Supporting Information

Long term outdoor performance evaluation of printed semitransparent organic photovoltaic modules for BIPV/BAPV applications

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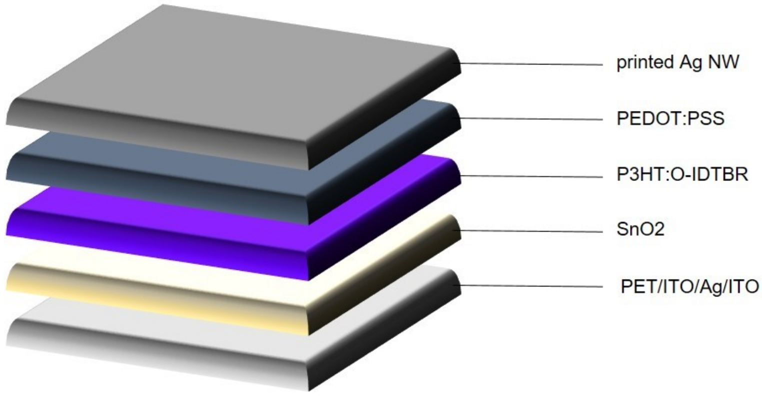


Figure S1: Stack layout of individual cells used for manufacturing printed semitransparent OPV modules.

Figure S2: Schematic layout of the module for modules area of < 64cm^2. The module consists of 12 individual cells connected in a series. The total area of the individual cells within the modules is around 4.93 cm^2. This translates to a total active area of around 59.2 cm^2 whereas the total area of the module including bus bars and electrical interconnection area stands at 64 cm^2. a) Red lines indicate P1 laser scribes, b) Blue lines indicate P2 laser scribes and c) Green lines indicate P3 laser scribes.

The large area modules that are monitored outdoors are made from a similar module layout, but the number of cells increased from 12 to 20 within the module and with the total area of the individual cells being 9.75cm^2. This results in a total active area of the OPV module, which is 195 cm^2 in total, whereas the total module area including cell interconnections and bus bars stood at 210 cm^2.

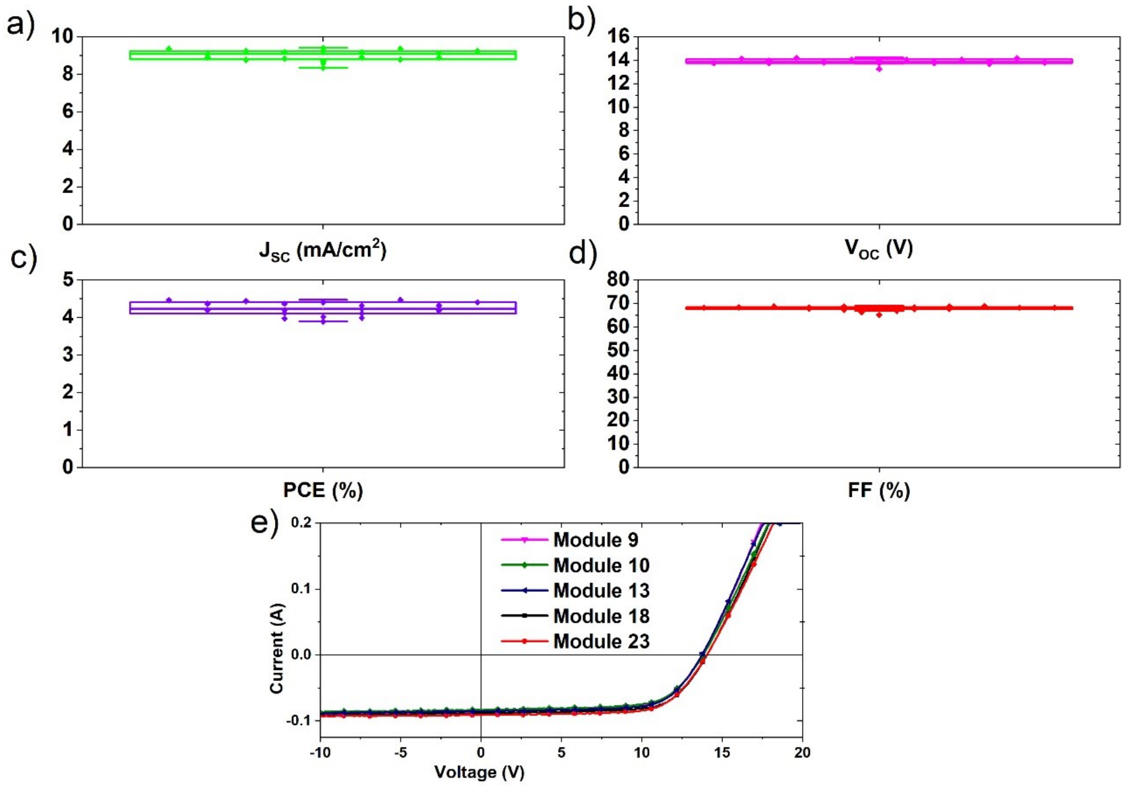


Figure S3: Initial performance (t_0) of the R2R manufactured OPV modules under STC (25°C module temperature, 1000W/m^2 light intensity & AM1.5G spectrum). a) Short-Circuit Current Density (J_{SC}), b) Open-Circuit Voltage (V_{OC}), c) Power conversion efficiency (PCE), d) Fill Factor (FF), and e) current-voltage (I-V) characterization of five randomly selected modules (module batch_A) from the production run.

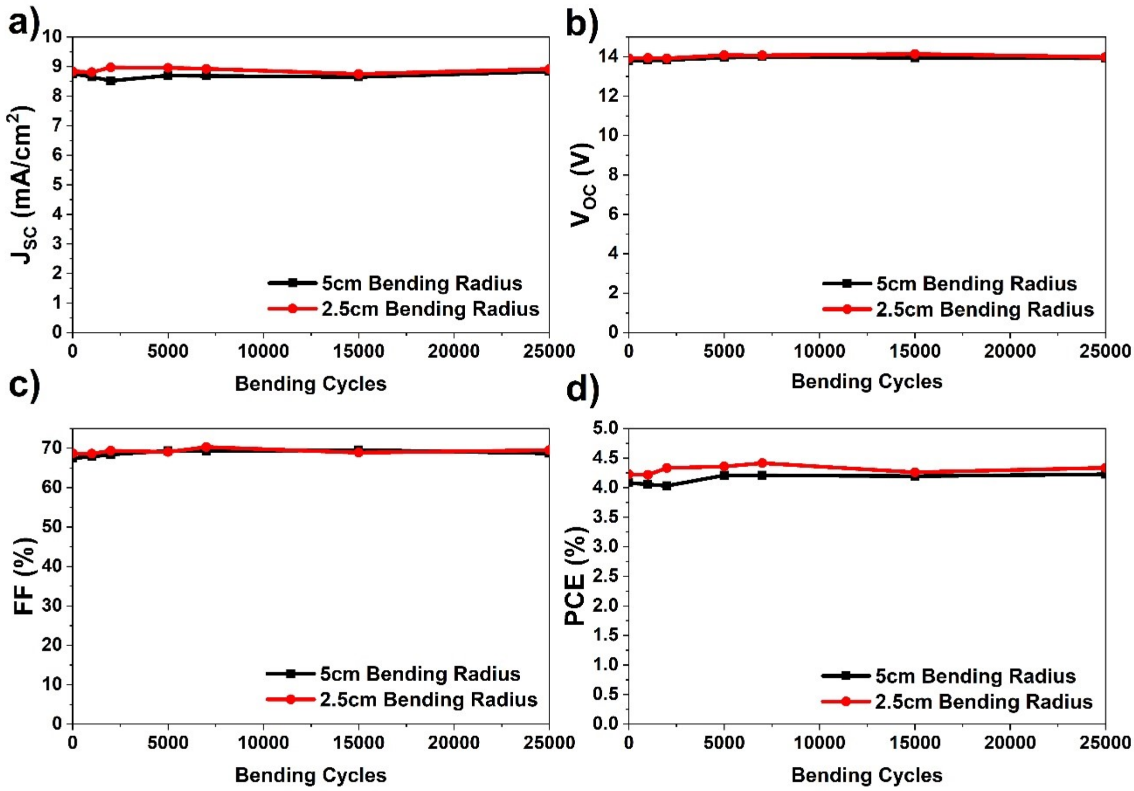


Figure S4: Key electrical parameters of the OPV modules over the bending radius of 2.5cm (red lines) and 5cm (black lines) respectively for 25000 bending cycles.

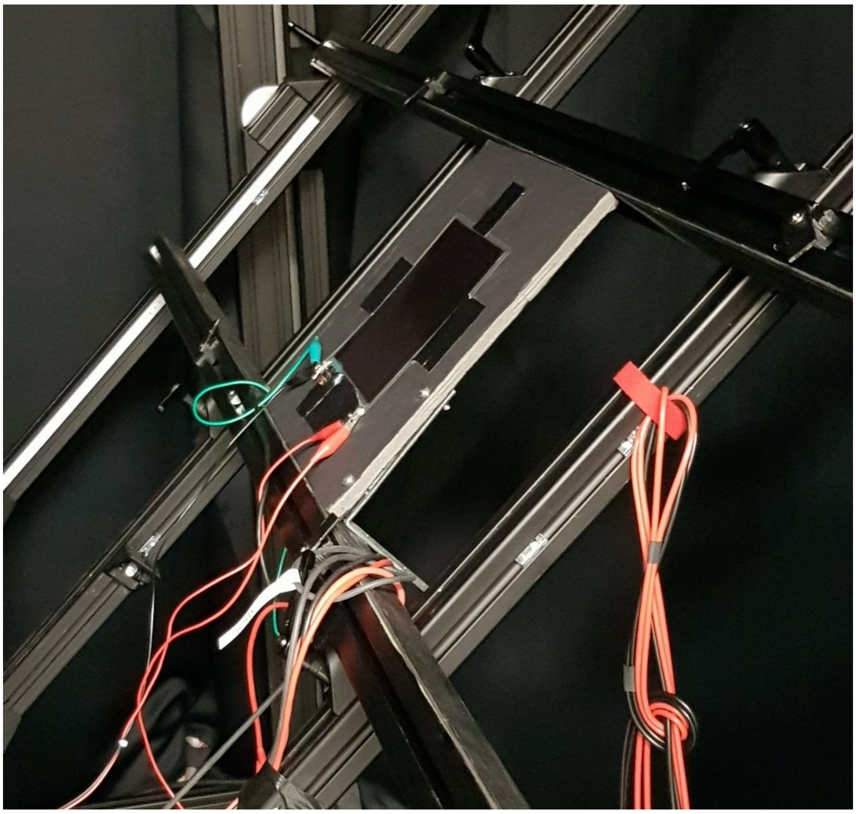


Figure S5: Indoor angle-dependent current-voltage (I-V) characterization of OPV and m-Si modules carried out using a flasher light source at a constant temperature of 25°C. The module angle was varied in increments of 5°, ranging from 0° to 80° between the surface normal of the module and the flasher.

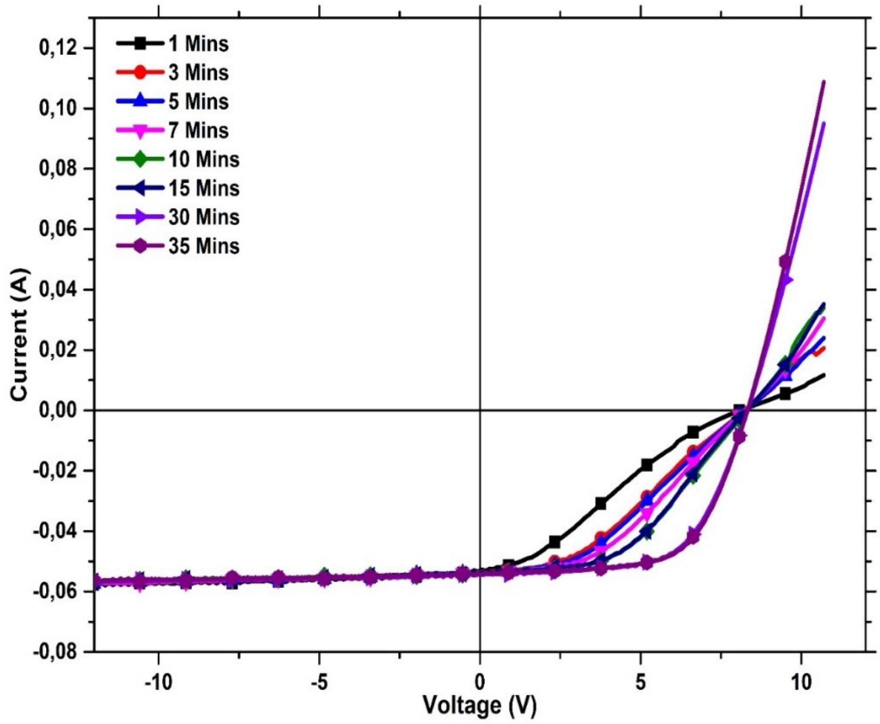


Figure S6: Effect of light soaking on the I-V evaluation of OPV modules when measured under 1 sun conditions using a class AAA solar simulator (LOT Quantum Design).

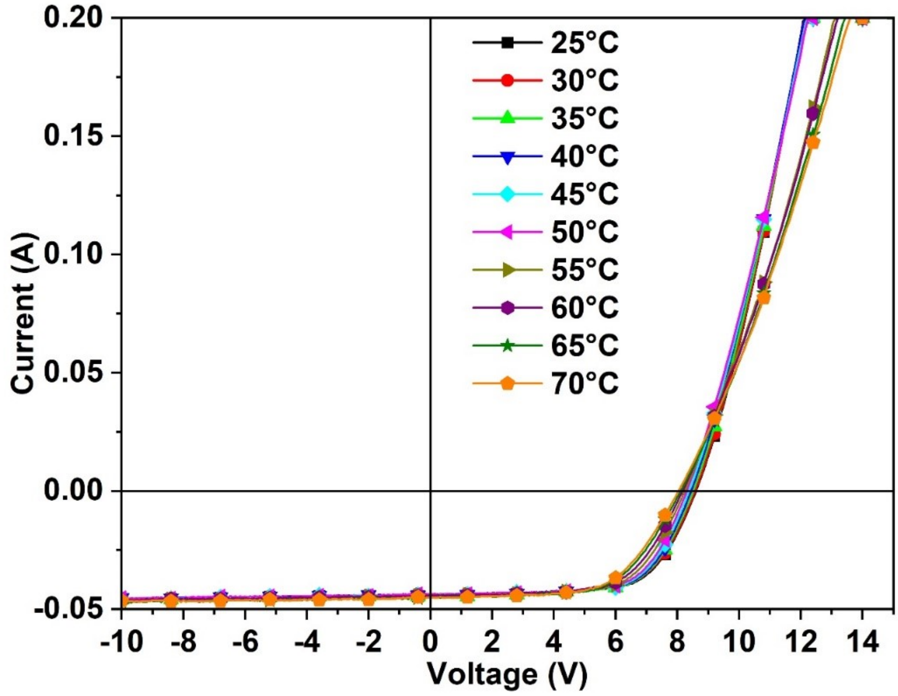


Figure S7: Temperature-dependent current-voltage (I-V) characterization of OPV module over the temperature range of 25°C-70°C.

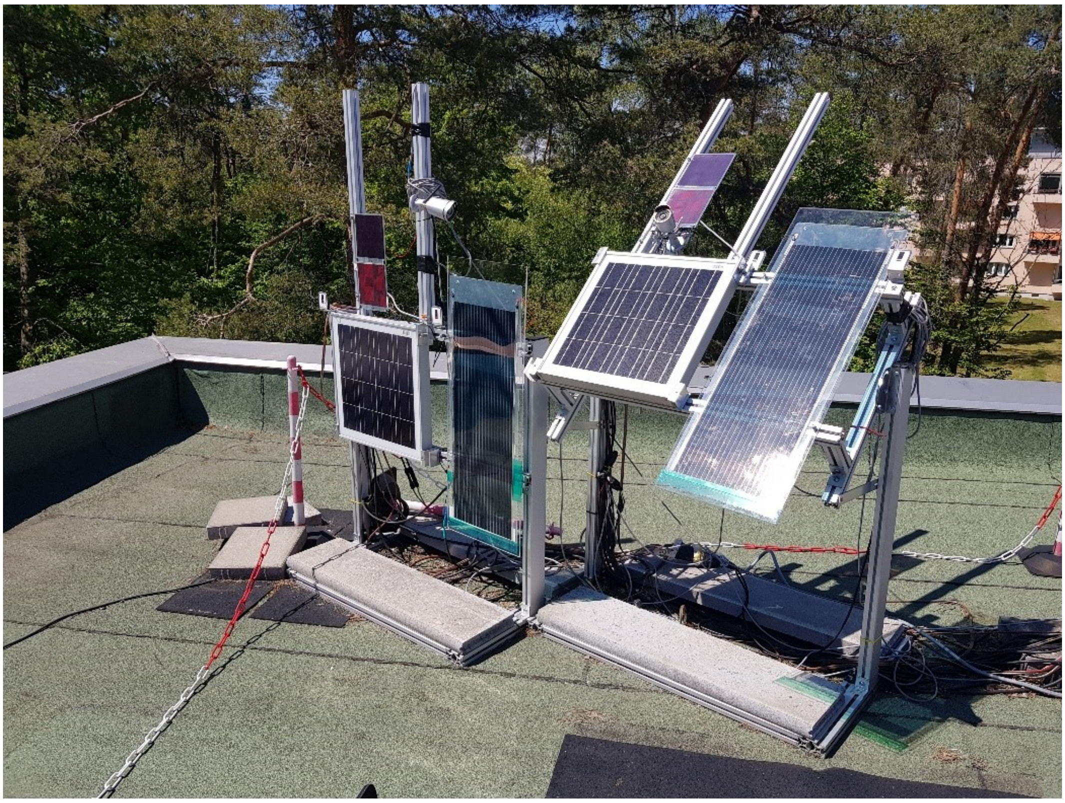


Figure S8: Outdoor monitoring setup at the rooftop of Hi-ERN building in Erlangen, Germany (49.5897°N and 11.0120°E). Both OPV and m-Si modules were mounted at an inclination of 45° and 90° with respect to the horizontal facing south.

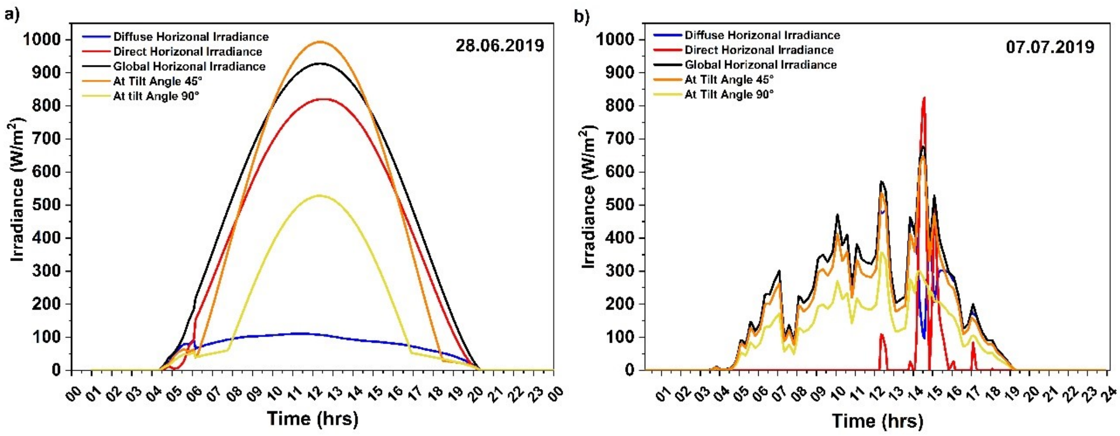


Figure S9: Variation in components of incident solar irradiance for sunny (28.06.2019) and overcast (07.07.2019) days at the site. The plots show the solar irradiance components for a) 45° inclination on 28.06.2019, b) 90° inclination on 28.06.2019, c) 45° inclination on 07.07.2019, and d) 90° inclination on 07.07.2019. The weather data was obtained from Solcast.

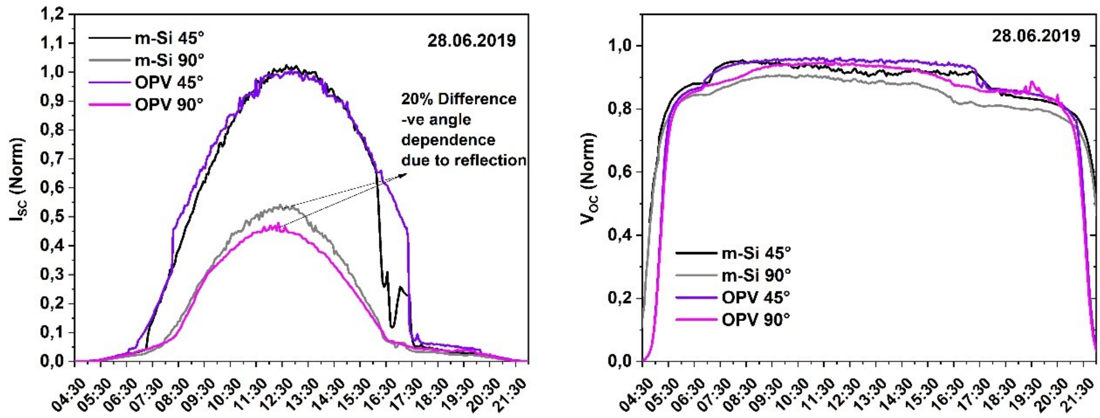
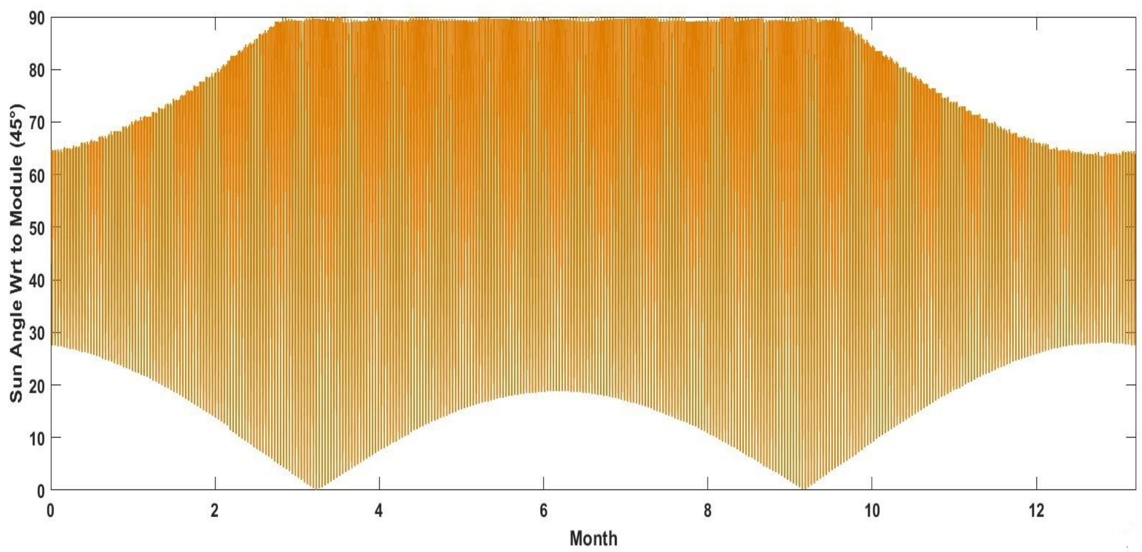


Figure S10: Outdoor monitored electrical parameters of OPV and m-Si modules on a sunny day. Short circuit current (left) and Open circuit voltage (Right). The measured outdoor ISC and VOC values are normalized to their STC values. The ISC limitations arising from reflection losses at the module and air interface are pronounced for the OPV module mounted at 90° inclination.



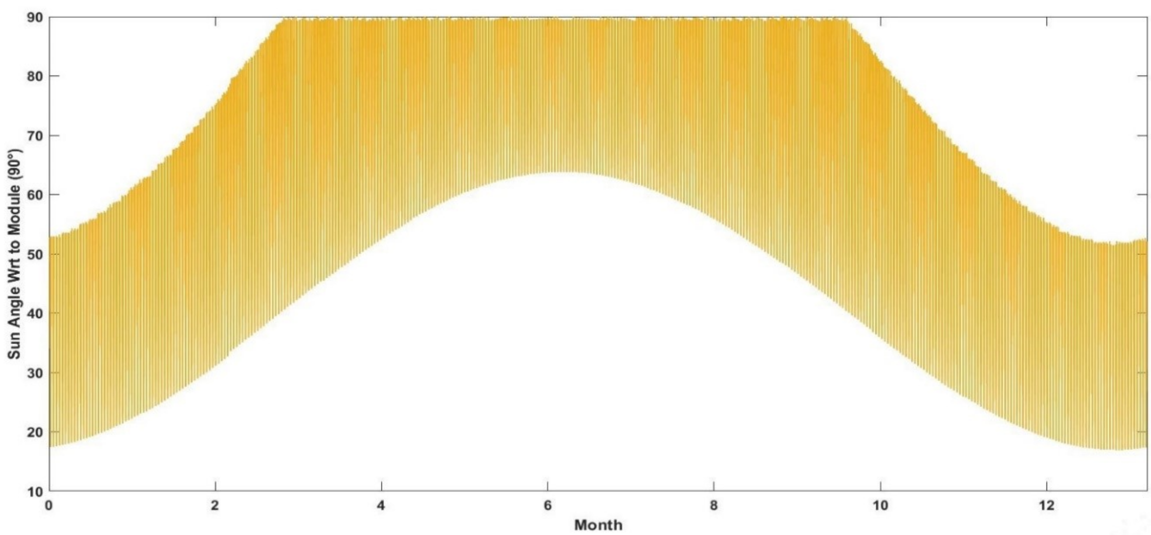


Figure S11: Yearly variations in the solar elevation angle with respect to the modules at both 45° (top) and 90° (bottom) inclinations.

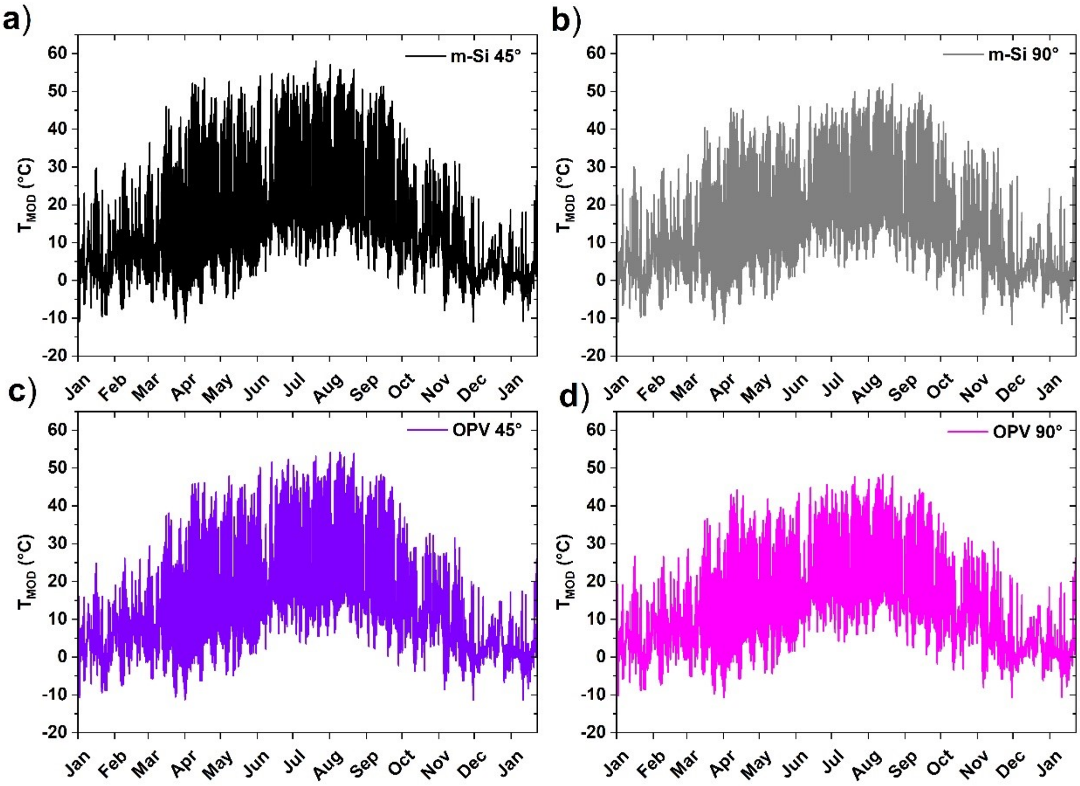


Figure S12: Module temperatures (T_{MOD}) observed over the year-long outdoor monitoring. a) m-Si 45°, b) m-Si 90°, c) OPV 45° and d) OPV 90°.

Figure S13: Visual inspection of the modules OPV 45° (left) and OPV 90° (right) after outdoor exposure.

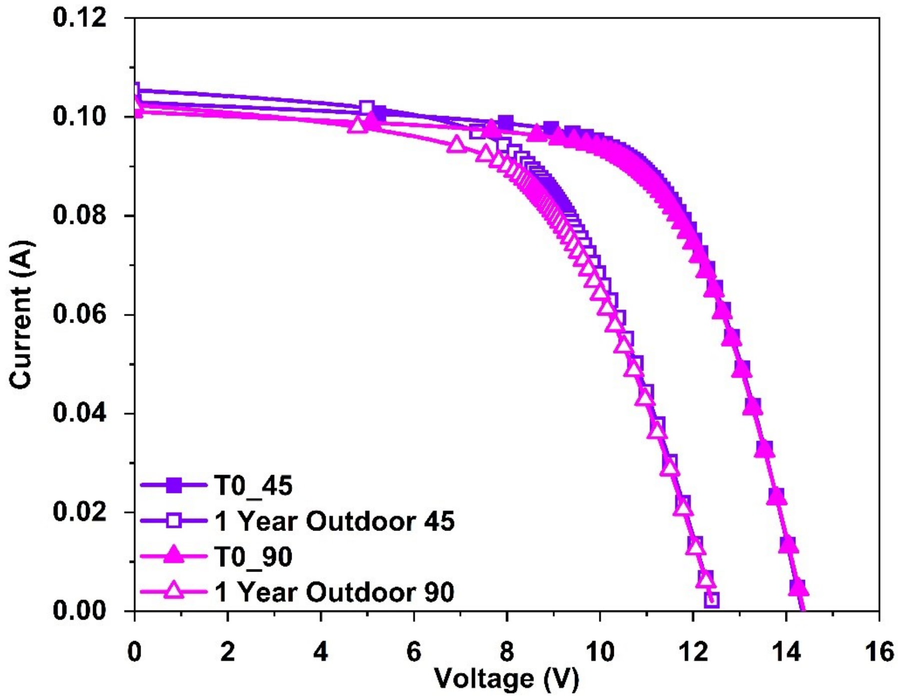


Figure S14: Current-Voltage characteristics of OPV modules (at 45° and 90° inclination angles) before (solid symbols) and after one year of outdoor exposure (open symbols).

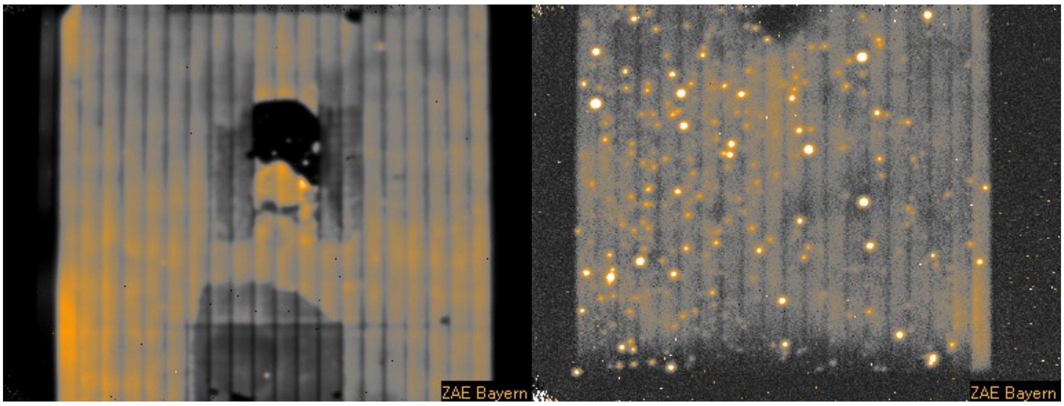
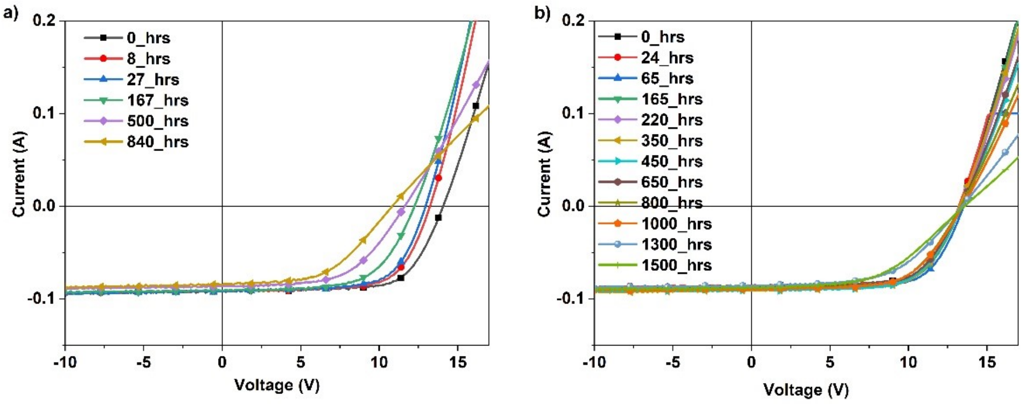


Figure S15: Dark lock-in thermography (DLIT) images of OPV modules before and after one year of outdoor operation, demonstrating the development of localized shunts.



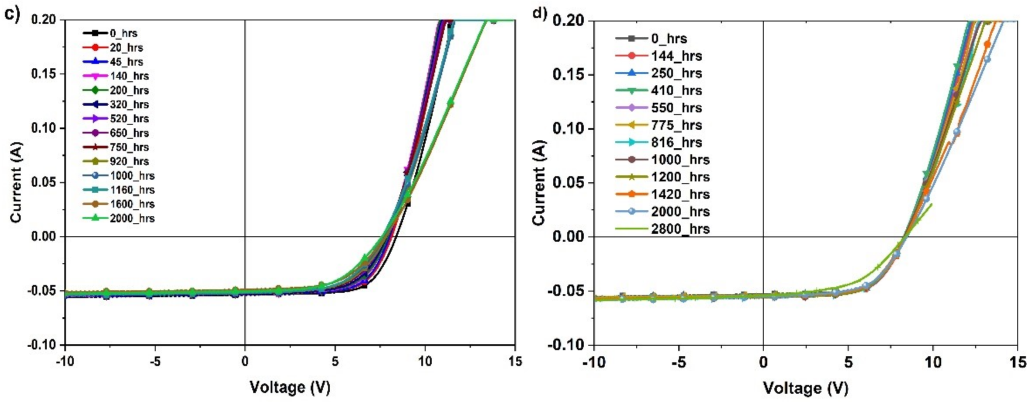


Figure S16: Temporal evolution of current-voltage (I-V) characteristics during accelerated lifetime (ALT) testing of module batches A and B. a) I-V evolution of module batch_A under ISOS-L2 conditions (1000W/m² & 65°C module temperature), b) I-V evolution of module batch_A under ISOS-D3 conditions (65°C module temperature & 85%RH), c) I-V evolution of lifetime optimized modules (module batch_B) under ISOS-L2 conditions (1000W/m² & 65°C module temperature) and d) I-V evolution of lifetime optimized modules (module batch_B) under ISOS-D3 conditions (65°C module temperature & 85%RH).

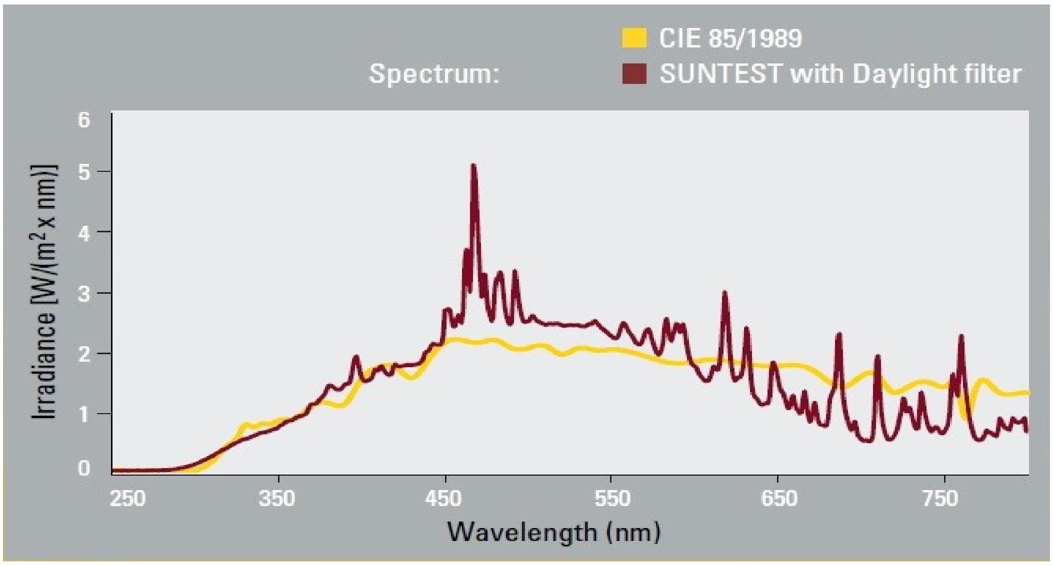


Figure S17: Spectral distribution of the light source used for accelerated lifetime testing (ALT) under ISOS-L2 conditions.

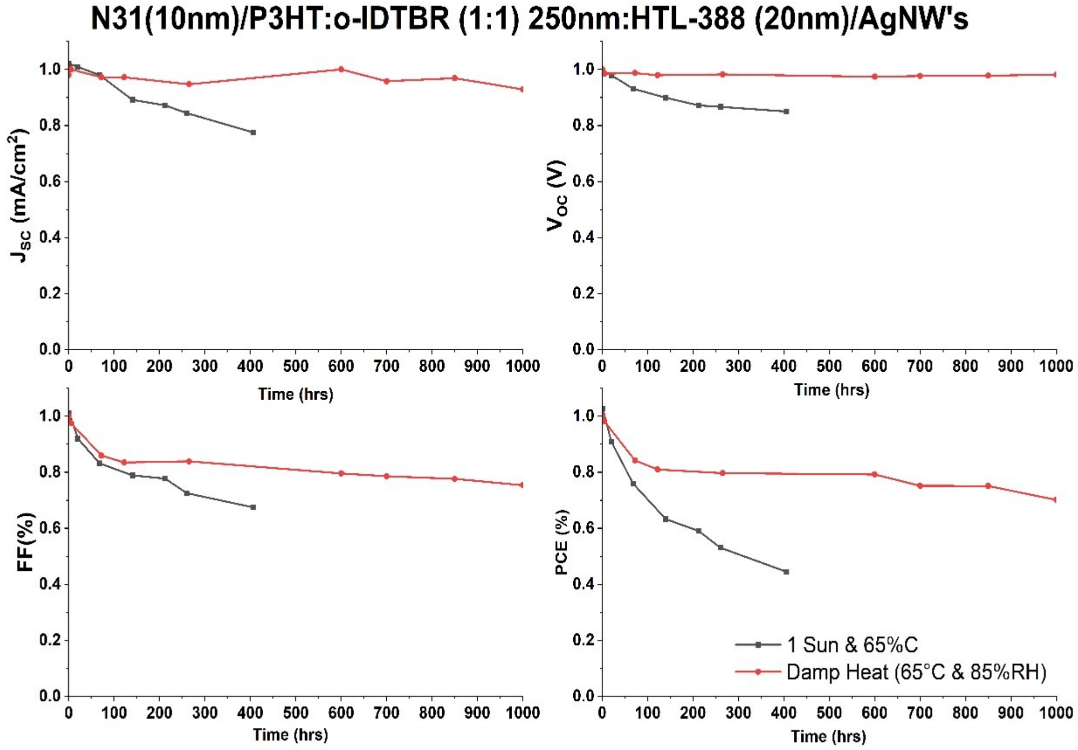


Figure S18: ALT tests of modules based on PAL with Donor:Acceptor ratio of 1:1 and with thin HTL (20 nm). Time traces of the key PV performance indicators, normalized to their respective t_0 values (a) short-circuit current density (J_{SC}), b) open-circuit voltage (V_{OC}), c) Fill Factor (FF), and d) power conversion efficiency (PCE). Black line indicates accelerated lifetime testing (ALT) under ISOS-L2 conditions (1000 W/m^2 light intensity and 65°C module temperature). The red lines indicate accelerated lifetime testing (ALT) under ISOS-D3 conditions (65°C & 85%RH).

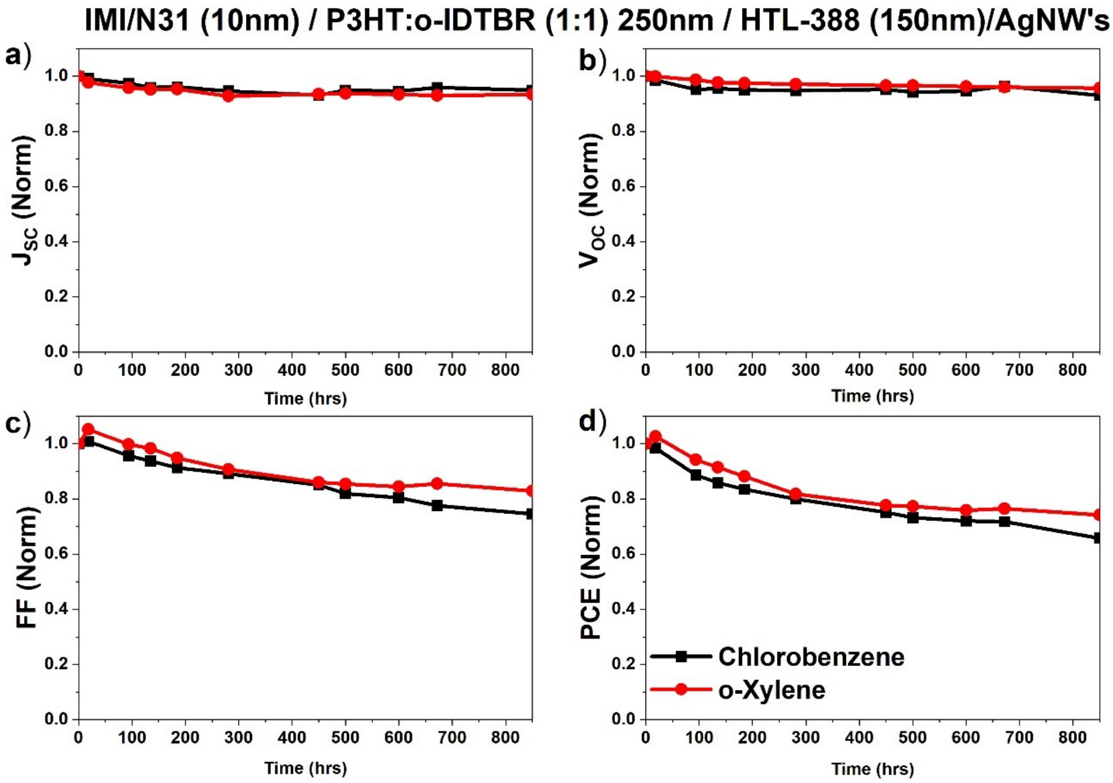


Figure S19: ALT tests of modules based on PAL with Donor:Acceptor ratio of 1:1 and with thick HTL (150nm) under ISOS-L2 conditions (1000 W/m^2 light intensity and 65°C module temperature). Time traces of the key PV performance indicators, normalized to their respective t_0 values (a) short-circuit current density (J_{SC}), b) open-circuit voltage (V_{OC}), c) Fill Factor (FF), and d) power conversion efficiency (PCE), during ALT. Black lines: PAL processed using chlorobenzene: 4-bromoanisole solvent blend, Red lines: PAL processed using o-Xylene: 1-methyl naphthalene solvent.

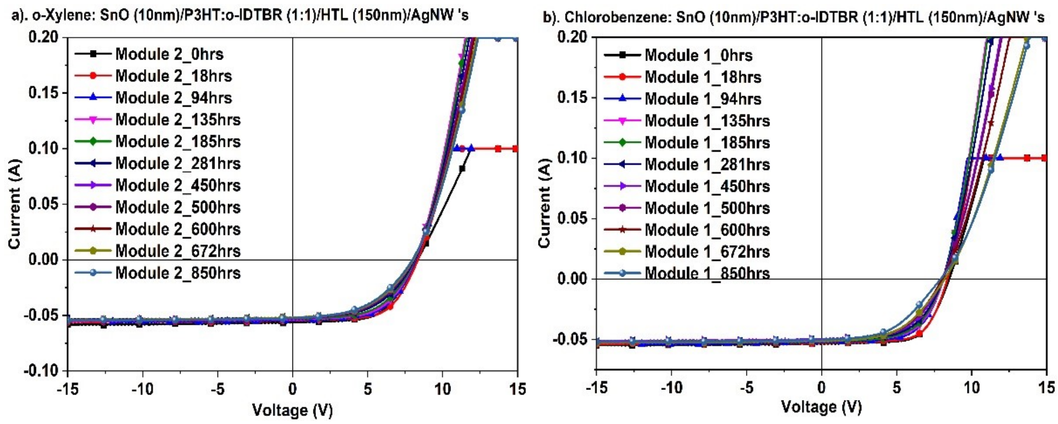


Figure S20: Temporal evolution of the current-voltage (I-V) characteristics during the accelerated lifetime (ALT) tests of OPV modules under ISOS-L2 conditions (1000W/m^2 & 65°C). a) PAL processed from o-xylene solvent and b) PAL processed from chlorobenzene: 4-bromoanisole solvent.

Table S1: Laboratory light intensity dependent electrical parameters of m-Si and OPV modules.

Irradiance (W/m$_2$)	I_{SC} (A)	V_{OC} (V)	F.F (%)	P_{OUT} (W)	Efficiency (%)	I_{SC} (A)	V_{OC} (V)	F.F (%)	P_{OUT} (W)	Efficiency (%)
	m-Si	**m-Si**	**m-Si**	**m-Si**	**m-Si**	**OPV**	**OPV**	**OPV**	**OPV**	**OPV**
1000	3.97	10.05	75.90	30.35	12.11	0.10	14.40	68.20	0.98	4.68
996.19	3.95	10.05	75.95	30.24	12.11	0.10	14.40	68.25	0.98	4.68
984.8	3.90	10.05	76.01	29.87	12.10	0.10	14.40	68.32	0.97	4.68
965.93	3.83	10.03	76.23	29.33	12.12	0.10	14.40	68.56	0.95	4.70
939.69	3.72	10.02	76.45	28.58	12.14	0.09	14.39	68.86	0.93	4.71
906.3	3.59	9.99	76.76	27.62	12.16	0.09	14.37	69.23	0.90	4.73
866.03	3.43	9.96	77.14	26.44	12.18	0.09	14.35	69.57	0.86	4.75
819.15	3.25	9.93	77.61	25.07	12.21	0.08	14.32	69.98	0.82	4.77
766.04	3.04	9.88	78.15	23.51	12.25	0.08	14.28	70.45	0.77	4.79
707.1	2.80	9.83	78.71	21.75	12.27	0.07	14.23	70.95	0.71	4.81
642.79	2.55	9.77	79.30	19.80	12.29	0.06	14.17	71.47	0.65	4.82
573.57	2.28	9.70	79.97	17.70	12.31	0.06	14.11	72.05	0.58	4.84
500	1.98	9.61	80.62	15.42	12.31	0.05	14.03	72.62	0.51	4.85
422.62	1.68	9.50	81.32	13.00	12.28	0.04	13.94	73.29	0.43	4.87
342.02	1.36	9.38	81.89	10.47	12.21	0.03	13.81	73.87	0.35	4.87

259	1.03	9.24	82.21	7.85	12.10	0.03	13.66	74.17	0.26	4.84
173	0.69	9.08	82.28	5.18	11.95	0.02	13.46	74.35	0.17	4.79
94	0.38	8.86	82.04	2.76	11.72	0.01	13.23	74.15	0.09	4.72

Table S2: Laboratory angle dependent electrical parameters of m-Si and OPV modules.

Angle (°)	**I_{SC} (A)**	**V_{OC} (V)**	**F.F (%)**	**P_{OUT} (W)**	**Efficiency (%)**	**I_{SC} (A)**	**V_{OC} (V)**	**F.F (%)**	**P_{OUT} (W)**	**Efficiency (%)**
	m-Si	**m-Si**	**m-Si**	**m-Si**	**m-Si**	**OPV**	**OPV**	**OPV**	**OPV**	**OPV**
0	3.97	10.05	75.90	30.35	12.11	0.10	14.40	68.20	0.98	4.68
5	3.96	10.05	75.94	30.27	12.12	0.10	14.41	68.26	0.97	4.66
10	3.91	10.05	76.02	29.94	12.13	0.10	14.39	68.33	0.96	4.66
15	3.84	10.03	76.19	29.38	12.14	0.10	14.39	68.48	0.94	4.66
20	3.73	10.02	76.49	28.64	12.16	0.09	14.38	68.76	0.92	4.68
25	3.59	10.00	76.83	27.68	12.19	0.09	14.36	69.09	0.89	4.68
30	3.43	9.98	77.28	26.52	12.22	0.09	14.33	69.49	0.85	4.69
35	3.24	9.95	77.76	25.14	12.25	0.08	14.31	69.96	0.81	4.70
40	3.03	9.91	78.30	23.56	12.27	0.08	14.28	70.48	0.76	4.71
45	2.79	9.86	78.91	21.76	12.28	0.07	14.25	71.07	0.70	4.72
50	2.53	9.82	79.48	19.78	12.28	0.06	14.20	71.62	0.63	4.71
55	2.25	9.76	80.14	17.63	12.27	0.06	14.13	72.18	0.56	4.69

60	1.95	9.66	80.74	15.28	12.19	0.05	14.04	72.73	0.49	4.64
65	1.64	9.56	81.43	12.81	12.09	0.04	13.93	73.33	0.40	4.57
70	1.32	9.44	81.90	10.19	11.89	0.03	13.77	73.73	0.32	4.42
75	0.98	9.30	82.33	7.52	11.58	0.02	13.58	74.12	0.23	4.20
80	0.64	9.12	82.59	4.80	11.07	0.01	13.36	74.29	0.14	3.78

Table S3: Recorded and simulated monthly specific energy yield (Y_{FM}) of both OPV and m-Si modules and their respective outdoor door inclinations over the course of outdoor monitoring.

Month	**Measured Y_{FM} m-Si 45° (Wh/W_P)**	**Measured Y_{FM} m-Si 90° (Wh/W_P)**	**Measured Y_{FM} OPV 45° (Wh/W_P)**	**Measured Y_{FM} OPV 90° (Wh/W_P)**	**Simulated Y_{FM} m-Si 45° (Wh/W_P)**	**Simulated Y_{FM} m-Si 90° (Wh/W_P)**	**Simulated Y_{FM} OPV 45° (Wh/W_P)**	**Simulated Y_{FM} OPV 90° (Wh/W_P)**	**% Difference Measured & Simulated (m-Si 45°)**	**% Difference Measured & Simulated (m-Si 90°)**	**% Difference Measured & Simulated (OPV 45°)**	**% Difference Measured & Simulated (OPV 90°)**
Jan 20	30.9	23.1	32.1	21.4	30.2	23.3	32.8	22.0	2.3	-0.9	-2.1	-2.7
Feb 20	49.8	35.8	50.0	33.2	49.2	36.1	49.3	33.4	1.2	-0.8	1.4	-0.6
Mar 20	117.1	83.3	118.4	76.3	117.7	83.8	115.7	77.0	-0.5	-0.6	2.3	-0.9
April 20	163.4	107.4	176.1	99.5	162.0	106.2	168.9	99.9	0.9	1.1	4.3	-0.4
May 20	147.6	78.3	156.6	73.2	146.8	77.8	150.5	73.2	0.5	0.6	4.1	0.0
June 20	130.1	61.4	141.7	62.3	130.3	60.9	140.7	65.7	-0.2	0.8	0.7	-5.2
July 20	162.4	81.7	182.1	79.0	163.1	78.6	185.8	82.3	-0.4	3.9	-2.0	-4.0

August 20	133.5	77.8	152.2	74.1	133.7	77.8	158.9	77.2	-0.1	0.0	-4.2	-4.0
Sept 20	129.5	91.0	140.5	79.0	127.1	91.9	155.3	80.0	1.9	-1.0	-9.5	-1.3
Oct 20	56.2	38.8	57.1	36.2	55.7	39.1	59.8	38.2	0.9	-0.8	-4.5	-5.2
Nov 20	53.9	43.6	50.2	36.5	54.1	45.3	54.2	43.2	-0.4	-3.8	-7.4	-15.5
Dec 20	16.8	14.7	16.8	11.9	16.4	15.0	20.6	16.5	2.4	-2.0	-18.4	-27.9
Total	**1191.2**	**736.9**	**1273.8**	**682.6**	**1186.3**	**735.8**	**1292.5**	**708.6**	**8.6**	**-3.2**	**-35.4**	**-67.7**