Progress and Demonstration of Micro-CPV Module with Integrated Planar Tracking and Diffuse Light Collection

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***Abstract*—Several technologies have been identified that could produce a new type of high-performance solar product optimized for space-constrained applications: micro-CPV, planar microtracking, and diffuse capture. The Swiss start-up Insolight and the Hiperion consortium are bringing such a device to the industrial level. In this work we share the latest results for full-scale modules, discuss improvements to the design and resulting performance gains, and will report the results from pilot installations in Madrid and Freiburg.**

Keywords— integrated planar tracking, diffuse light collection, micro-concentrator photovoltaics.

I. INTRODUCTION

As has been reported previously [1-4], a European consortium is developing a high-performance rooftop compatible hybrid solar device whose goal is to maximize the specific energy generation per unit area. Such a device has the potential to provide high value for spaced constrained applications, such as urban rooftops. This novel solar module applies three separate technologies that up until now have only been seen at the laboratory level:

- "**Microscale" concentrators**, or Micro-CPV, where-in the solar cells are 1mm in size. CPV modules can have a form factor similar to flat plate (a few cm or less in thickness. [5]
- **Planar microtracking**: By employing a second optical surface, that high concentration optics can be designed which achieve focusing for high angles of incidence (AOI) [6], making rooftop CPV feasible.
- **Diffuse capture**: Low-cost solar cells (eg. c-Si) can be combined with III-V cells under concentration to produce hybrid modules which capture direct light with high efficiency, and diffuse light with a lower efficiency. [7-8], increasing overall energy generation.

Development of the Insolight technology is proceeding with both private and public funding, including a significant grant from the EU Commission for the *Hiperion* Project, which will lead to an operational pilot production line and multiple demonstration arrays by the end of 2023. Modules have been scaled up to commercial size. [4]

The Solar Energy Institute at Madrid Technical University (IES-UPM), along with the Fraunhofer Institute for Solar Energy (ISE) and the PV-center at the Swiss Center for Electronics and Microtechnology (CSEM) are charged with characterizing new module designs developed within the program, as well as creating new measurement methods, standards, and equipment adapted for the specifics of this new technology. In this work we present the results of indoor and outdoor measurement of modules of the first of "Gen2" modules, the final design to be produced on the Hiperion pilot line, as well as a full year's worth of field data at two pilot installations installed at IES-UPM and Fraunhofer ISE. (Fig. 1).

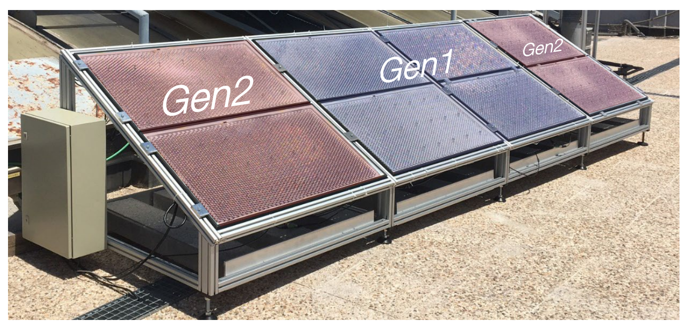

Fig. 1. An 8-module Insolight/Hiperion pilot array at the IES-UPM in 2021.

The Insolight technology employs a biconvex lens designed such that focusing is possible when the angle of incidence (AOI) approaches 60°, although the focal spot does travel as the sun moves, as shown in Fig. 2, and the entire back plane is translated to follow it and maintain alignment. The back plane consists of an array of commercial triple junction microcells with approximately 42% efficiency combined with conventional 6" monocrystalline Silicon solar cells. The microcell size is 1mm and the approximate geometric concentration ratio is 180X. Because the optical elements are refractive, diffuse light which is not focused onto the III-V cells is instead collected by the Si cells, which cover the area not taken up by III-V cells. Voltages are not matched between III-V and Si cells, so a four terminal output is provided. We will refer to these separate PV systems as the “CPV” and “Si” output, respectively.

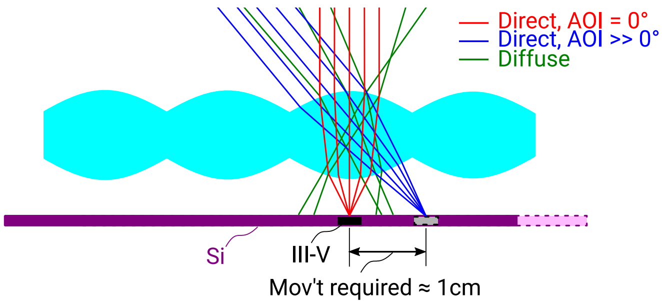

Fig. 2. Working principal of the micro-planar tracking system and diffuse collection.

II. TECHNICALOGICAL PROGRESS

The status of the technological development of the Insolight technology and early experimental results were presented in a previous IEEE PVSC in 2019 [2]. Since that time, and with the support of the Hiperion grant and consortium, great strides have been made towards the industrialization of this technology. Within the Hiperion two generations of device designs have been developed, “Gen1,” which was designed and tested within the first two years of the project and the final “Gen2” design which incorporates lessons learned from the first generation, will be the technology to be produced at the pilot production line and installed in various demonstration arrays.

One of the main changes has been increasing module size. The pre-Hiperion design (referred to here as “Gen0”) was only about 0.1m2. For Gen1, the size was increased significantly to 0.6m2. Though smaller than modern flat plate modules, with around 3000 micro-cells and lenses, it is a manufacturing challenge. For “Gen2”, the generation to be produced on the Hiperion pilot line, the size is maintained but lessons from Gen1 validation are adopted. Insolight also envisions a later “Gen3” module that matches the size of common 72-cell crystalline silicon modules. Such a module would have over 8000 cells and have a total power rating of 670W. See Fig. 4 for a comparison of modules sizes and Table 1 for a comparison of measured nominal electrical characteristics. For a discussion of how these results are obtained, see Section III.

Before Hiperion, off the shelf components, including an “Arduino” device, were used to quickly progress with core

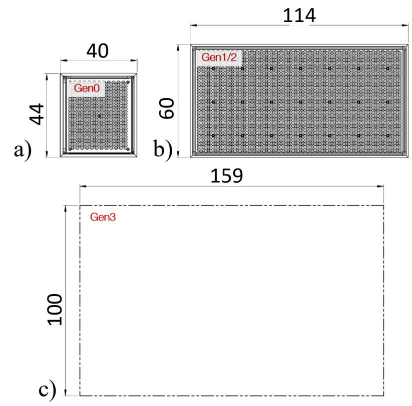

Fig. 3. Scale drawing of increasing module size with succesive generations. (a: Gen0, b: Gen1/2 c: Gen3.) All dimensions in cm.

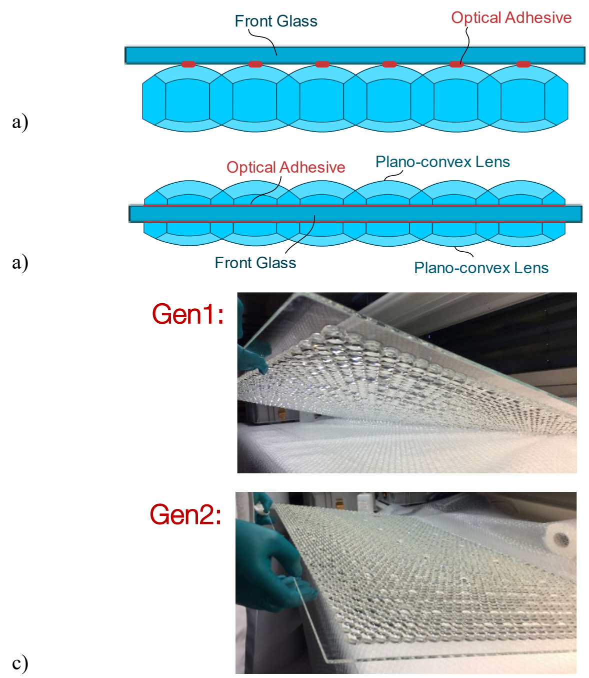

Fig. 4. Schematic comparison of the Gen1 (a) and Gen2 (b) optical design. (c) Photographic comparison of the two optical layers.

aspects of the technological development. With the support of Hiperion consortium industrial partners, custom electronics and actuators have been incorporated. It is also important to note that for a self-tracking module, firmware development is also

TABLE I. COMPARISON OF, SIZES AND NUMBER OF CELLS AND PERFORMANCE OF DIFFERENT MODULE GENERATIONS.

Gen.	Description	Area* (m^2)	Cells*	CPV: Measured and Estimated I-V Params[1†]					Si: Nominal
				V_{OC} [V]	I_{SC} [A]	FF [%]	P_{MP} [W]	Eff. [%}	P_{MP} [W]
Gen0 [2]	Pre-Hiperion	0.1	600	38.2	0.96	82%	30	29.0%	*15*
Gen1	Hip. Initial	0.6	3000	42.1	4.27	78%	141	26.0%	*90*
Gen2	Hip. Final	0.6	3000	42.0	4.57	81%	156	29.0%	
Gen3	Post- Hiperion	1.6	8000				*430*		*240*

[1]For CPV output of Gen0/1/2, I-V parameters at CSTC by indoor/outdoor measurement at IES-UPM is giv
[2]For Gen3 CPV output and all Si output (*in italics)*, nominal values provided by Insolight are giv
* Values are approximate; † Rated at CSTC Conditions (DNI = 1000 W/m^2); § Rated at Diffuse = 300 W.

critical, and we will discuss important improvements in this area in Section IV.

The most significant advance in the past year has been a redesign of the architecture for this bi-convex lens. For Gen0/Gen1, the two-surface lens was molded as a single part and then mated to a front window glass that serves both as a rigid support as well as environmental protection. (Fig. 4a) This has two drawbacks. First, two additional air-glass interfaces lead to unnecessary Fresnel losses. Second, it is difficult to attach lenses to the glass at their apex while balancing reliability and efficiency, due to limited surface area. In Gen2, the lens has been broken apart into two PMMA pieces, which are laminated on either side of the front glass pane using a transparent silicone adhesive (Dow Silicones). (Fig. 4b). In this paper we will compare the performance and demonstrate the improvement achieved with this redesign. See Fig. 4c for photographs of both generations of optical layer.

III. Indoor/Outdoor Characterization

In this paper we will section we will present results of individual module measurements of different module generations. Gen1 prototypes were produced in various batches from late 2020 until early 2021. In spring 2021, 22 modules employing Gen2 optics and tracking hardware were produced by Insolight and CSEM. These modules represent nearly all aspects of the final design for the 100s of modules to be produced on the HIPERION pilot line, only the secondary silicon solar cells for diffuse capture were not incorporated (mechanical design changes made changes to the cell layout necessary). All modules were flash-tested on the solar simulator provided for the pilot line by the IES and installed at, and it was found that, except a few outliers, the distribution of the power output was reasonably narrow. (Fig. 5). Finally, production of hybrid Gen2 modules on the pilot line has started in spring of 2022. Their characterization is ongoing.

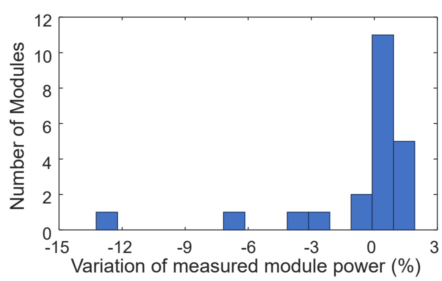

Fig. 5. Histogram of 22 modules measured at CSEM pilot line flash tester from Gen2 prototype batch in Summer 2021.

Fraunhofer ISE has taken the lead in developing a specific rating procedure for this complex solar technology [9]. A Round Robin to test this procedure is planned for Summer 2022 using final Gen2 modules. We will present results of three types of measurement campaign on individual modules of both Gen1 and Gen2 technologies, with an emphasis on a comparison between the two:

1. **Outdoor measurements at AOI = 0°** (normal incidence): Mounted on a solar tracker, I-V curves taken over a few clear days. These measurements are important for characterizing nominal performance, specifically of the CPV output.
2. **Indoor measurements at AOI = 0° & AOI > 0°**: IES-UPM large area collimated light flash tester used to determine CSTC performance. Module may also be rotated with respect to beam to characterize the off-axis performance.
3. **Outdoor measurements at AOI > 0°**: Module I-V curves of different generations have also been meaused in fixed-tilt configuration, using the integrated tracking system, to evaluate its performance as well as the diffuse characteristics of the module. However, for the sake of brevity, in this paper we will present similar modules made on the pilot installation.

a)
b)
c)
d)

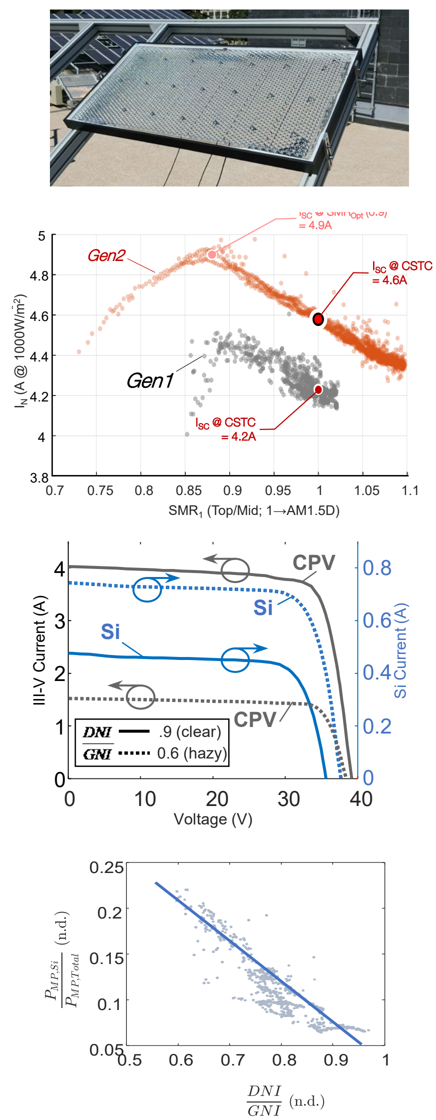

Fig. 6. a) An early Gen2 prototype (translucent version) moutned on the IES 2-Axis lab tracker. b) Comparison of Module I_{SC} normalized to DNI outdoors (on-2-axis tracker) for Gen1 vs. Gen2. c) I-V curves for both CPV and Si outputs under different atmospheic conditions (Gen 1). d) Relationship beween diffuse fraction and proportion of module power contributed by Si output.

A. Outdoor measurements at AOI = 0°

We first present the outdoor measurements of prototype modules mounted on our two-axis lab tracker. (Fig. 6a) Usually CPV modules are mounted with provisions for making small angular adjustments with respect to the tracker frame to maximize power output, but in the case of self-tracked modules, the modules can be directly clamped to the frame and the on-board tracking mechanism used for fine alignment. The Insolight software include a mode for maximizing power output when used on dual-axis trackers which was used for these measurements.

An important product of these measurements is relationship the normalized CPV current versus the *Spectral Matching Ratio* (SMR). This allows us to use a self-reference technique for the indoor characterization shown in the next section. The results for Gen2 versus Gen1 optics are shown in Fig 6b. As expected, the normalized current is increased by nearly 10% due to the change in the optical layer. We can also use Outdoor on-axis I-V curves to examine the performance of the diffuse light collection. The I-V curves from two specific moments in time, chosen as examples of a clear (DNI/GNI = 0.9) vs hazy (DNI/GNI = 0.6) conditions are shown in Fig. 6c. Taking data filtered for atmospheric stability, we show the relationship between the Si output power (as a proportion of the whole) to the DNI fraction (Fig. 6d). As is expected, the contribution to the total power of the Si output is inversely proportional to the ratio of the direct to global normal irradiance (DNI/GNI). These results are for the Gen1 design, and Gen2 measurements are underway, although we expect similar behavior.

B. Indoor measurements at AOI = 0° & AOI > 0°

Indoor measurements were taken with the IES indoor large area collimated beam xenon flash tester (2m beam, >1000 W/m2, ±0.4° collimation angle, AM1.5D matched by SMR). The setup is shown in Fig. 7a. As in the outdoor measurements at AOI = 0°, we used the internal tracking method to perform fine alignment of the module to the collimated beam, using an optimization algorithm and repeated flash measurements of power (P_{MP}). To preserve lamp life, the flash power has been greatly reduced for this alignment process, since relative but not absolute power is important for determining the optimum internal tracker position.

The goal of the indoor measurements was to establish the performance of the III-V at Concentrator Standard Test Conditions. These results are calibrated using the outdoor results presented in the previous section; that is the solar simulator was tuned such that the III-V output of the module produced the short circuit current observed outdoors in conditions of CSTC irradiance and spectrum.

In Fig. 7b we show the CSTC I-V curve for three successive generations. The resulting I-V parameters were presented previously in Table 1. It is observed that the Gen2 efficiency and fill factor are nearly the same as the Gen0 result, for a much larger module with 5X as many 1mm solar cells, indicating good alignment quality for nearly 3000 solar cells and lenses. It is also noted that during slightly red-shifted spectra (which are more prevalent in many areas than AM1.5) the normalized value of current is 6% higher (4.9A instead of 4.6A), so if we were to calibrate the simulator to this spectrum the indoor efficiency would increase to 31%.

We can also study the effect of incidence angle on power for AOI ≠ 0° in a repeatable way in the solar simulator. To do this, the, the module tilted with respect to the collimated beam of light produced by the simulator. At each angle, the micro-tracking used to align the cells to the focal spot produced by the biconvex lens and the I-V curve is measured. The CSTC results, both I-V curve and I-V parameters, for Gen0 and Gen1 are shown in Fig. 7c. We observe a significant improvement. While the Gen2 prototypes have not yet been measured using this method (which is rather time-consuming) the angular response of the modules can also be derived from the outdoor self-tracking results, and it has been shown Gen2 improves even further (see section IV).

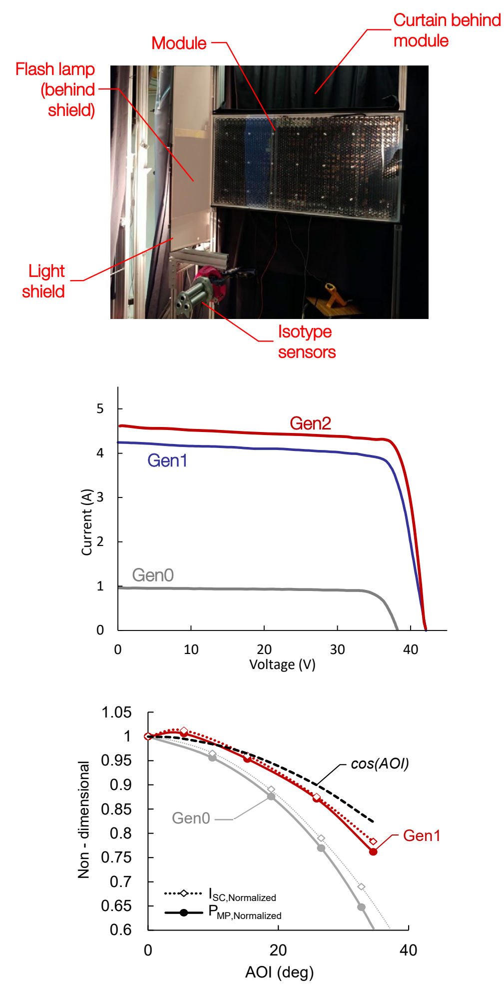

Fig. 7. a) Indoor measurement setup. b) Comparison of CSTC I-V Curves for sucesive measurements. c) Comparison o fangular performance of Gen0 and Gen1.

IV. Pilot Installation

As mentioned previously a grid-connected 8-module pilot has been operational at the IES since April 2021, and a similarly sized pilot is also operational at ISI. In the IES pilot (Fig. 1), Enphase micro-inverters are used to provide a load and MPPT tracker for the panels. For hybrid modules, each output was connected to a different micro-inverter (four terminal

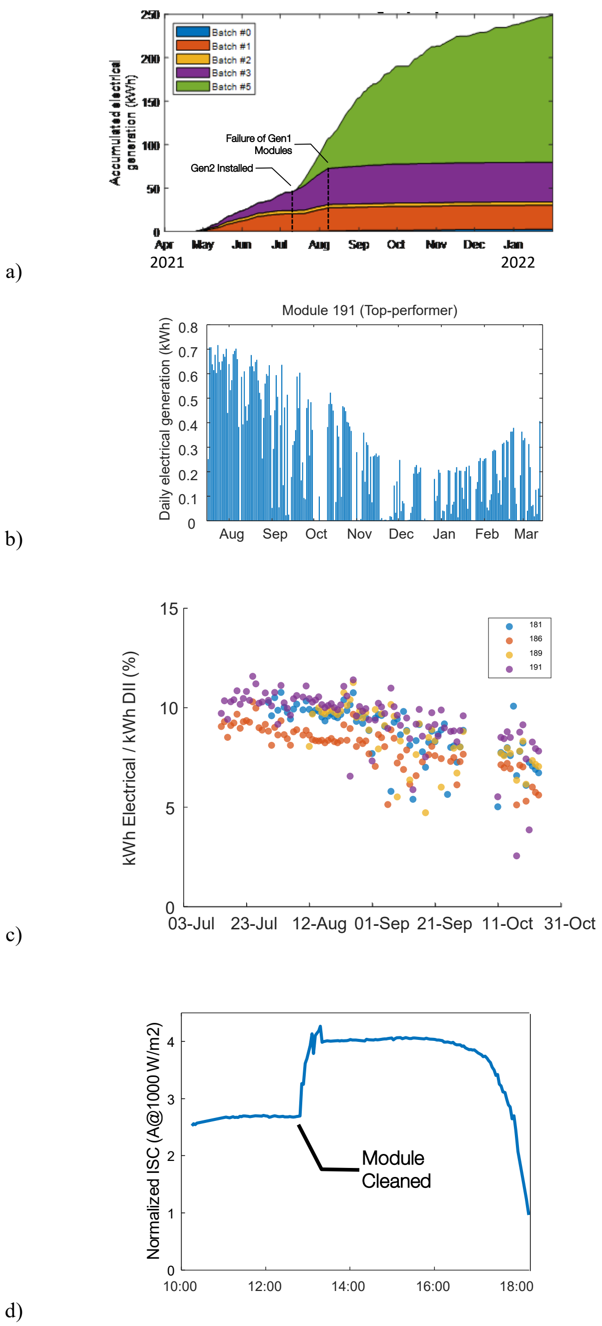

Fig. 8. Preliminary pilot data: a) nine months of daily elecrical generation from the CPV and Si systems in 2021 and 2022. b) eight months of daily CPV electrical generation for top-performing Gen2 prototype (Module 191) c) daily electrical generation for all Gen2 prototypes as aproportion of daily integrated direct inclined irradiance (DII). d) Cleaning experiment on soiled Gen2 prototype.

operation). For Si output, microinverters are also used for monitoring of current and voltage, while for CPV output the embedded module electronics performs this function. It should be noted that the modules were installed initially were Gen1 modules and many of these have experienced failures due to known problems resolved in Gen2. Half of these modules were replaced in July 2021 with Gen2 prototypes. The current distribution is shown n Fig. 1. These prototypes are "translucent" modules, that is they do not have diffuse collection. The rest of the modules will be replaced in the coming months as new modules are produced with the final Gen2 design. By June 2022 we expect pilot results from multiple generation of designs in a realistic setting, with the initial Gen2 prototypes in operation for nearly a year. Here we show preliminary results to date.

In Fig. 8a we show the accumulated electricity generation since pilot installation. Initial production was low due to firmware issues that were later resolved. The peak production was in July in August after installation of four prototype Gen2 modules. CPV production from September onwards corresponds only to the four Gen2 prototypes due to Gen1 failures. In Figure 8b, we show the daily electrical generation from highest performing Gen2 prototype. While a seasonal dip is observed, these results show continuous operation over many months (with no intervention or maintenance) has been observed. We do observe a strong soiling effect, which produces a decrease in the daily normalized electrical generation (Fig 8c). This is because, with no cleaning had been performed in this time, due to a lack of established procedures given that the module outer surface is a PMMA lenses. However, an experiment has shown that this lost power is recovered on cleaning (Fig. 8d).

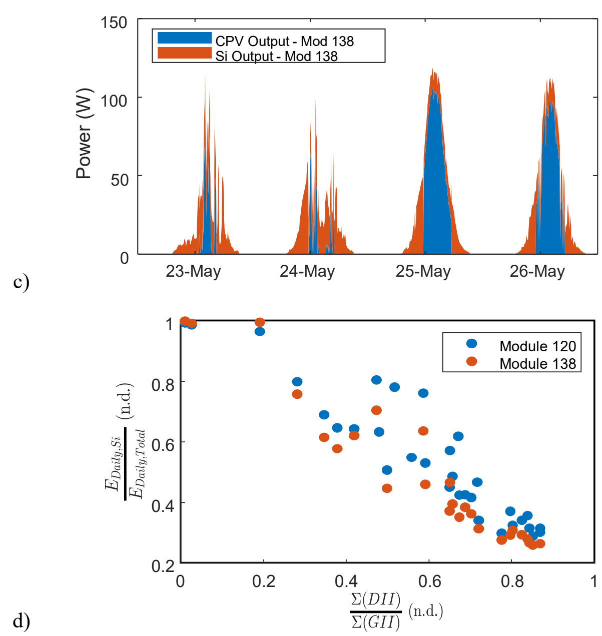

Fig. 9. b) Detail of four days of electrical power produced by a Gen1 hybrid module, showing both CPV and Si output (diffuse collection). c) Analysis of contribution of Si cells to daily generation verus daily direct irradiance fraction.

In Fig. 9a, we show an example of hybrid production of a Gen1 module. Similar experiments are ongoing for the recently received hybrid Gen2 prototypes. It is clear that the Si cells produce power on the first two (cloudy) days when the CPV module production is minimal. On the second two (sunny) days generation is dominated by CPV output, but Si till produces, especially during morning and evening when the planar tracking system is out of range. This is summarized in Fig. 9b, which shows the percentage of the total daily energy generation which can be attributed to Si output as a function of the direct fraction (integrated) for that day. We see a linearly relationship as expected.

Results from the pilot also indicate that the real-world performance enhancement of the Gen2 design over Gen1 is significantly greater than increase in CSTC power shown in the last section. As discussed previously failure to Gen1 modules shortly after Gen2 installation reduced the time in which all modules were functioning to about one month in the summer of 2021. In Fig. 5a we see the CPV power output from two Gen1 and two Gen2 modules on a representative day (19-July-2021). Not only is peak power about 25% higher, but the tracking system has a wider range and the behavior farther from solar noon is improved, due to advances in the tracking algorithm as well as the mechanical design. In fact, if we integrate the power output of the course of the day, we can see that the Gen 2 modules generated approximately 75% more energy. (Fig. 10b). To further understand this increase, we can examine the relationship of the CPV output efficiency for Gen1 and Gen2 modules over the course July 2021 (filtering for clear sky conditions. We observe that the Gen2 module has a much wider range and follows a near-cosine curve until almost AOI = 40°, with only a slight reduction afterwards. The nominal tracking range of ±55° is obtained. This result shows that the specifically designed concentrator optics, the actuator mechanism, and the firmware all all working together as designed to achieve high-performance integrated tracking at 180X concentration.

V. Conclusions

In this work we have present the latest progress, results, and difficulties encountered in the development of a novel hybrid solar panel aiming to provide the highest specific energy production for space constrained applications, focusing on indoor and outdoor power measurement of both the CPV and Si output terminals and a comparison between different generations of the Insolight technology We have demonstrated clear improvements for the Gen2 module with respect to the interim Gen1 design, based on improvements made with the support of the Hiperion consortium. The Gen2 module design, already under production at CSEM in Swizterland meets performance targets in efficiency and tracking performance.

The reliability program within the project identified potential failure modes to the Gen1 design, most importantly due to the optical architecture, which were addressed in Gen2. Shortly afterwards these failures began to occur in the pilot installations at the IES and ISI. Focusing on Gen2 pilot results, the only issue discovered has been unusually high soiling, which will be addressed with specific cleaning procedures currently being developed. However, four Gen2 modules have been in continous operation for nearly 1 year with no electrical or mechanical failures, which is cause for high confidence in the viability of this novel solar technology.

Acknowledgment

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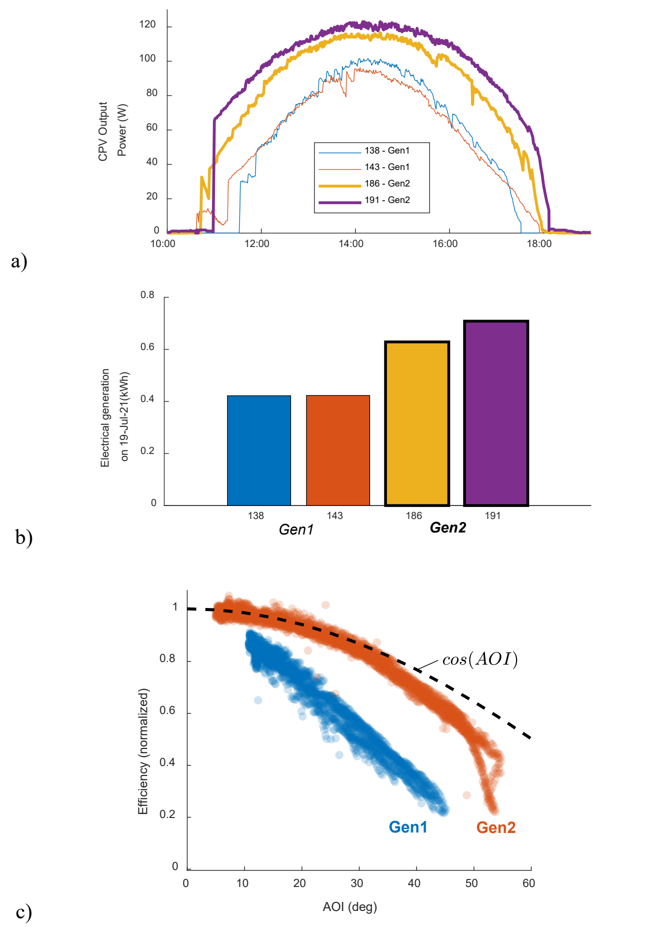

Fig. 10. a) Gen1 and Gen2 instantaneous CPV power production over the course of a clear day. b) Integrated CPV electrical generation for the same four modules over the course of the day shown in (a). c) Normalized efficiency of Gen2 vs Gen module verus AOI of sun vector.

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