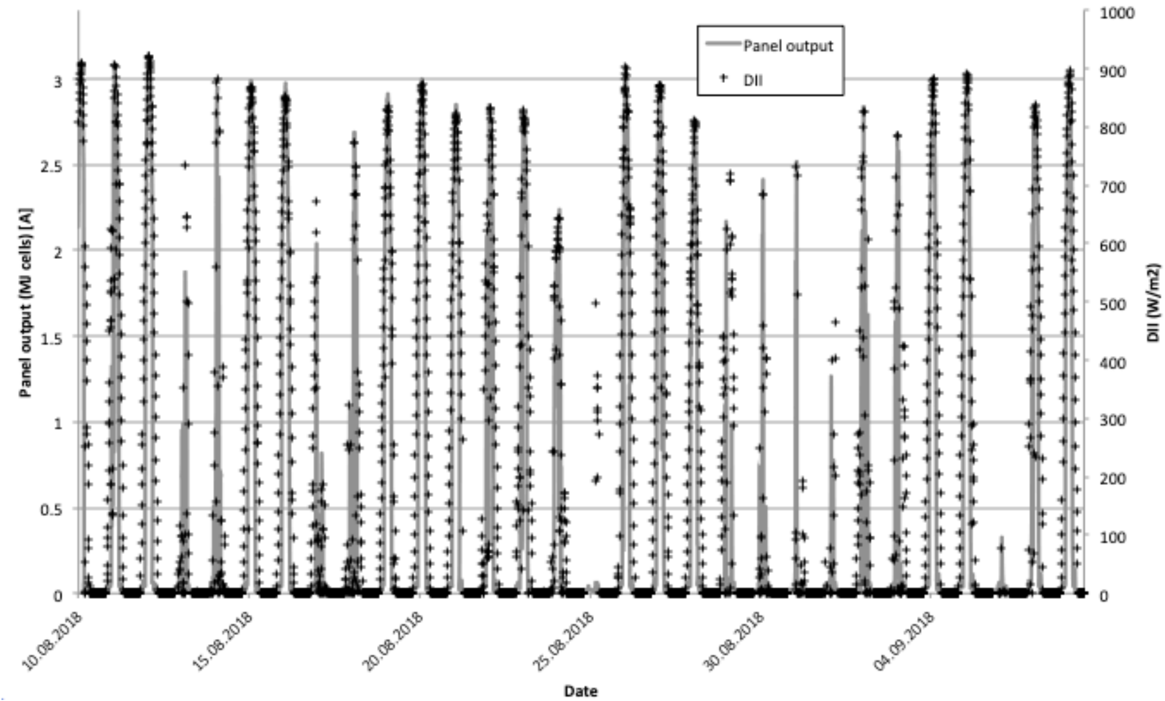

FIGURE 4. Example of data subset from the pilot site in Lausanne from 10.08.2018 to 13.09.2018, showing reliable conversion of DII into current. *Gray line*: panel output current (MJ cells). *Black crosses*: Direct Inclined Irradiance (DII)

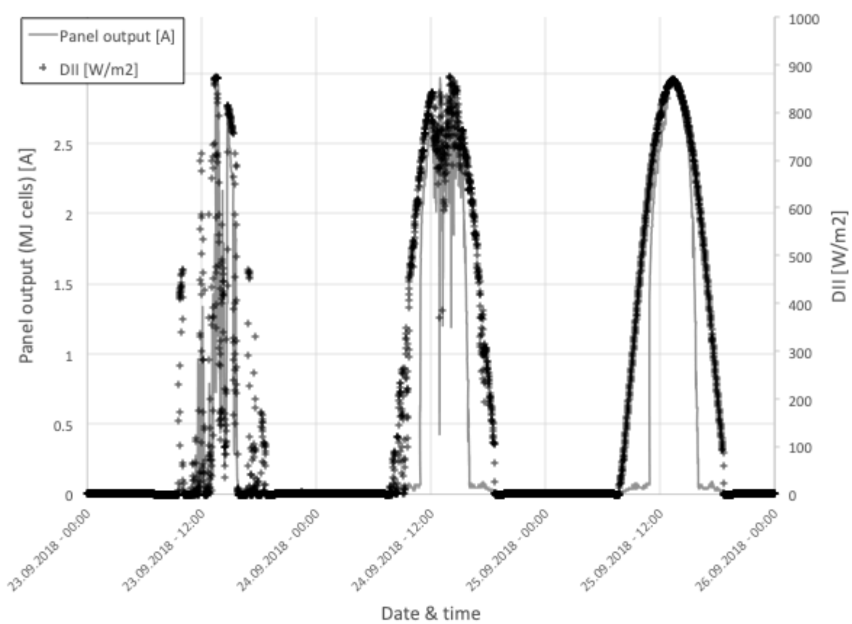

FIGURE 5. Example of data subset from the pilot site in Lausanne for three consecutive days (Sept 23-25, 2018), going from cloudy (Sept 23) to clear day (Sept 25). *Gray line*: panel output current (MJ cells). *Black crosses*: Direct Inclined Irradiance (DII)

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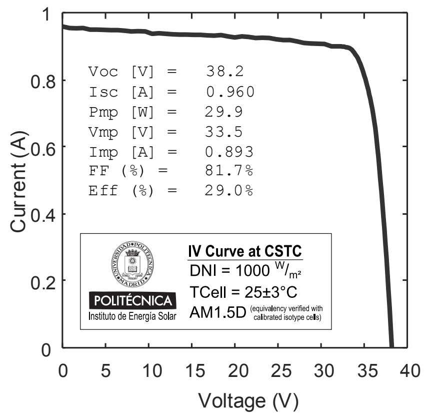

FIGURE 6. IV-curve of Insolight module measured at IES – Madrid at C-STC conditions (using IES indoor large area collimated tester, at normal incidence) showing an efficiency of 29%.

HYBRID MODULES

As can be seen in Figs 4 & 5., the amount of current produced under concentration is linked to the quantity of direct irradiance. Hybrid PV-CPV approaches can extend conversion efficiency to diffuse sunlight by including a sheet of Si cells. The goal of hybrid architecture is to approach the efficiency of Si panels in diffuse light conditions, and provide an efficiency boost in case of direct illumination. It was shown that the addition of a PV layer provides a substantial improvement in module efficiency compared to pure CPV, and has the potential to expand the market of CPV to locations with less favorable DNI conditions [12]. Different approaches are described in the literature, such as Si cells mounted around the MJ cells [12], MJ cells mounted on a transparent substrate above the Si cells [12,13], or MJ cells directly mounted on top of the Si cell [14]. We are currently evaluating different hybrid architectures for Insolight modules in terms of their cost/benefit.

To predict the performance of hybrid PV-CPV architecture, it is essential to assess the transmission of diffuse sunlight through the optical lens array. In Fig. 7a, we show the result of ray tracing simulations (Zemax®) through the lens array as a function of AOI, including absorption, reflection and total internal reflection (TIR) losses. The drop of transmission beyond 60° is dominated by TIR within the lens array. The transmission of light at normal incidence is 91.7%. The transmission of arbitrary angular distribution of light can be calculated by integrating the transmission profile of Fig. 7a on the sky dome, weighted by a geometrical factor cos(AOI)*sin(AOI) (dashed line in Fig 7a - cosine for projection on the module plane, sine to take into account the size of the solid angle elements at each AOI). The result for a fully diffuse (lambertian) light is 73.8%. Subtracting an average relative transmission loss of 5% through the protection glass, the optical transmission through the optical layer should span between 70.1% (fully diffuse) and 87.1% (fully direct).

A hybrid module has been assembled, featuring Si cells in which apertures for MJ cells have been cut (Fig. 8). Architecture and performance of the hybrid module will be described in a further contribution. We use it here to produce experimental results that can be compared to the predictions given in the previous paragraph. In Fig 7b, irradiance on the Si PV cells within the hybrid module are measured from the cell conversion efficiency and effective area, and plotted as a function of Diffuse Horizontal Irradiance (DHI – measured by an on-site weather station), for different fractions of direct light (Direct/Global Normal Irradiance - DNI/GNI). This measurement tells us how much of the diffuse light outside the module is eventually collected by the Si cells inside the module. By this way we are able to experimentally measure the optical transmission of the optical layer (lenses + protection glass) in various diffuse outdoor conditions. We observe that in case of highly diffuse light (DNI/GNI<10%), data points line up closely with the expectation for optical transmission of fully diffuse light. In case of highly direct light (DNI/GNI> 50%), data points are close to the expectation for optical transmission of fully direct light. Outliers may be due to delay between measurement of module power and weather (up to 15s).

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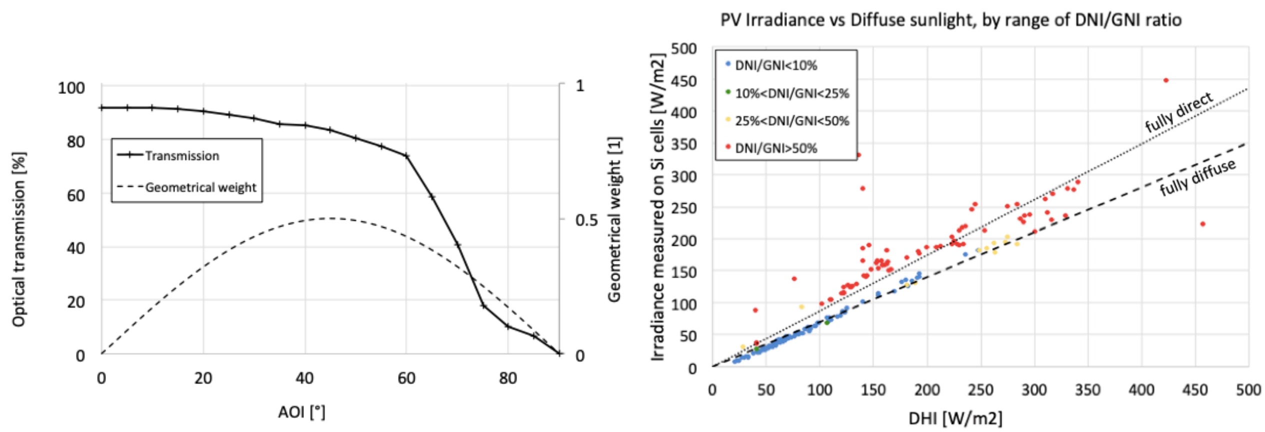
CONCLUSION

We have shown the evolution of Insolight's planar micro-tracking system from lab prototypes to fully protected and operational rooftop fixed-tilt modules. Monitoring of a pilot site over a year enables us to demonstrate reliability of the module and its integrated micro-tracking mechanism. A module conversion efficiency of 29% was recently measured at C-STC conditions. Hybrid architectures combining III-V MJ cells and a sheet of Si cells for conversion of global irradiance are currently under evaluation. Transmission of diffuse light through the lens array was calculated and compared to outdoor measurements. An ongoing measurement campaign of the hybrid PV-CPV planar micro-tracking modules promises insight in the energy rating of the hybrid architecture. In parallel to the analysis of the module performance, tools are being developed for the high-volume manufacturing of the systems.



(a) (b)

FIGURE 7. (a) Modelled optical transmission of the lens array as a function of AOI (value plotted for each angle is an average over +/- 2.5°). Dashed line: geometrical weight of solid angle elements as a function of AOI. (b) Irradiance measurements on the Si PV cells within a hybrid module, measured between 21.11 and 28.11.2018 in Madrid (Spain), as a function of diffuse irradiance (DHI), for different fractions of direct light (DNI/GNI). For these measurements, the module was always facing sun direction. Dashed (dotted) line indicates conversion limits expected for fully diffuse (direct) sunlight.

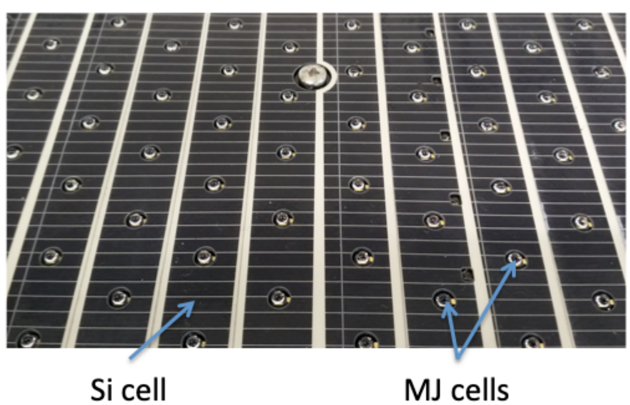


FIGURE 8. Photograph of the hybrid backplane of the module used to collect data of Fig 7b. Apertures were laser cut in 6'' Si cells to match the MJ cell pattern.

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