

A Platform for Outdoor Real-Time Characterization of Photovoltaic Technologies

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Supplementary Information

1. Related Works

Table S1. Platforms for characterization of PV technologies found in the state of the art.

Ref.	Weather Measurement Technology	PV Measurement Technology	Irradiance Sensor/ accuracy	Temperature Sensor.	PV Technologies	Test Type /Time	Data Integration	Real-time	UI Support
[9]	WS600 Station	IV500 Tracer	Pyranometer MS800 / High	-	OPV	Outdoor/ -	No	No	No
[15]	Weather camera QSUN Xe3	-	-	-	OPV	Indoor/ -	-	-	-
[16]	Davis Pro weather station	Solar Analyzer Sensor Box Fronius	Calibrated cell Spektron 210 / Low	Pt1000	Si PV	Outdoor/ 3 months	Yes	Yes	No
[17]	Spectrum radiometer (MS711 and 712, EKO)	-	Spectrum radiometer MS711 / High	Pt100	CPV	Outdoor / 36 months	No	No	No
[18]	- Windmeter-CYG-5108 - CVS-HUMI-CAP180	-	Pyranometer CHF-SR20 Spectrum radiometer MS-711/ High	Thermocouple	Si A-Si CIGS	Outdoor / 24 months	No	No	No
[19]	- SMU Botest - System (Egnitec, UK)	PVMS250 Egnitec UK	Calibrated cell / Low	Pt100	Perovskite	Outdoor / -	No	No	No
[20]	- Sun Simulator - Davis Pro weather station	PVMS250 Egnitec UK	Calibrated cell / Low	Pt100	OPV BIPV	Outdoor / 8 months	No	No	No
[21]	- Humidity (MT-063A), - Wind Monitor (A-110/MI-360), - Rain Gauge (MW-010) - Barometer (MY-021)	I-V curve tracer MP165	Pyranometers (MS-802) / High	Thermocouple	HIT CIGS PERC CdTe	Outdoor	No	No	No
[22]	Weather station	Solar analyzer	Pyranometer Secondary Standard/ High	(RTD) Thermal imaging camera	OPV mc-Si CIS	Outdoor	No	No	No

This Work	Davis Pro weather station	Solar analyzer	Smart_Pyr- anometer Class C— SMP3 / High	RTD Pt100	OPV CdTe CIGS A-Si	Outdoor	Yes	Yes	Yes
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2. Photovoltaic Monitoring Stations (PVMs)

The physical distribution of the PVMs components was carried out by considering the following: (1) the dimensions of PV panels and OPV mini modules, (2) the orientation of PV technologies facing south at a tilt equal to 10°, (3) the position of the measuring equipment (PV/OPV analyzers, weather station, temperature sensors, and pyranometer), and (4) the localization of the backup energy system. The physical distribution of a PVMs is presented in Fig. 1a, and PVMs2 installed at 1000 meters is shown in Figure S1b.



Figure S1. (a) 3D model of PVMs; (b) PVMs installed.

Figures S2–S4 show the three PVMs installed at different altitudes. PVMs1 was installed at 0 meters above sea level (m.a.s.l.), PVMs2 was installed at 1000 m.a.s.l., and PVMs3 was installed at 2000 m.a.s.l.



Figure S2. PVMs1 installed at 0 m.a.s.l.



Figure S3. PVMS2 installed at 1000 m.a.s.l.



Figure S4. PVMS3 installed at 2000 m.a.s.l.

3. Comparison and verification of measurements

The correct operation of PVMS was validated by reconstructing the I-V curves of PV technologies with a commercial solar analyzer (PROVA 210) under conditions of high, medium, and low irradiance. Then, the results obtained with PROVA 210 were compared with the I-V curves and parameters obtained with the developed platform, as shown in Figures S5–S10 for the CdTe technology.

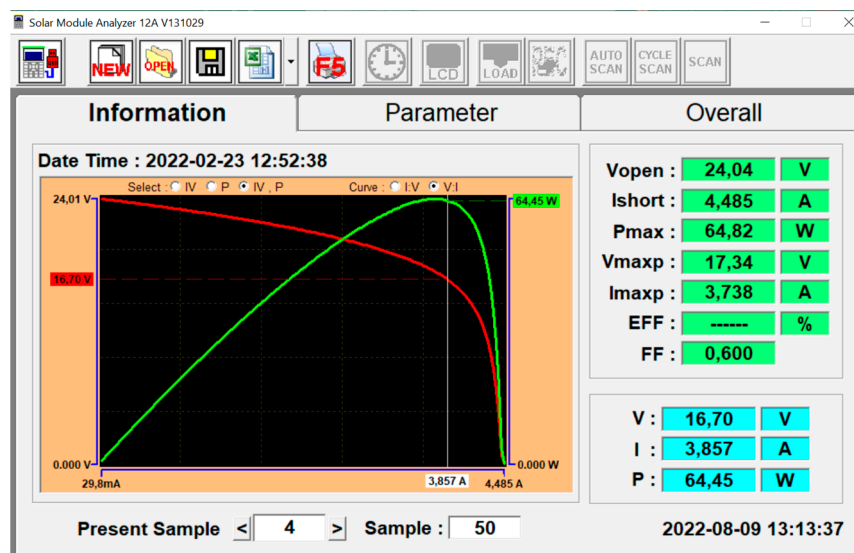


Figure S5. I-V and P-V curves of the CdTe solar panel using the PROVA 210 Solar analyzer—high irradiance.

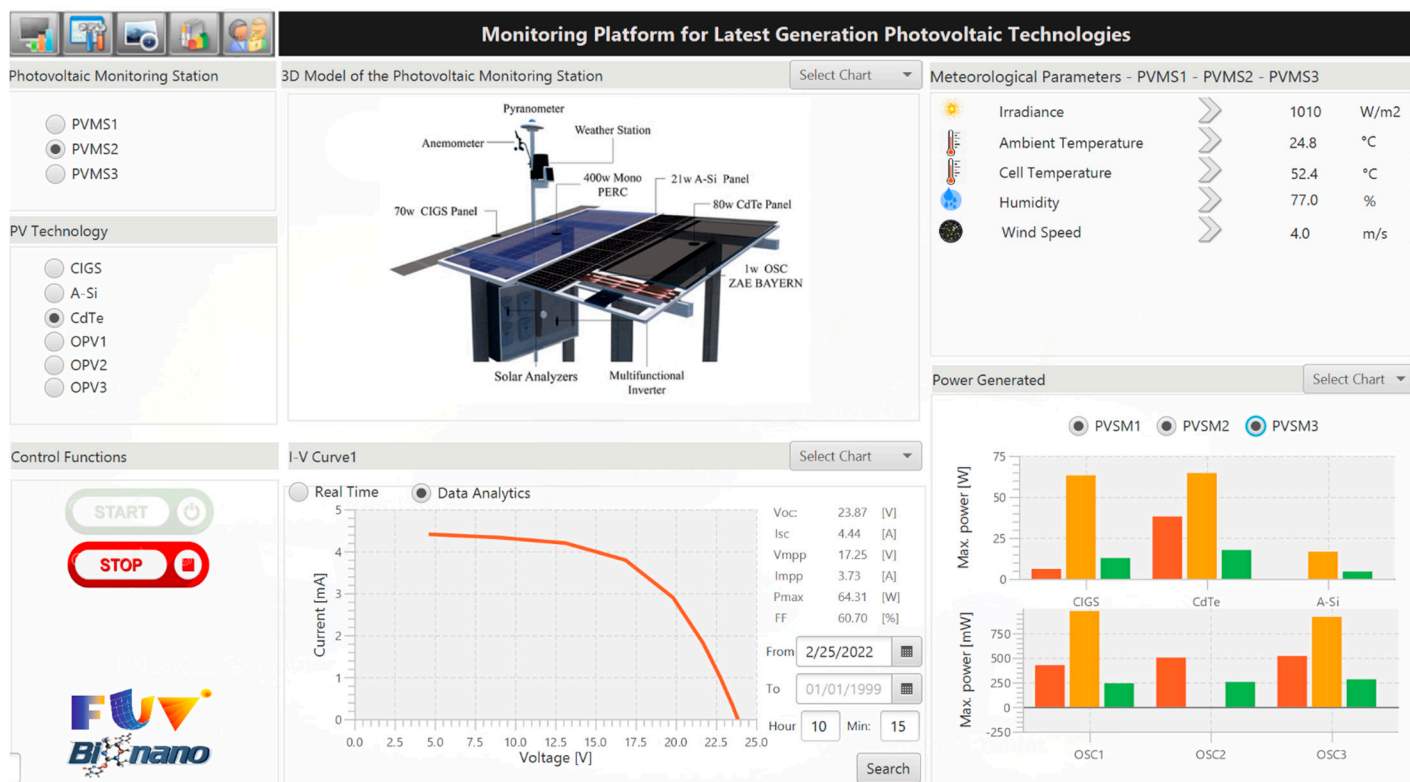


Figure S6. I-V curve and PV parameters of the CdTe solar panel using the PVMS2—high irradiance.

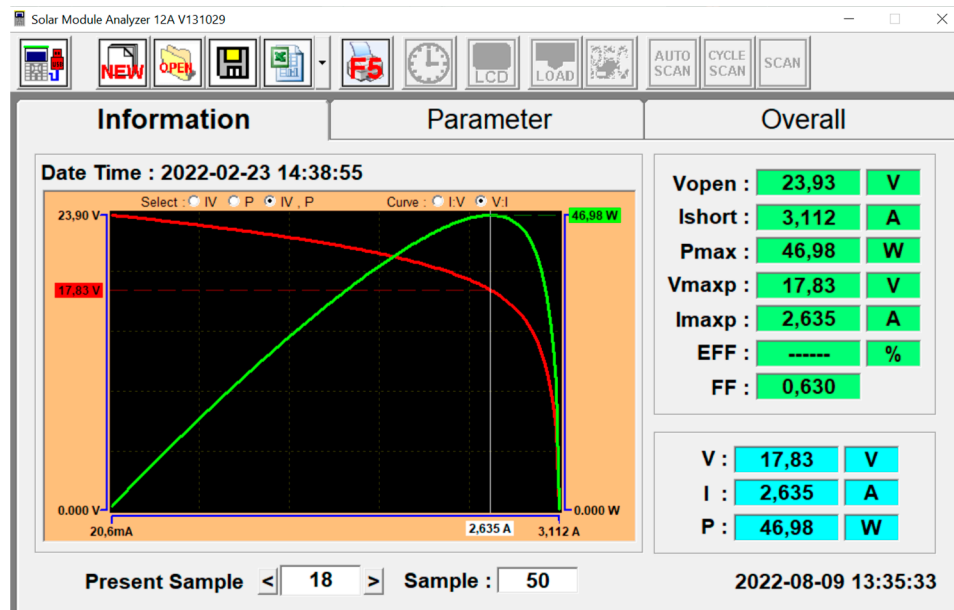


Figure S7. I-V and P-V curves of the CdTe solar panel using the PROVA 210 Solar analyzer—medium irradiance.

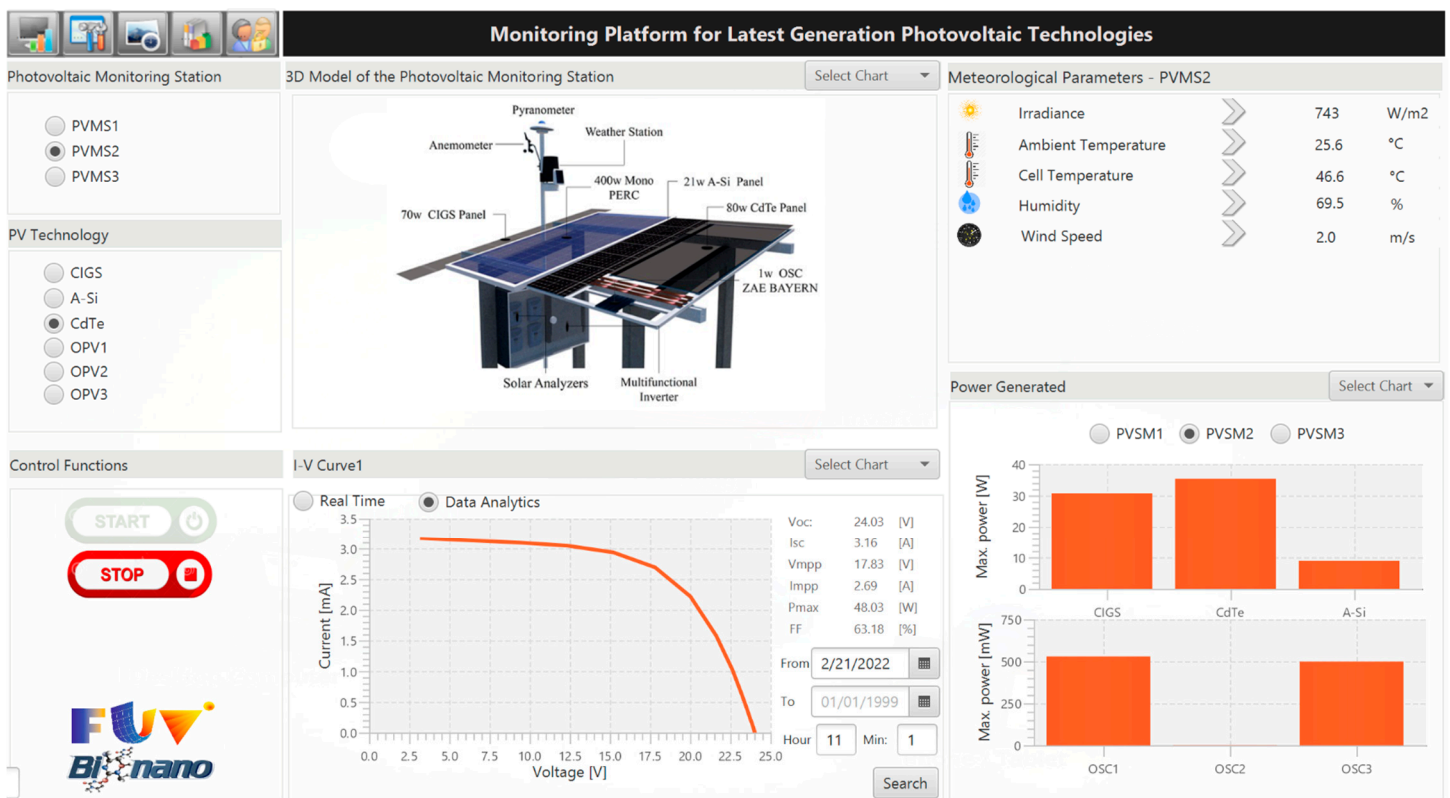


Figure S8. I-V curve and PV parameters of the CdTe solar panel using the PVMS2—medium irradiance.

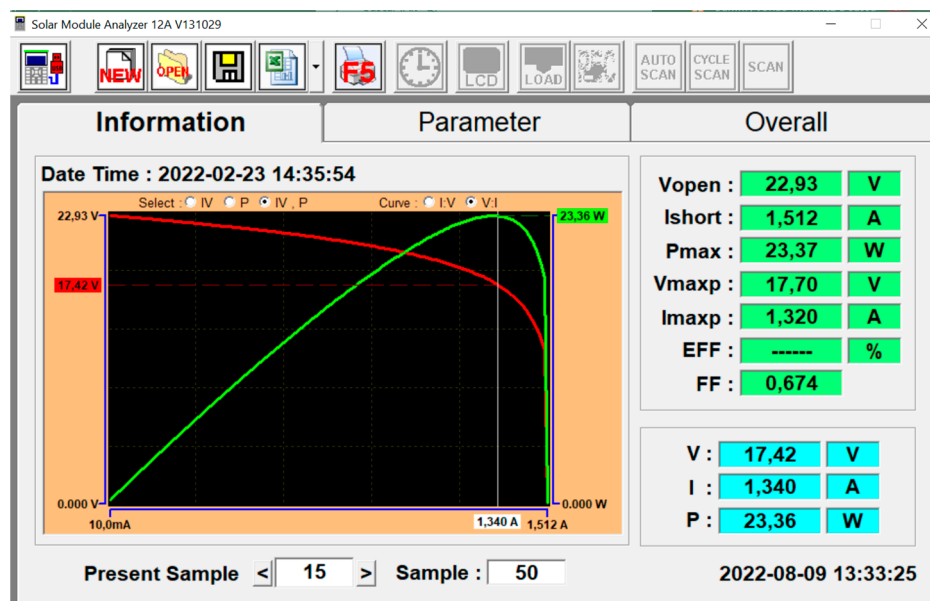


Figure S9. I-V and P-V curves of the CdTe solar panel using the PROVA 210 Solar analyzer—low irradiance.

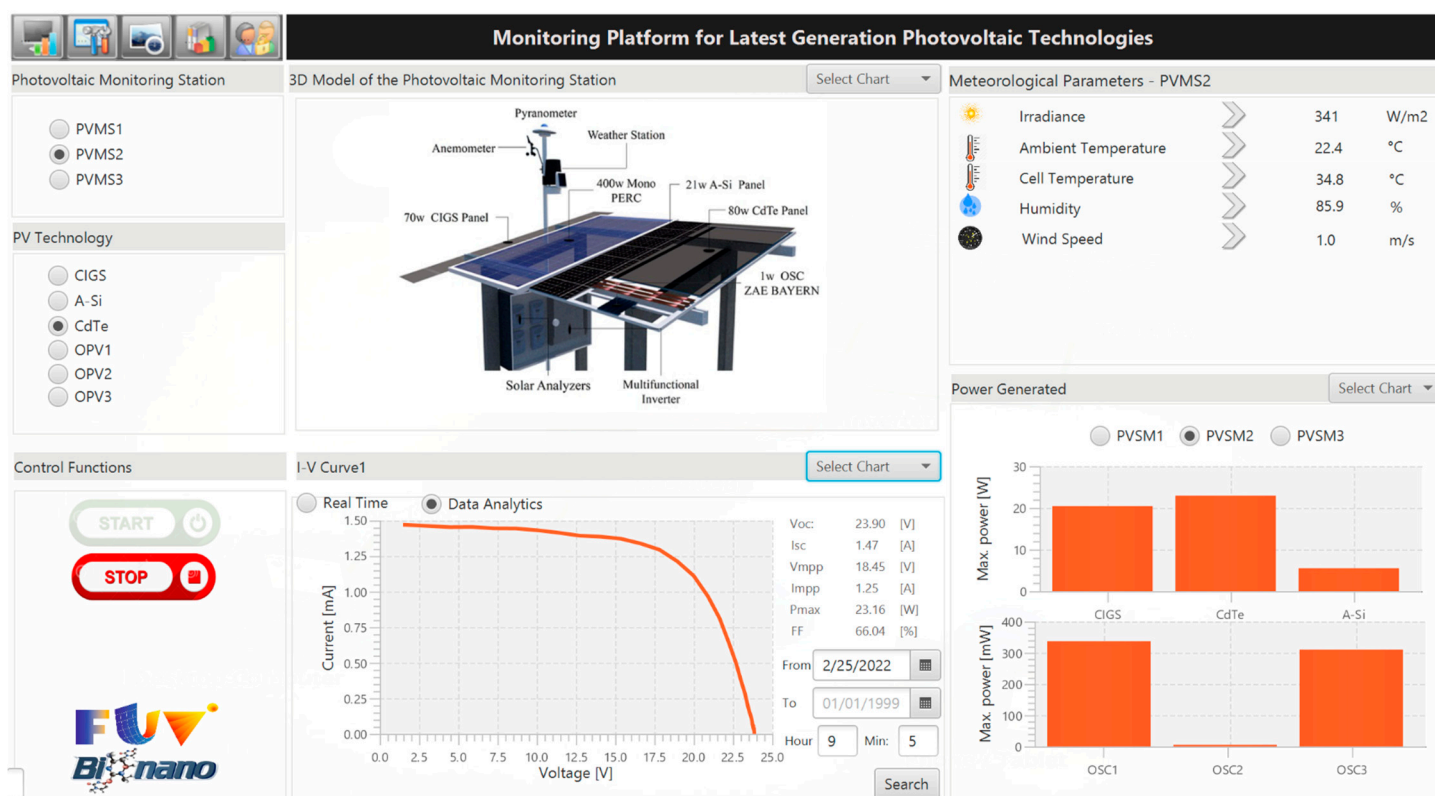


Figure S10. I-V curve and PV parameters of the CdTe solar panel using the PVMS2—low irradiance.

Table S2. Electrical parameter values of the CdTe solar panel measured with the commercial solar analyzer PROVA 210 and with PVMS2 under similar test conditions.

Measured by	Date	PV Tech	Irr (W/m ²)	Voc (v)	Isc (A)	Pmax (W)	Vmax (v)	Imax (A)	TA (°C)	Tc C (°C)	RH (%)
PROVA 210	Feb 23 12:52:33 COT 2022	CdTe	1008.00	24.04	4.49	64.82	17.34	3.78	84.90	51.50	59.20
PVMS2	Feb 25 10:15:31 COT 2022	CdTe	1008.00	23.89	4.45	64.59	17.26	3.74	76.60	52.10	77.00
PROVA 210	Feb 23 14:38:32 COT 2022	CdTe	743.00	23.93	3.11	46.98	17.83	2.63	86.20	46.50	52.90
PVMS2	Feb 21 11:01:34 COT 2022	CdTe	743.00	24.03	3.16	48.03	17.83	2.69	78.00	46.60	69.50

PROVA 210	Feb 23 14:36:33	COT 2022	CdTe	341.00	22.93	1.51	23.37	17.70	1.32	86.10	46.50	53.50
PVMS2	Feb 25 09:05:31	COT 2022	CdTe	341.00	23.90	1.47	23.16	18.45	1.25	72.30	34.80	85.90

4. Calibration of PV solar panel analyzers

Tables S3 and S4 present the results obtained by setting voltages and currents in the calibration range. V_{test} y I_{test} are the voltages and currents set using external sources, while V_m y I_m are the average values of 167 measurements, and Std is the respective standard deviation of the results.

Table S3. Validation of voltage measurement.

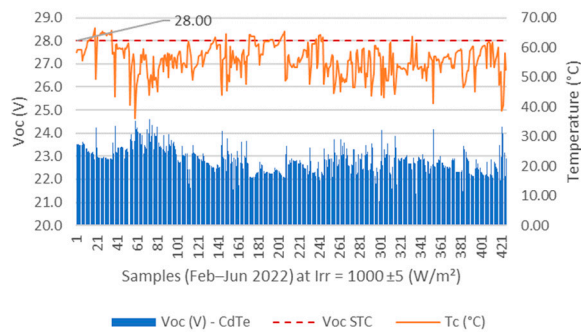
$V_{test} (V)$	$V_m (V)$	$Std (V)$
30.512	30.514566	0.004236
25.4	25.40085	0.005093
16.141	16.14185	0.0070226
5.5033	5.50907	0.006872
0.95536	0.95645	0.0061218

Table S4. Validation of current measurement.

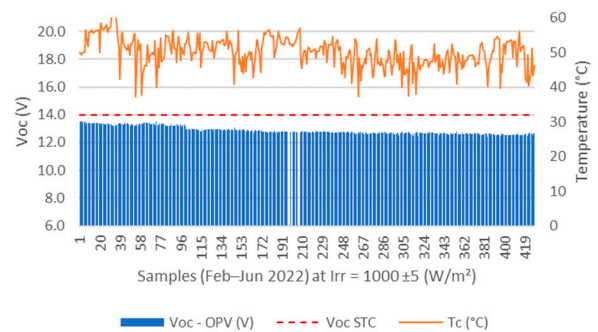
$I_{test} (A)$	$I_m (A)$	$Std (A)$
0.55	0.549795	0.01631
1.12	1.119916	0.014989
2.45	2.452113	0.016601
3.88	3.880597	0.01615
4.55	4.550493	0.01461

5. Variations in Voc with respect to the temperature for all PV technologies

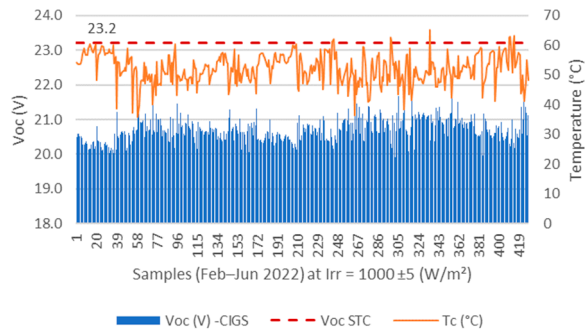
Figure S11 shows the variations of Voc with respect to the temperature with a constant irradiance ($1000 \text{ W/m}^2 \pm 5$) during the 5 months of monitoring in PVMS2. The dotted red line indicates the Voc at STC (25°C) of each technology reported in its technical datasheet, which is the reference value for our analysis of voltage loss due to temperature increase. From Figure 11b, we can deduce that organic technology responds well to high temperatures.



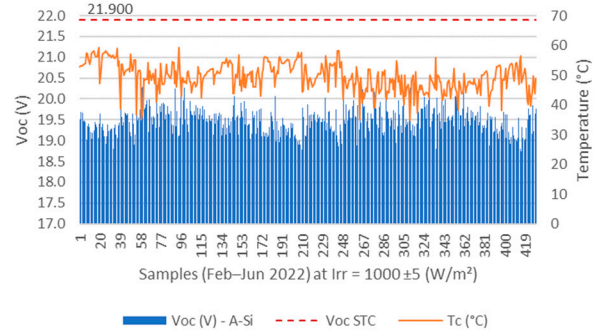
(a)



(b)



(c)



(d)

Figure S11. Voc/Tc at Irr = 1000 (W/m²) in five months for a) CdTe technology, b) OPV technology, c) CIGS technology, and d) A-Si technology.

Figures S12–S14 show the variation of Voc with respect to the surface cell temperature for all the PV technologies in each PVMS

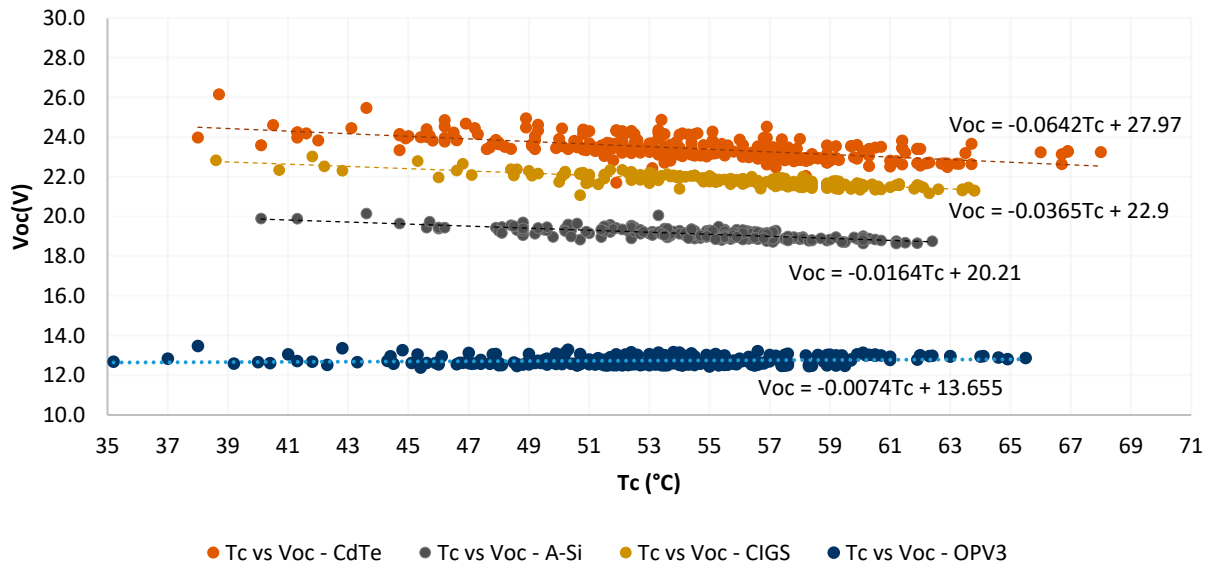


Figure S12. Voc vs. Tc at the PVMS1 station at Irr = 1000 ± 5 (W/m²) for a testing time of 5 months (Feb–Jun 2022).

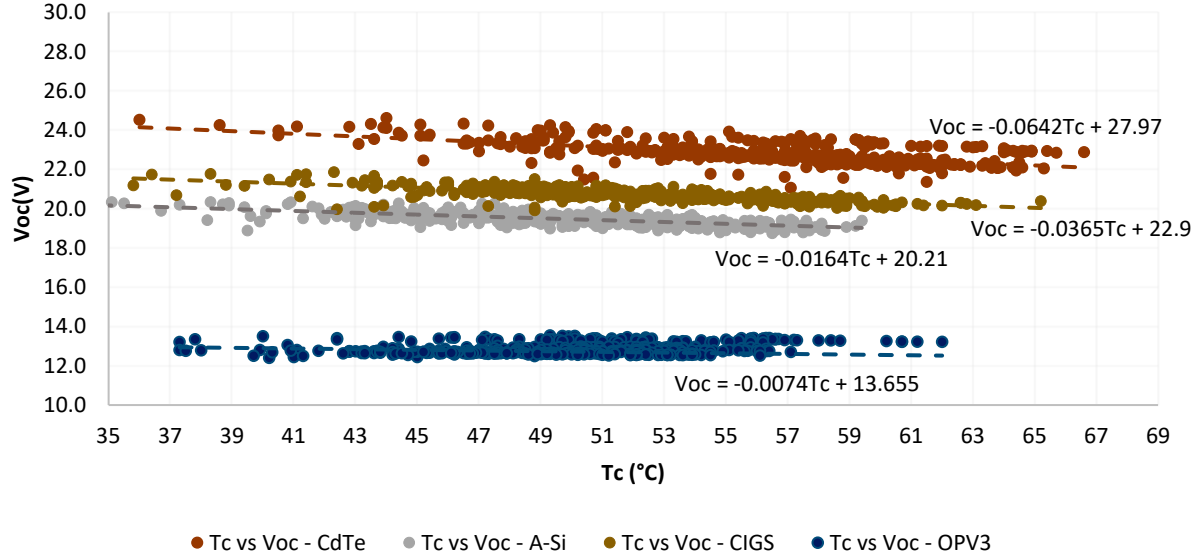


Figure S13. Voc vs. Tc at the PVMS2 station at $Irr = 1000 \pm 5$ (W/m^2) for a testing time of 5 months (Feb–Jun 2022).

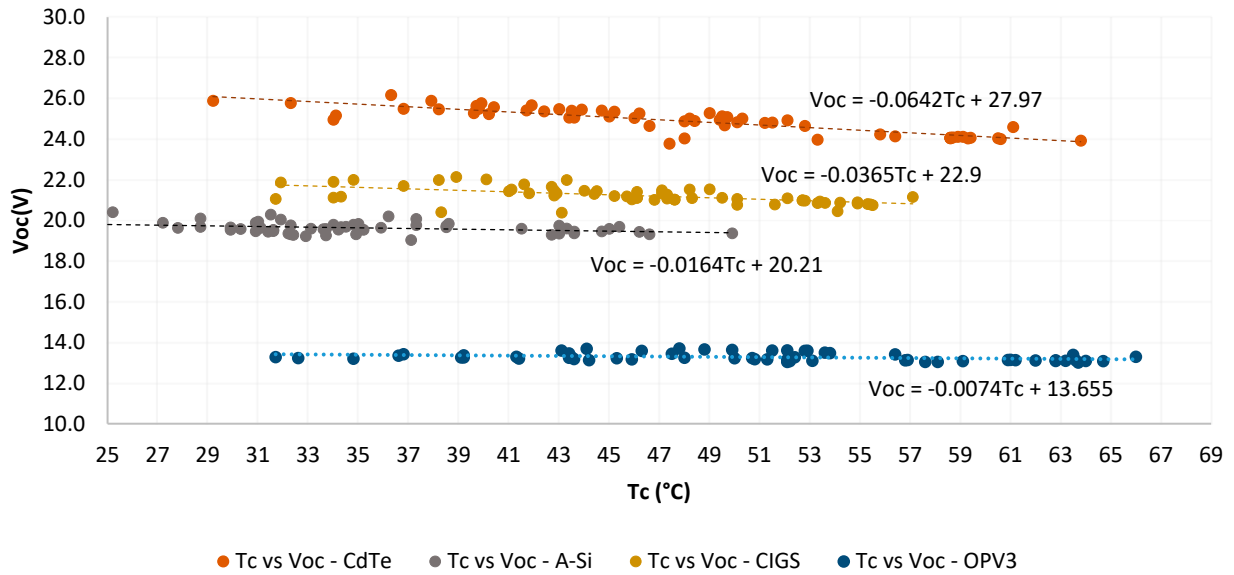
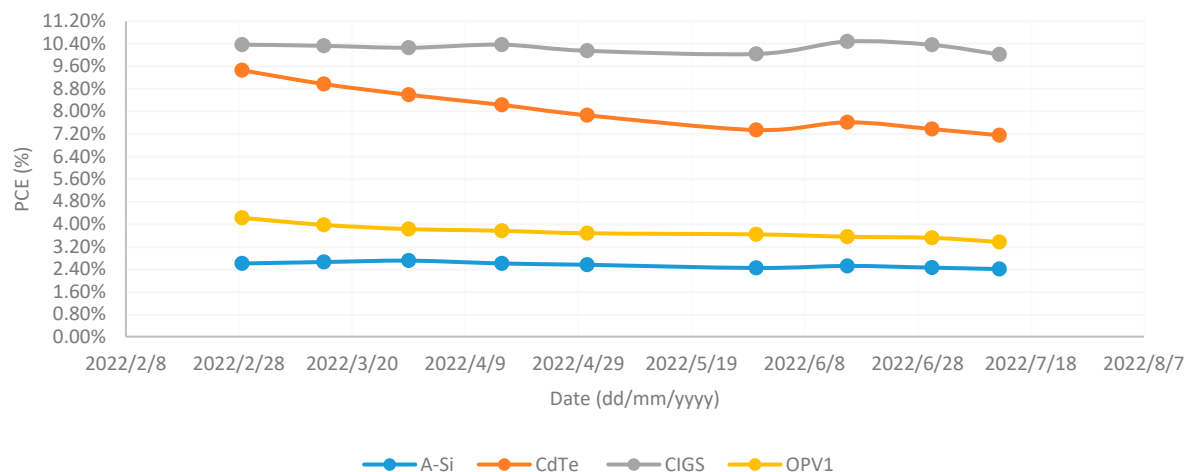


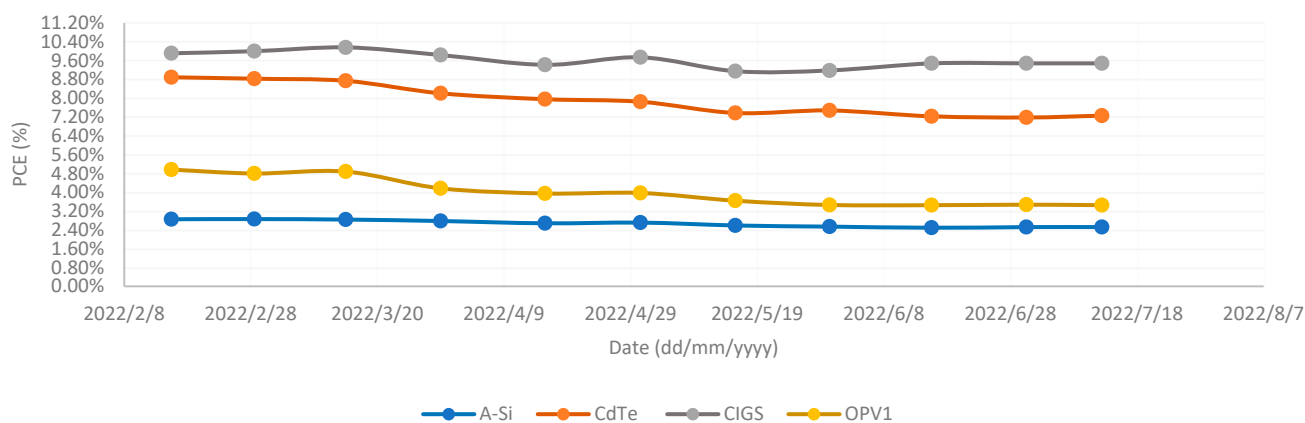
Figure S14. Voc vs. Tc at the PVMS3 station at $Irr = 1000 \pm 5$ (W/m^2) for a testing time of 5 months (Feb–Jun 2022).

In the case of the PVMS3 station, there are fewer points since there are fewer data after applying the filter for $Irr = 1000$ (W/m^2), given the location conditions.

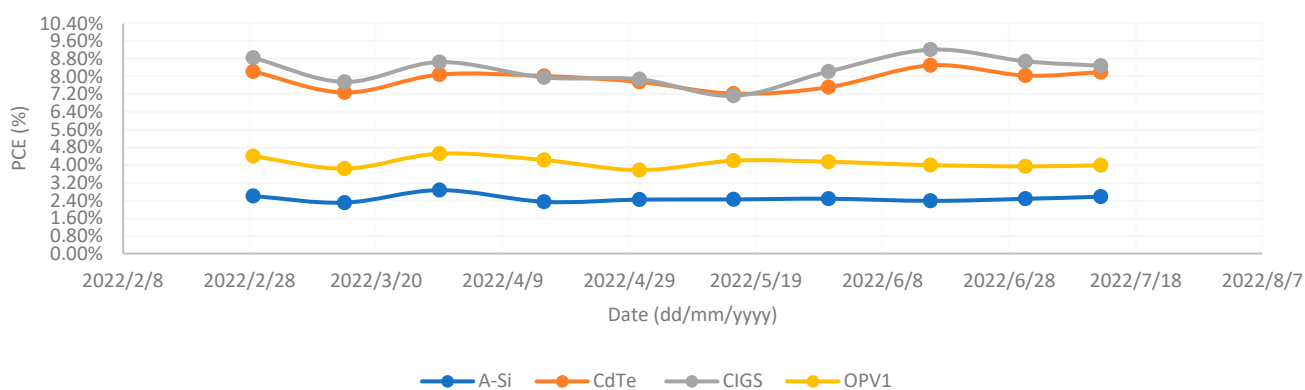
6. Average PCE of PV technologies in all PVMSs through four months



(a)



(b)



(c)

Figure S15. Variation of PCE during four months at $I_{rr} = 1000 \text{ (W/m}^2\text{)}$. **(a)** PVMS1 with average ambient temperature (TA) = 31.9°C , average relative humidity (RH) = 76.19%, **(b)** PVMS2 with average TA = 27.53°C , average RH = 66.86%, and **(c)** PVMS3 with average TA = 20.1°C , average RH = 84.78%.