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Supporting Information

Three dimension corrugated Organic Photovoltaics for building integration; improving the efficiency, oblique angle and diffuse performance of solar cells

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SI-1 Repeated solar cells performance parameters data for Module A, B, C, D and flat (reference) under direct irradiation from sun (850W/m^2), mounted onto a solar tracker

JV data was repeated by measuring in outdoor conditions using a solar tracker. The irradiance was approximately constant at 850W/m^2 as it was a cloudless day. Modules were initially measured flat, then mounted onto a corrugated structure, and then remeasured. An average of four modules was used for each configuration. The relative enhancement is not significant as in section 3.1 as the data here reports direct irradiation. When using a solar simulator, the proportion of diffuse light is greater, leading to better solar cell enhancements.

	Flat	**Module A**	**Flat**	**Module B**	**Flat**	**Module C**	**Flat**	**Module D**
PCE (%)*	2.14	2.19	2.09	2.01	1.99	1.77	1.63	1.43
V_{OC} (V)	5.72	5.67	6.10	5.95	5.90	5.70	5.38	5.17
J_{SC}* (mA/cm^2)	-0.77	-0.81	-0.7	-0.73	-0.71	-0.61	-0.71	-0.61
FF	41.23	40.57	41.28	39.72	40.28	38.24	36.48	35.15

* Note PCE and J_{SC} refer to 'effective PCE' and 'effective $J_{SC,}$' based on the footprint area of the curved module

SI-2 Effect of corrugation angle of PV performance parameters

a. Overview

To provide some insight into how the curvature affects the performance parameters of an OP, further tests were taken using a series of 3D-printer PLA-based substrates. For these tests, 3D profiles with side wall angles of 15°, 30°, 40°, 50°, 60 °, 70°, 80° were used as the substrate and the OPV modules were laminated onto them [see figure SI-2(a)]

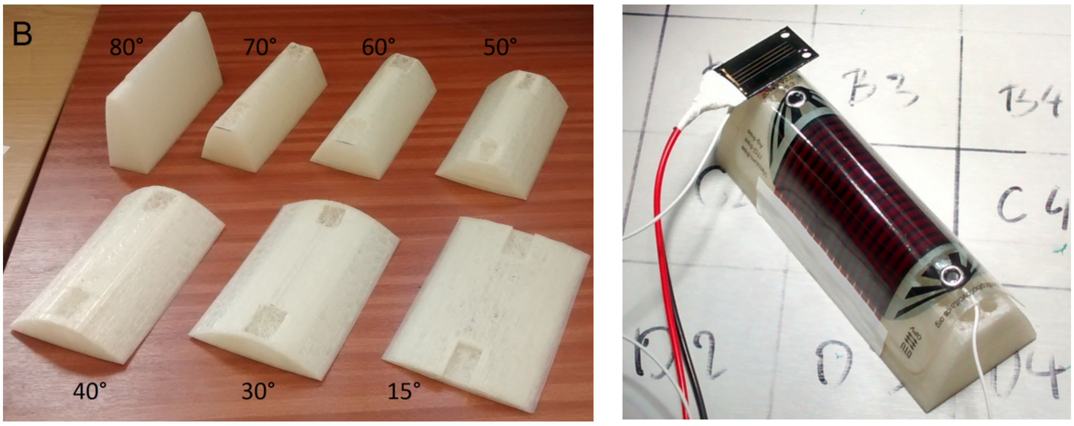


Fig. SI-2(a) (left) Substrates used for experiments and (right) image of a module mounted onto the corrugated substrate

b. Results – effect of corrugation angle on performance

The data in figure SI-2(a) shows how effective PCE, V_{OC}, effective J_{SC} and FF change as a function of substrate corrugation angle. It is apparent that the effective PCE increases with increasing corrugation angle, so to obtain the best performance; a high sidewall angle is desired. In practice, a high sidewall angle is likely to lead to delamination effects, so potentially a trade-off exists between best performance and long term stability. The effective J_{SC} increases with corrugation angle, but entirely due to the reduced module footprint. The in-coupling of light actually reduces with corrugation angle, but this reduction in light in-coupling is offset by the reduced module footprint. The V_{OC} appears to decrease with increasing corrugation angle; this is due to the reduced in-coupling of light. Finally, the FF appears not to vary, with <2% relative change for all corrugations angles.

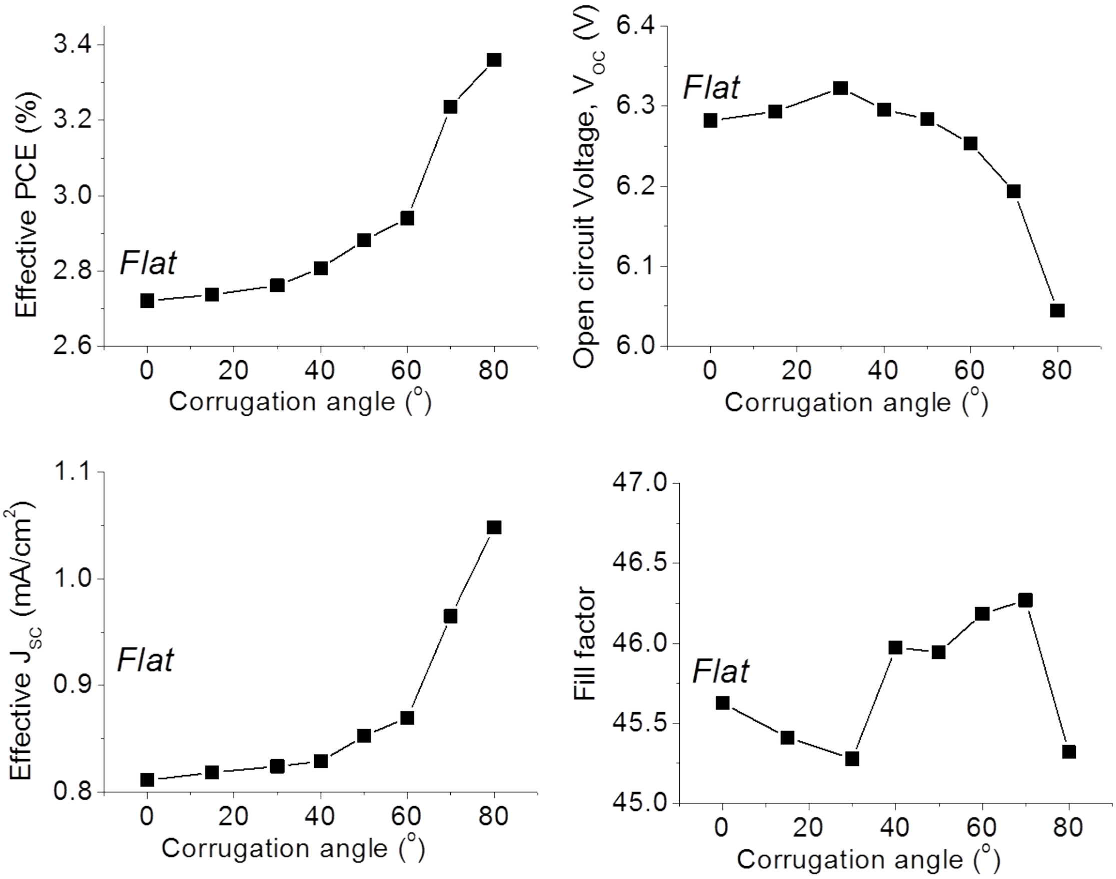


Figure SI-2(b) Effect of corrugation angle on (top left) Effective PCE (top right) V_{OC} (bottom left) Effective JSC and (bottom right) FF.

c. Variation in Effective PCE versus effective area ('footprint') of the module

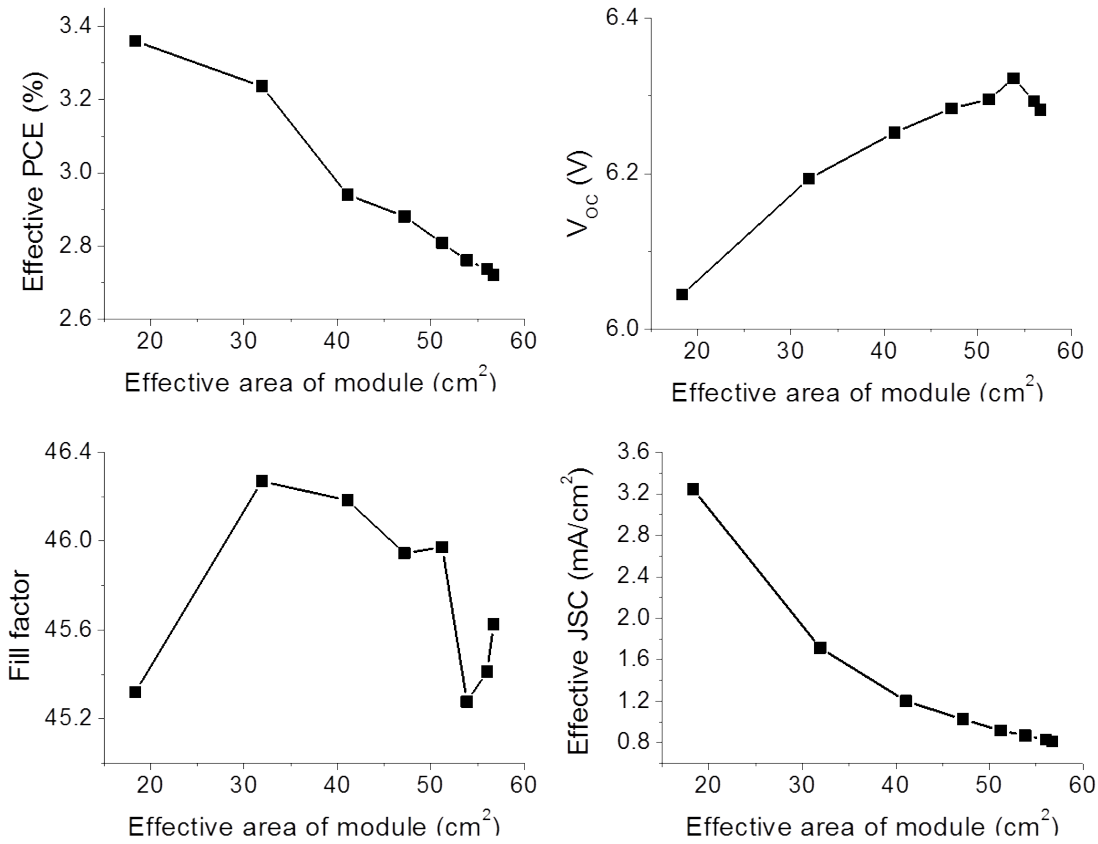
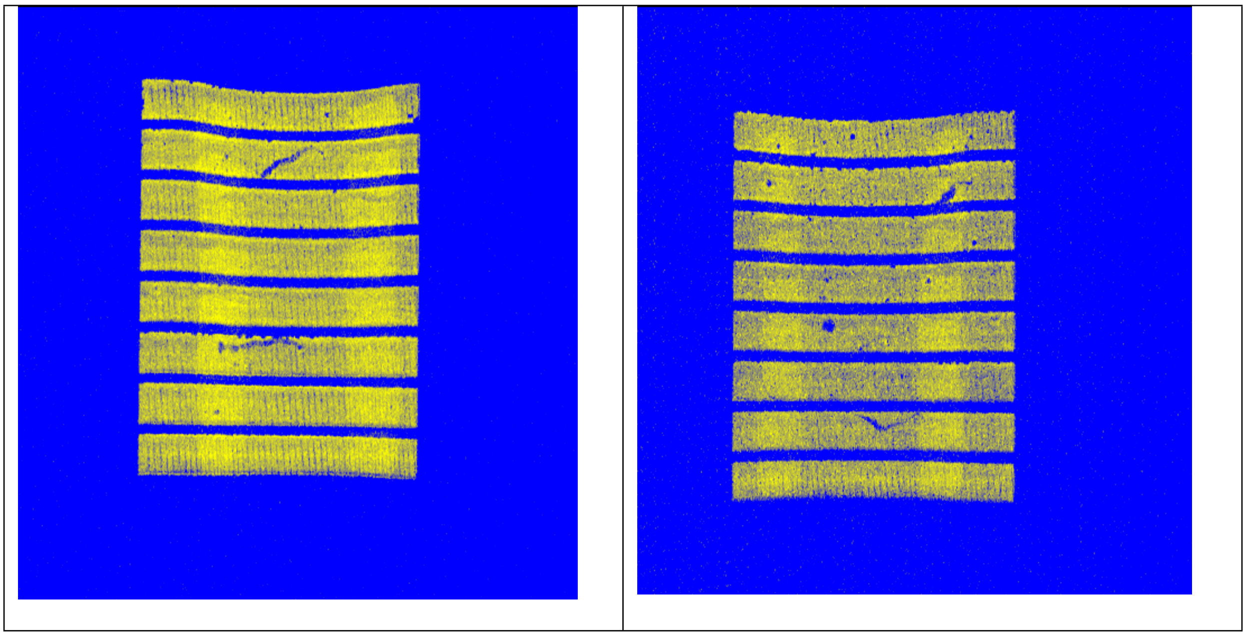


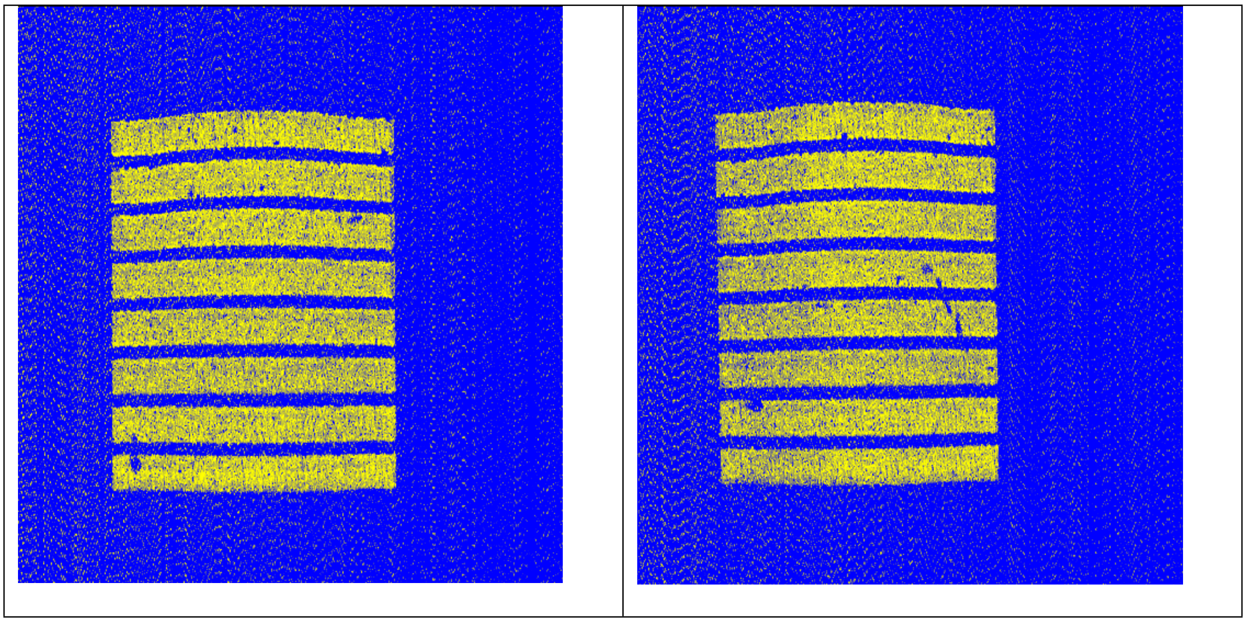
Figure SI-2(b) Effect of module footprint ('effective area') on (top left) Effective PCE (top right) V_{OC} (bottom left) Effective JSC and (bottom right) FF.

SI-3 Repeated Laser Beam induced current (LBIC) data of Modules A-D showing the reproducibility of data from section 3.2.

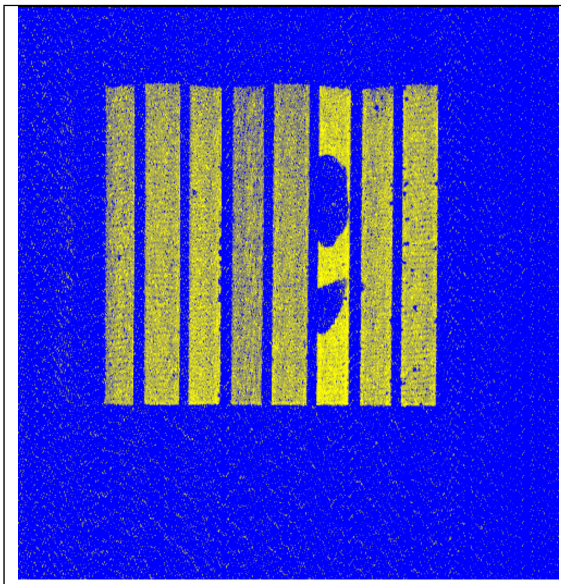
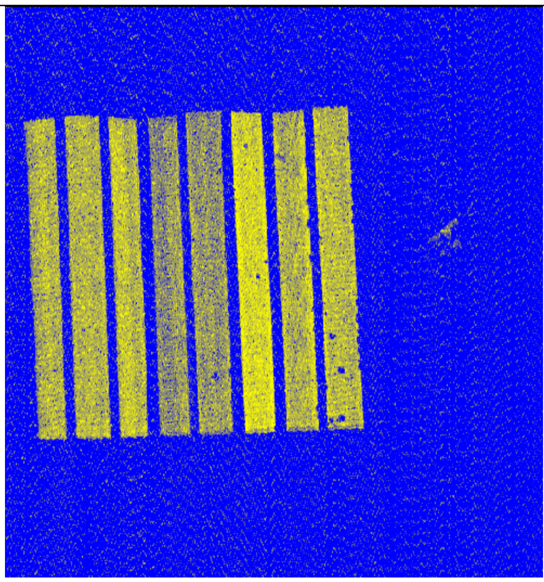
Module A



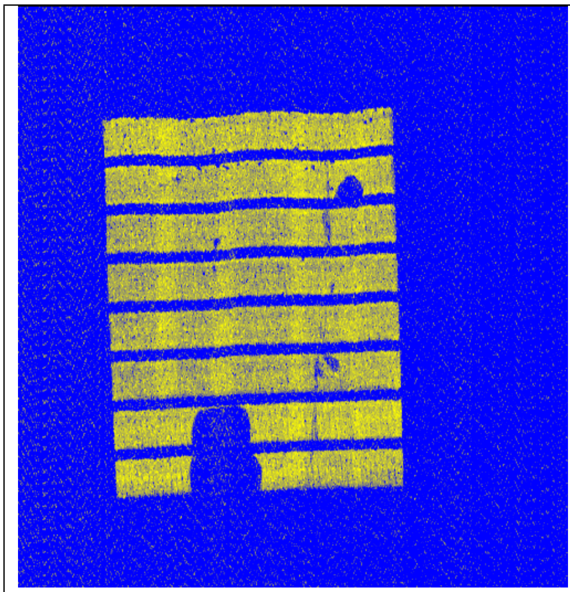
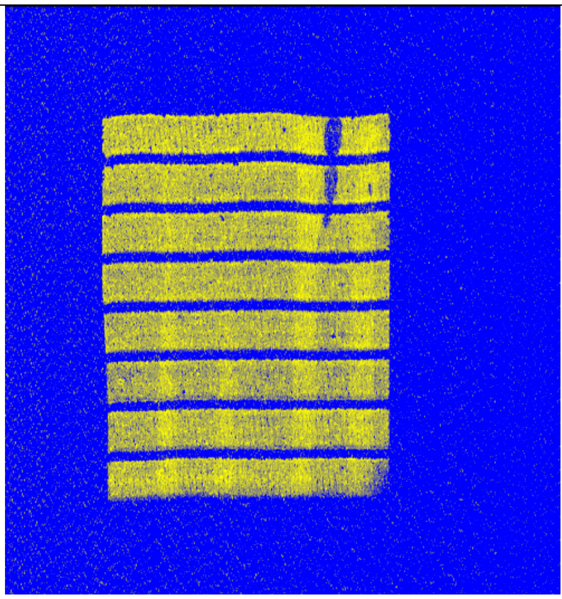
Module B



Module C

Module D

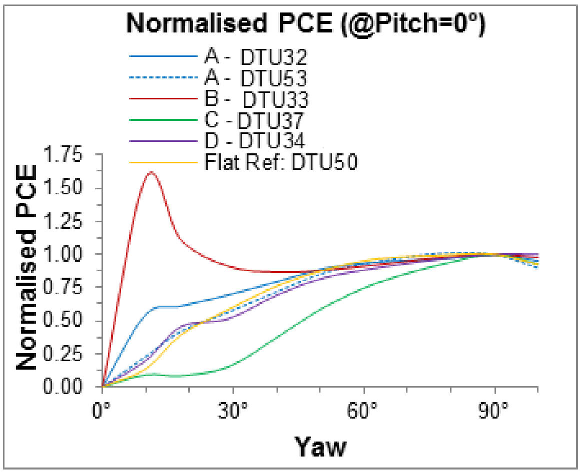
	

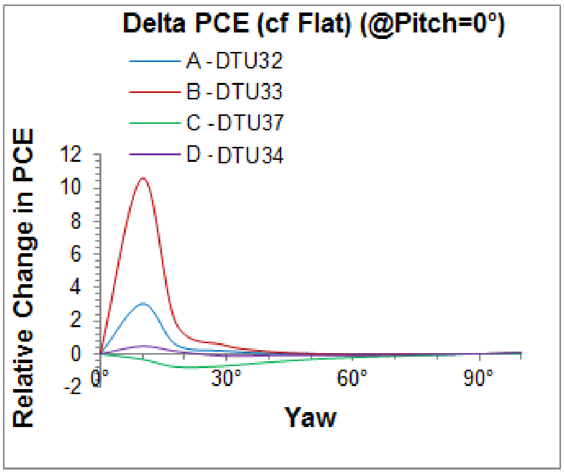
SI-4 Repeated indoor angular tests of Modules A-D, demonstrating the reproducibility of data from section 3.3.

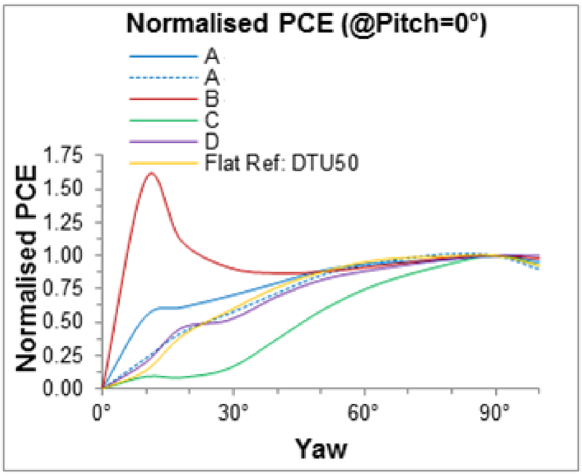
To confirm the reproducibility of the data in section 3.3 („Indoor angular testing"), two additional sets of modules (module sets 2 &3) were tested. For the Module set 2, a variety of yaw and pitch positions were used. For Module set 3, only yaw is varied.

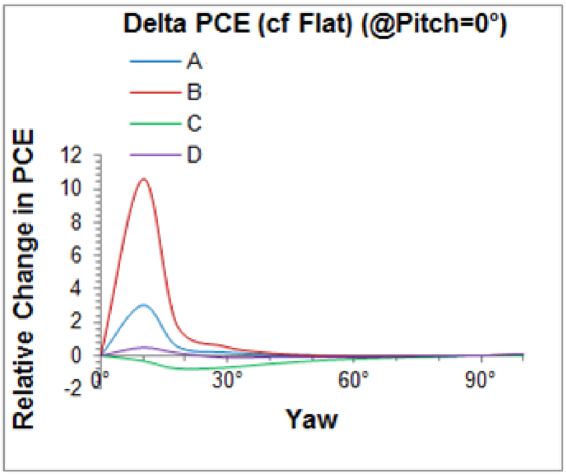
Module set 2

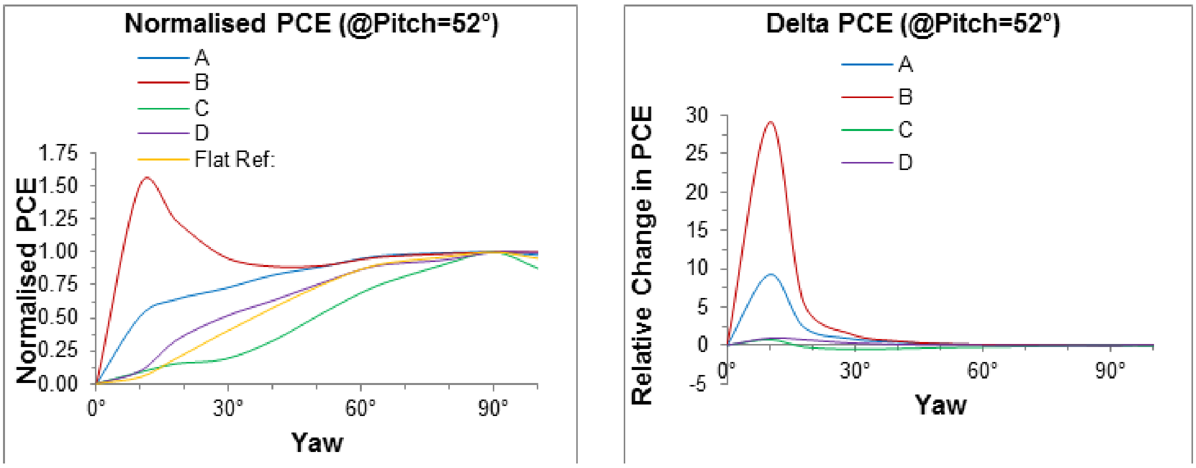
The overall trends are the same as in the manuscript. The best improvements in efficiency are seen when tilt in both directions is conducted. The relative change of Module B is greater than reported in the manuscript, which is due to a slightly poorer performing flat reference module (PCE=1.5%).





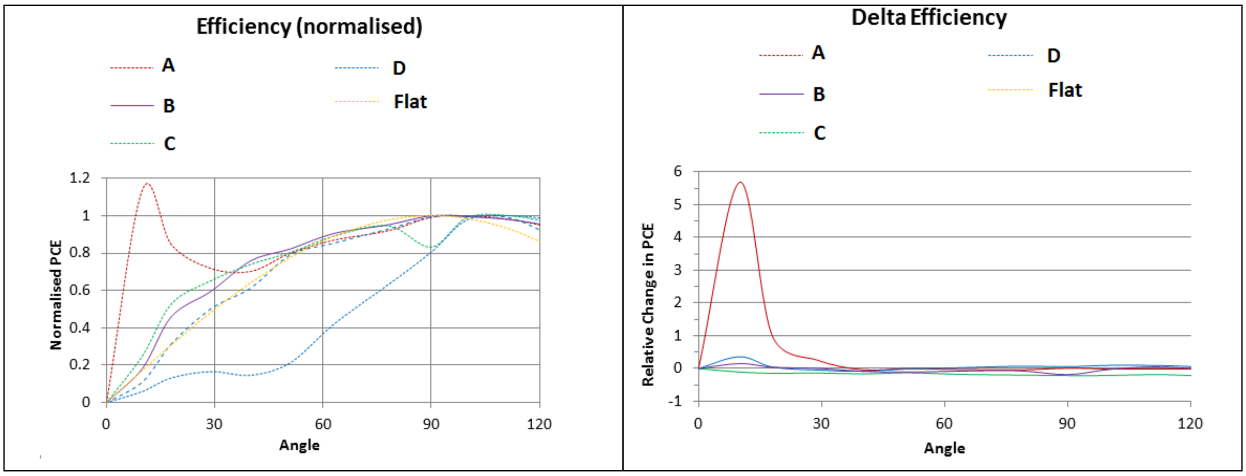






Module set 3

These modules were only measured with a pitch fixed at 0° (normal to the module in elevation).



SI-5 Raytracing simulation of enhancement in performance

a. Overview of raytracing simulation

The simulation is used to calculate the relative in-coupling efficiency of a flat versus corrugated module. In this particular simulation, light propagation is modelled using Thin Film Multiple Reflection (TFMR) models as reported previously by the group in [*J. Appl. Phys.* 116, 10 (2014): 103103 *J. Phys. D: App. Phys.* 45, no. 12 (2012): 125102.] However, the corrugated structure is broken up into a series of elements (n) and each element is assigned a different angle and length (see figure SI-5a). The Fresnel reflection at each element is calculated by the considering the individual segment angle and the angle of the incident light (which is varied from 90° to 0°).

The total in-coupling efficiency is then calculated based on the proportion of light incident on each segment length and the angle of this segment. For the results section, we used $n = 25$. The simulation was done with using all wavelengths in AM1.5G.

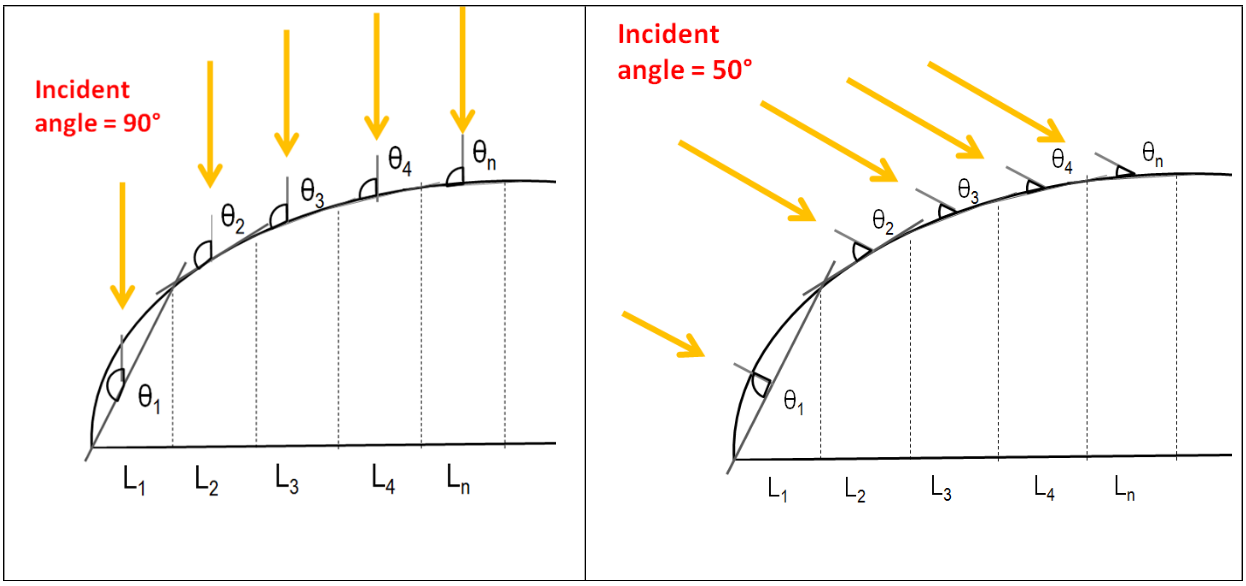


Figure SI-5a Schematic of the device used for simulation showing how the angles and lengths are calculated at incident angle (‘yaw’) =50° (i.e. under normal incidence) and (right) at incident angle =50°. The program simulates the in-coupling of light into a flat or corrugated module, which is the major loss mechanism to affect the photocurrent and efficiency.

Results

The performance of the flat module and Module B has been studied as a function of incident angle, with the data shown in Figure SI-5b. Currently, it is only possible to calculate the in-coupling efficiency (ICE) using the ray tracing simulation, which is determined by the reflection at the front interface. However, we know that this loss is the dominant loss mechanism assuming the active layer is kept constant, as reported in [*J. Phys. D: App. Phys.* 45, no. 12 (2012): 125102]. The simulated data in Figure SI-5b correlates well with the experimental data shown in section 3.3 of the paper, with the overall trends of the flat module and Module A overlaying close with one another. An enhancement of 9.3x is seen at an incident angle of 10°, which matches closely the enhancement seen in section 3.3 (10x at an ‘incident angle’/yaw of 15°). It is also important to note that the simulation confirms that the enhancement in performance is predominantly due to the macro-scale geometry of the module leading to reduced Fresnel reflection, rather than nanoscale or morphological changes.

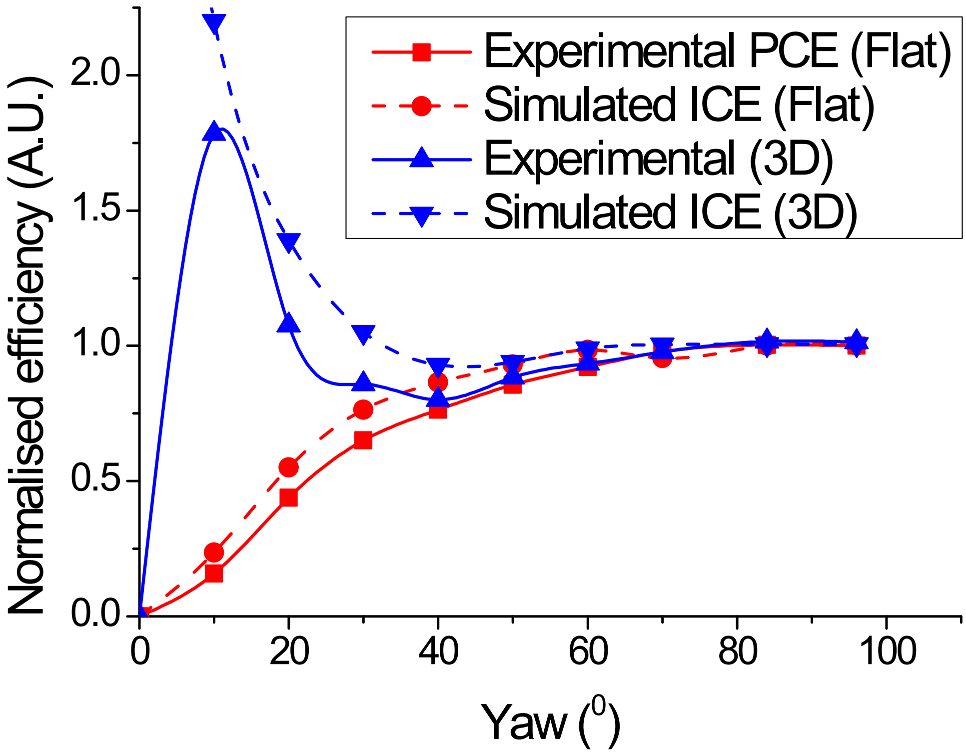


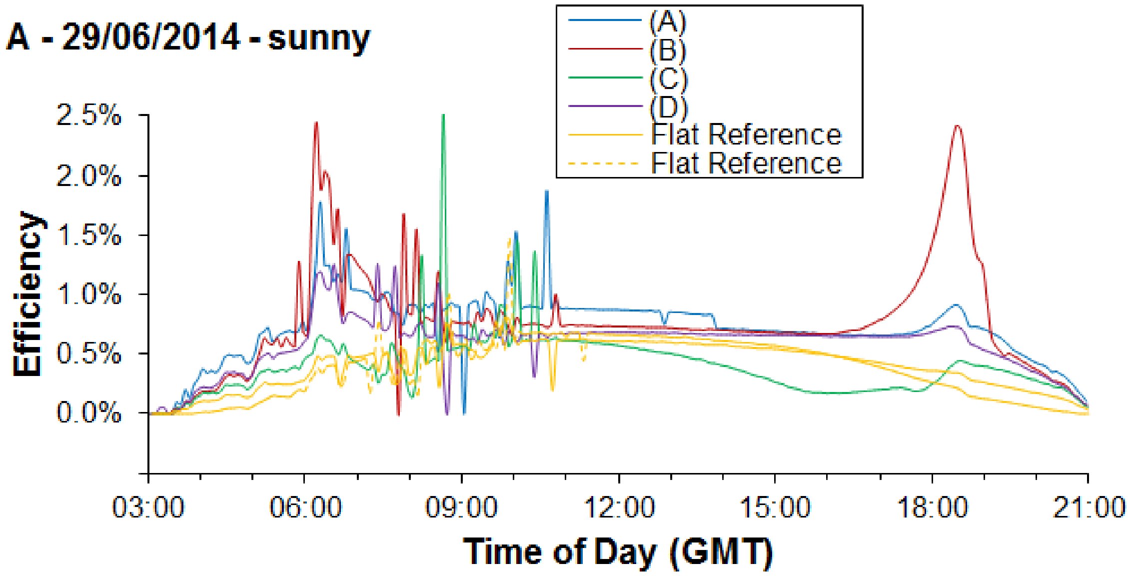
Figure SI-5b Experimental PCE data of the flat and Module A (pitch= 0°) as a function of yaw. Overlaid is the simulated in-coupling efficiency (ICE) of the flat module and Module A.

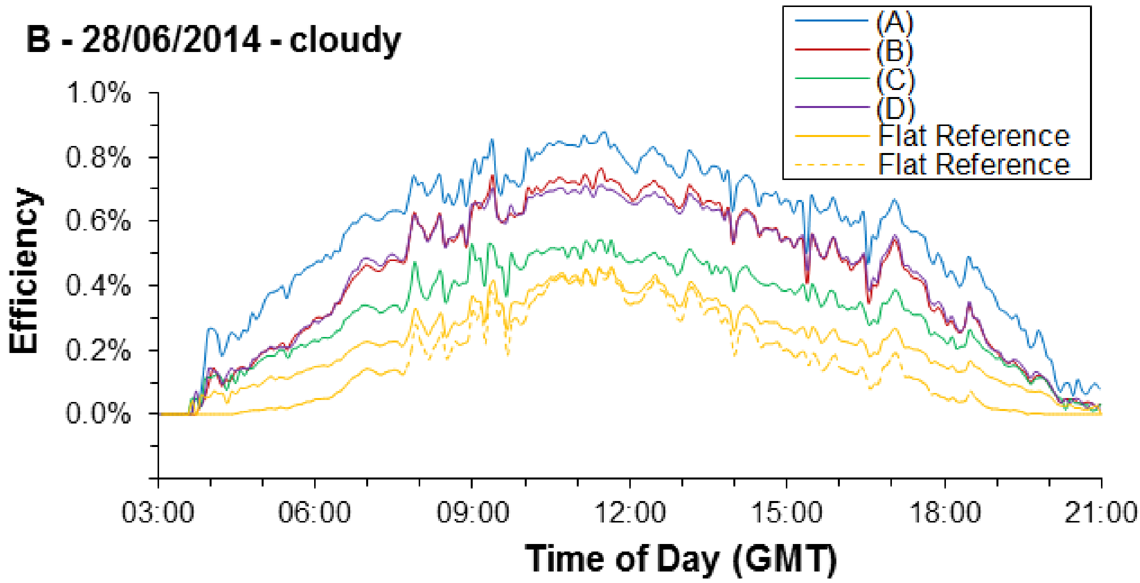
SI-6 Repeated diurnal outdoor measurements of Modules A and B showing the reproducibility of data from section 3.4.

To confirm the reproducibility of the outdoor data, additional data is included in the supplementary information. This is taken from two different batches of modules.

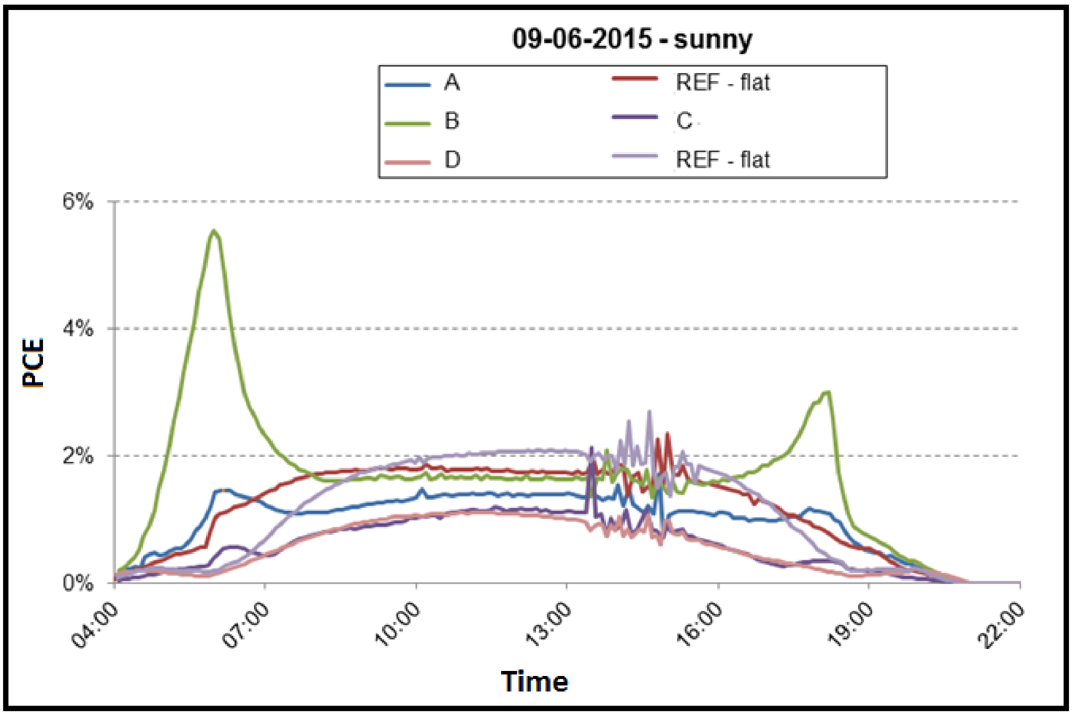
Batch 1 – Summer 2014

This data was undertaken in summer 2014 and is consistent with the reports in the paper. For Batch 1, the efficiencies of the modules is slightly lower than the paper, but is consistent with other outdoor monitoring reports of the 'freeOPV' modules supplied from DTU (see reference [16] in the paper).





<u>**Batch 2 – Summer 2015**</u>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A
B
D
REF - flat
C -
REF - flat
6%
4%
2%
0%
PCE
04:00
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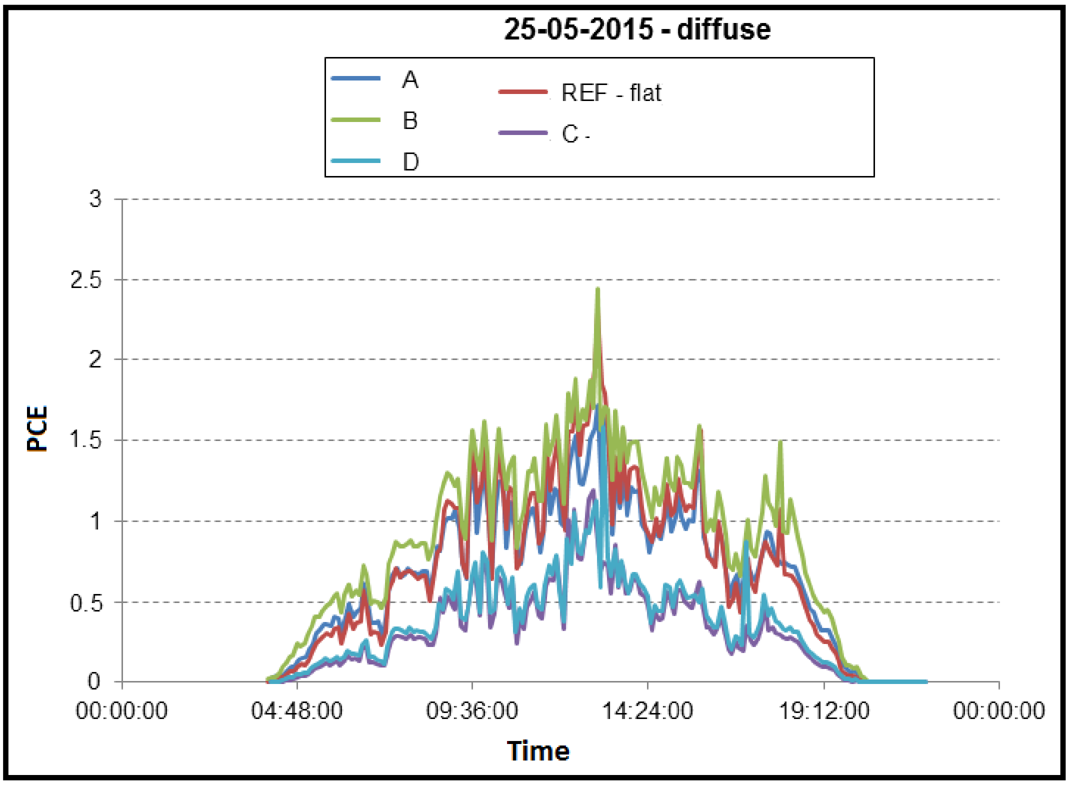
Time


25-05-2015 - diffuse
A
B
D
REF - flat
C -
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2.5
2
1.5
1
0.5
0
PCE
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Time