I. Supplementary Material

A. Indoor Test−bench

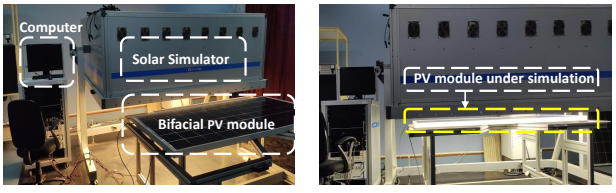
The indoors experiments were performed using a solar simulator (Eternal Sun, LA200150), as depicted in Fig. 1. Measured indoor solar simulator data from the front and rear sides are given in Table I.

B. Outdoor Test−bench

Outdoor test bench is shown in Fig. 2. The complete dataset is provided in Table II. Details of the irradiance and temperature measuring instruments used for this study are provided below.

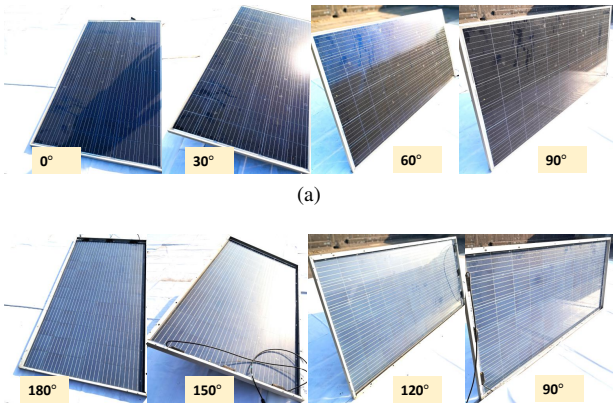
TABLE I
INDOOR EXPERIMENTAL DATASETS

Sl. No.	Irradiance (W/m^2)	Temp. (°C)	I_{ph} (A)	I_s (A)	a (V)	R_s (Ω)	R_{sh} (Ω)
Front-side							
1	649	38	7.4	1.72E-12	1.6	0.5	472
2	740	41	8.3	2.57E-12	1.6	0.5	464
3	751	42	8.4	3.74E-12	1.6	0.5	457
4	766	43	8.6	5.29E-12	1.6	0.4	450
5	789	44	8.8	8.14E-12	1.7	0.4	390
6	811	44	9.1	6.14E-12	1.6	0.4	363
7	830	45	9.3	1.63E-11	1.7	0.4	312
8	847	45	9.5	2.05E-11	1.7	0.4	300
9	863	46	9.6	2.04E-11	1.7	0.4	292
10	881	46	9.8	2.03E-11	1.7	0.4	233
11	893	47	9.9	1.28E-11	1.7	0.4	207
12	901	47	10.0	3.22E-11	1.7	0.4	209
13	908	48	10.1	2.23E-11	1.7	0.4	203
14	916	48	10.2	3.58E-11	1.7	0.4	186
15	920	49	10.2	1.36E-11	1.7	0.4	186
16	923	49	10.3	3.73E-11	1.7	0.4	196
17	925	50	10.3	2.84E-11	1.7	0.4	170
18	928	50	10.3	3.56E-11	1.7	0.4	184
19	931	50	10.4	4.55E-11	1.7	0.4	177
20	932	50	10.4	4.17E-11	1.7	0.4	174
Rear-side							
1	621	35	4.8	2.31E-18	1.1	0.6	144
2	751	37	5.3	4.79E-18	1.1	0.5	107
3	796	38	5.6	4.02E-17	1.2	0.5	104
4	873	40	6.0	3.90E-17	1.2	0.4	89
5	895	40	6.5	1.04E-16	1.2	0.4	87
6	908	41	6.7	1.56E-16	1.2	0.4	88
7	916	41	6.8	2.86E-16	1.2	0.4	81
8	924	42	6.8	4.75E-16	1.2	0.4	82
9	927	42	6.9	8.78E-17	1.2	0.4	83
10	933	42	7.0	1.23E-16	1.2	0.4	81
11	935	44	7.0	2.51E-16	1.2	0.4	79
12	943	45	7.0	2.87E-16	1.2	0.4	77
13	946	47	7.1	5.39E-16	1.2	0.4	76
14	950	54	7.1	1.31E-15	1.2	0.4	73



(a) (b)

Fig. 1. Indoor setup (a) Solar simulator, and (b) PV module under simulation.



(a)

(b)

Fig. 2. Outdoor setup, (a) Front side facing the sky, (b) Rear side facing the sky.

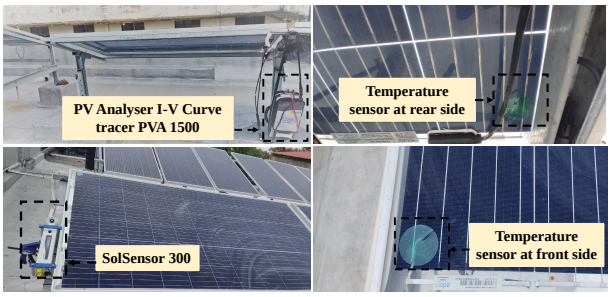


Fig. 3. Outdoor setup: Location of irradiance (SolSensor 300) and temperature sensors.

- Irradiance measuring instruments: The SolSensor 300 furnishes data related to irradiance, temperature, and module tilt to the PV model. It has an irradiance accuracy of ±2%, with 0.1s update interval. The SolSensor attaches to the module frame, automatically aligning the irradiance sensor with the PV module, as illustrated in Fig. 3.
- Temperature measuring device: SolSensor offers two external thermocouple inputs designed for measuring temperatures on module's backside and front side. The sensors are transparent for minimal shading impact, as depicted in Fig. 3. Its cell temperature accuracy is ±2%, and it provides updates at 1s intervals.

C. Parameter Extraction Error

To evaluate the accuracy of the parameter extraction, an error analysis was performed using the RMSE (Root Mean Square Error) metric, as shown in Eq. (1). The RMSE values for both indoor and outdoor tests are provided in Tables III and IV, respectively. The following steps outline the process used to conduct this error analysis:

TABLE II
OUTDOOR EXPERIMENTAL DATASETS

Sl.	**Tilt**	**Irradiance**		**Temperature**			**Front parameters**					**Rear parameters**					**Bifacial parameters**				
No.	(deg.)	(W/m^2)		(°C)			I_{ph}	I_s	a	R_s	R_{sh}	I_{ph}	I_s	a	R_s	R_{sh}	I_{ph}	I_s	a	R_s	R_{sh}
		F	R	B	F	R	(A)	(A)	(V)	(Ω)	(Ω)	(A)	(A)	(V)	(Ω)	(Ω)	(A)	(A)	(V)	(Ω)	(Ω)
1	0	648	0	35.2	35.3	-	6.5	4.73E-10	1.9	0.5	690	-	-	-	-	-	6.5	4.73E-10	1.9	0.5	690
2	10	747	57	35.8	35.7	35.5	7.5	5.98E-10	1.9	0.5	399	0.4	7.02E-10	2.1	0.6	180	7.7	6.04E-10	1.9	0.5	580
3	20	795	69	35.9	35.9	36.1	8.0	7.25E-10	1.9	0.5	375	0.4	1.45E-09	2.1	0.6	168	8.3	7.97E-10	1.9	0.5	541
4	30	836	80	36.2	36.2	36.1	8.4	8.62E-10	1.9	0.5	315	0.6	2.71E-09	2.1	0.6	159	8.8	1.08E-09	1.9	0.5	512
5	40	941	95	36.3	36.4	36.6	9.4	1.04E-09	2.0	0.5	282	0.7	7.19E-09	2.2	0.6	141	9.9	1.72E-09	2.0	0.5	453
6	50	930	107	36.9	36.7	36.7	9.3	1.13E-09	2.0	0.5	295	0.9	7.91E-09	2.2	0.5	141	9.9	1.85E-09	2.0	0.5	454
7	60	855	118	37.0	37.1	37.3	8.6	1.11E-09	2.0	0.5	351	0.9	8.09E-09	2.2	0.6	151	9.2	1.68E-09	2.0	0.6	487
8	70	809	121	37.6	37.6	37.5	8.1	1.18E-09	2.0	0.5	344	1.1	9.70E-09	2.2	0.6	158	8.8	2.05E-09	2.0	0.6	511
9	80	579	128	37.8	37.9	38.1	5.8	8.81E-10	2.0	0.5	393	1.1	1.02E-08	2.2	0.6	212	6.4	1.85E-09	2.0	0.5	683
10	90	537	131	38.4	38.2	38.2	5.4	8.31E-10	2.0	0.5	411	1.2	1.18E-08	2.2	0.6	225	6.1	1.93E-09	2.0	0.5	726
11	100	453	234	38.4	38.5	38.7	4.5	8.60E-10	2.0	0.5	488	1.7	1.42E-08	2.2	0.6	230	5.7	2.31E-09	2.1	0.5	740
12	120	316	270	38.9	38.8	38.7	3.2	9.50E-10	2.0	0.4	699	1.8	1.63E-08	2.2	0.6	280	4.4	2.60E-09	2.1	0.5	904
13	130	200	280	39.1	39.1	39.3	2.0	1.12E-09	2.1	0.4	891	1.8	1.54E-08	2.2	0.5	358	3.2	2.35E-09	2.1	0.5	1153
14	140	256	422	39.1	39.2	39.2	2.6	1.59E-09	2.1	0.5	640	2.4	2.06E-08	2.2	0.5	257	4.5	3.30E-09	2.1	0.5	827
15	155	255	437	39.4	39.4	39.3	2.5	1.79E-09	2.1	0.4	630	2.6	2.08E-08	2.2	0.5	253	4.5	3.89E-09	2.1	0.5	814
16	160	185	576	39.5	39.5	39.6	1.8	1.77E-09	2.2	0.4	600	3.5	3.43E-08	2.2	0.5	241	4.6	4.86E-09	2.2	0.5	776
17	100	131	611	39.9	39.8	39.8	1.3	9.83E-09	2.1	0.5	227	4.3	7.23E-10	2.0	0.4	632	4.6	1.75E-09	2.1	0.5	817
18	110	125	667	40.0	40.1	40.2	1.3	8.80E-09	2.1	0.5	238	4.6	6.56E-10	2.0	0.4	596	5.0	1.54E-09	2.1	0.5	771
19	120	121	887	40.3	40.3	40.2	1.2	6.11E-09	2.1	0.6	179	5.9	6.48E-10	2.0	0.4	476	6.3	1.16E-09	2.0	0.5	615
20	130	112	990	40.4	40.4	40.5	1.1	5.16E-09	2.1	0.5	160	6.5	6.40E-10	1.9	0.5	438	6.9	9.74E-10	2.0	0.5	567
21	140	98	1009	40.6	40.6	40.5	1.0	4.14E-09	2.1	0.5	157	6.6	5.55E-10	1.9	0.5	439	7.0	8.85E-10	2.0	0.5	567
22	150	89	1005	40.6	40.7	40.7	0.9	3.53E-09	2.1	0.5	158	6.4	5.07E-10	1.9	0.5	445	6.7	7.98E-10	2.0	0.5	576
23	160	75	940	40.9	40.8	40.8	0.7	2.79E-09	2.1	0.5	169	6.0	4.23E-10	1.9	0.5	482	6.3	6.14E-10	1.9	0.5	623
24	170	69	804	40.9	40.9	40.9	0.7	1.10E-09	2.0	0.5	197	5.6	3.08E-10	1.9	0.5	559	6.0	3.76E-10	1.9	0.5	722
25	180	0	786	-	41.1	41.1	-	-	-	-	-	5.2	7.12E-10	1.8	0.5	760	5.2	7.12E-11	1.8	0.5	760

*F: front, R: rear, B: bifacial

TABLE III
PARAMETER EXTRACTION ERROR-INDOOR TEST

INDOOR TEST-Front		
Sl. No.	Irradiance (W/m^2)	RMS Error (%)
1	649	0.55
2	740	0.72
3	751	0.52
4	766	1.64
5	789	0.67
6	811	1.54
7	830	0.54
8	847	0.75
9	863	0.66
10	881	0.65
11	893	0.48
12	901	1.86
13	908	0.79
14	916	2.14
15	920	0.64
16	923	2.34
17	925	1.35
18	928	2.04
19	931	3.02
20	932	2.68
INDOOR TEST-Rear		
1	621	0.63
2	751	1.07
3	796	0.56
4	873	0.70
5	895	0.77
6	908	1.39
7	916	2.79
8	924	2.13
9	927	0.54
10	933	0.94
11	935	2.31
12	943	2.62
13	946	1.31
14	950	1.57

- The five parameters of the single-diode model were extracted using the Two-Step Least Linear Squares (TSLLS) method.
- Using the extracted parameters, the I-V curve was reconstructed in MATLAB, generating a theoretical curve based on the extracted model values.
- The reconstructed I-V curve was compared to the

TABLE IV
PARAMETER EXTRACTION ERROR-OUTDOOR TEST

Sl. No.	Tilt (deg)	RMS Error (%)		
		F	R	B
1	0	0.49	0.60	0.35
2	10	0.95	0.31	0.83
3	20	0.37	0.27	0.58
4	30	0.58	0.46	0.54
5	40	0.22	0.97	0.91
6	50	0.75	0.82	0.28
7	60	0.25	0.69	0.75
8	70	0.50	0.31	0.75
9	80	0.69	0.95	0.38
10	90	0.89	0.34	0.56
11	100	0.95	0.43	0.07
12	120	0.54	0.35	0.05
13	130	0.13	0.76	0.53
14	140	0.14	0.79	0.77
15	155	0.25	0.16	0.93
16	160	0.84	0.48	0.12
17	100	0.25	0.44	0.56
18	110	0.81	0.64	0.46
19	120	0.24	0.70	0.01
20	130	0.92	0.75	0.33
21	140	0.34	0.27	0.16
22	150	0.19	0.67	0.79
23	160	0.29	0.65	0.31
24	170	0.61	0.16	0.52
25	180	0.47	0.11	0.16

experimentally measured I-V curve. The error between the estimated and measured currents was calculated using the RMSE formula, as given in Eq. (1).

$$I_{rms} = rms\left(\frac{I_{est} - I_{meas}}{I_{nominal}}\right) \tag{1}$$

Here, I_{rms} represents the root mean square error, I_{est} is the estimated current from the reconstructed I-V curve, I_{meas} is the measured current, and $I_{nominal}$ is the nominal current value given in the datasheet.