Supplementary information

Impact of Current Mismatch among Individual Cells on the Performance of Perovskite Photovoltaic Module

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1. Impact of reverse breakdown voltage on the PSM with non-uniform I_{SC}

The effect of reverse breakdown voltage (V_{BR}) of PSC on the performance of PSM without bypass diode was systematically analyzed under various $\sigma_{ISC.}$ When the I_{SC} of each PSC is uniform (σ_{ISC} of 0), all PSCs are operating under forward bias and the power output of PSM is independent on the V_{BR}. In addition, the effect of V_{BR} is very limited under low σ_{ISC}. Up to 6% of σ_{ISC}, the change of power output due to different V_{BR} is almost negligible. On the other hand, the low V_{BR} can improve the I_{MPP} of PSM with reduced loss of V_{MPP} under high σ_{ISC}. For example, the I_{MPP} of PSM consisted of PSCs with V_{BR} of 5 V (19 mA) is higher than that of PSM consisted of PSCs with V_{BR} of 30 V (17.9 mA). Under non-uniform I_{SC}, a strong reverse bias is applied to a poor performance cell among cell-string. If the V_{BR} of PSC is very high, the operating voltage loss to maintain high I_{MPP} is significant. As a result, it is more beneficial to reduce I_{MPP} rather than V_{MPP}. In contrast, in the case of low V_{BR}, the V_{MPP} loss to maintain high I_{MPP} caused by high σ_{ISC} is relative low. Thus, it is possible to maintain high I_{MPP} with reduced V_{MPP} loss, thereby leading to improved performance of PSM with low V_{BR}. The additional gain to use PSCs with low V_{BR} is 0.4% in this work. Similar effect has been reported in the commercialized c-Si PV module.

However, in most cases, low V_{BR} of PSC provoke stability issue of field installed PSM. The PSM will frequently face partial shading and non-uniform degradation of PSCs, which applies strong reverse bias to poor performance PSCs. To withstand such a reverse bias, it is recommended to demonstrate high V_{BR} in the PSC. Many research group have suggested methods to increase V_{BR} for electrically stable PSCs and PSMs. Recent work suggested that the V_{BR} of PSC can be similar to that of c-Si PV cells. Thus, we assumed that V_{BR} of PSC is 30 V during this simulation.

The effect of the V_{BR} of PSCs on the performance of a PSM without a bypass diode was systematically analyzed under various σ_{ISC}. When the I_{SC} of each PSC is uniform (σ_{ISC} = 0), all PSCs operate under forward bias, and the power output of the PSM becomes independent of V_{BR}. Furthermore, the influence of V_{BR} remains minimal under low σ_{ISC} conditions. Up to a σ_{ISC} of 6%, the variation in power output due to differences in V_{BR} is almost negligible.

However, under high σ_{ISC} conditions, a lower V_{BR} can enhance the maximum power point current (I_{MPP}) of the PSM while minimizing losses in the maximum power point voltage (V_{MPP}). For instance, a PSM composed of PSCs with a V_{BR} of 5 V exhibits a higher I_{MPP} (19 mA) compared to that composed of PSCs with a V_{BR} of 30 V (17.9 mA). Under non-uniform I_{SC} conditions, a poor-performing cell within the string can be applied to a strong reverse bias. If the V_{BR} is high, a significant operating voltage loss is required to sustain a high I_{MPP}, making it more advantageous to sacrifice I_{MPP} rather than V_{MPP}. Conversely, with a low V_{BR}, the V_{MPP} loss required to maintain a high I_{MPP} under large σ_{ISC} is relatively small. Therefore, it becomes feasible to sustain a high I_{MPP} with minimal V_{MPP} loss, resulting in improved PSM power output. In this study, the additional power gain achieved by using PSCs with a low V_{BR} was approximately 0.4%, as shown in Fig S1 and summarized in Table S1. A similar effect has also been observed in c-Si PV modules under non-uniform light irradiation among cells.

Nevertheless, in most practical applications, a low V_{BR} in PSCs raises concerns regarding the stability of field-installed PSMs. These modules often experience partial shading and non-uniform degradation, applying severe reverse bias to poor performance PSCs. To withstand such conditions, PSCs with high V_{BR} are generally preferred. Numerous research groups have proposed strategies to enhance V_{BR} for electrically stable PSCs and PSMs. Recent studies suggest that the V_{BR} of PSCs can be engineered to match that of c-Si PV cells through buffer and electrode engineering. Additionally, the introduction of bypass diode, whose reverse voltage is below 1 V, can mitigate additional losses caused by improved V_{BR}. In the PSM with bypass diode, the bypass diode provides alternative current path to PSC string under large σ_{ISC}, so that the voltage loss caused by high V_{BR} of PSC can be negligible. The PCE of PSM with bypass diode is almost independent on the V_{BR}. Based on this insight, a V_{BR} of 30 V was assumed for PSCs in this simulation despite of power loss under high σ_{ISC}.

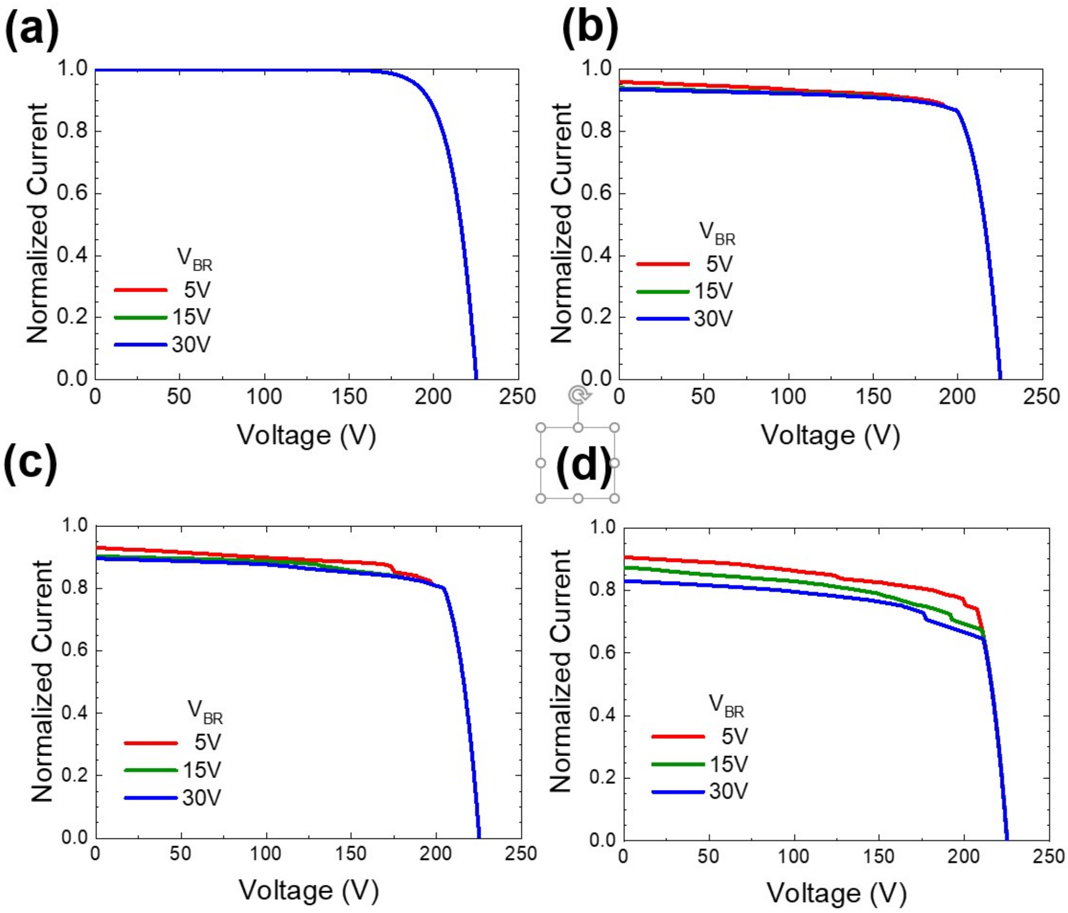

Fig S1. Simulated I-V characteristics of PSM with V_{BR} of 5, 15 and 30 V under σ_{ISC} of (a) 0%, (b) 4%, (c) 8%, and (d) 10%. The graph shows that low V_{BR} of PSC might contribute to improved performance of PSM, but it would cause poor stability of PSM.

Table S1. The average I_{SC}, V_{OC}, FF, I_{MPP}, V_{MPP}, and PCE of PSM having different V_{BR}. Here, the average value is achieved from 6 different cases having the same σ_{ISC}.

V_{BR}	σ_{ISC} (%)	I_{SC} (mA)	V_{OC} (V)	FF (%)	I_{MPP} (mA)	V_{MPP} (V)	PCE (%)
5 V	0	25.5	225.1	80.2%	24.1	191.0	23.0 (-)
	2	25.1	225.1	81.2%	23.9	191.8	22.9 (-0.4 %)
	4	24.5	225.0	80.7%	22.5	198.1	22.3 (-3.3 %)
	6	24.0	225.1	79.6%	21.5	200.2	21.5 (-6.4 %)
	8	23.6	225.1	77.9%	20.6	201.3	20.7 (-10.0 %)
	10	22.9	224.9	74.1%	19.0	200.9	19.1 (-17.1 %)
15 V	0	25.5	225.1	80.2%	24.1	191	23.0 (-)
	2	25.0	225.1	81.5%	23.9	191.8	22.9 (-0.4 %)
	4	24.1	225.0	82.0%	22.5	198.1	22.2 (-3.3 %)
	6	23.5	225.1	81.5%	21.3	201.7	21.5 (-6.4 %)
	8	22.8	225.1	79.9%	20.1	204.7	20.5 (-10.8 %)
	10	21.7	224.9	76.8%	18.3	204.9	18.7 (-18.5 %)
30 V	0	25.5	225.1	80.2%	24.1	191.0	23.0 (-)
	2	25.0	225.1	81.5%	23.9	191.8	22.9 (-0.4 %)
	4	24.0	225.0	82.3%	22.5	198.1	22.3 (-3.3 %)
	6	23.3	225.1	82.1%	21.3	201.7	21.5 (-6.4 %)
	8	22.4	225.1	81.4%	20.1	204.7	20.5 (-10.8 %)
	10	20.9	224.9	79.4%	17.9	208.2	18.7 (-18.8 %)

2. Procedure to simulate PSM with σ_{ISC}

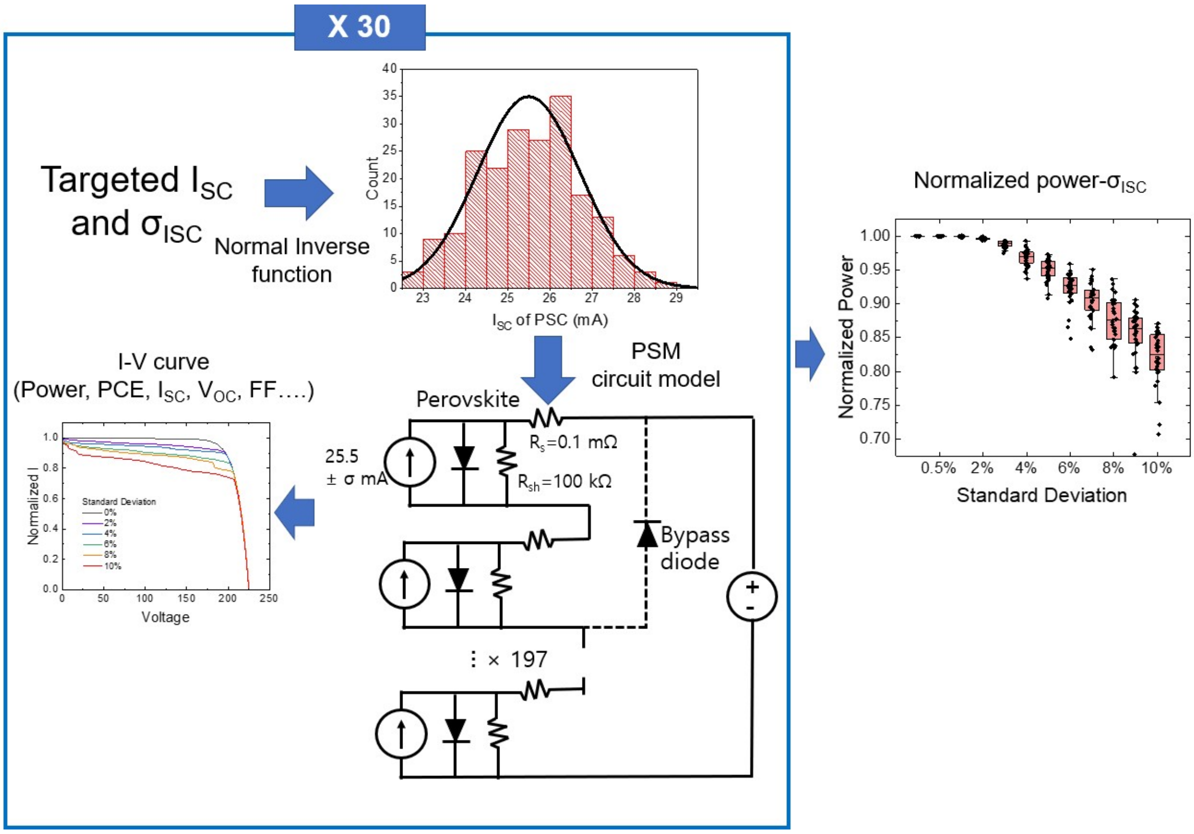

Fig S2. Schematic for calculating power (PCE) distribution of PSM with different σ_{ISC}. We generated distribution of I_{SC} using normal inverse function provided a commercial static analysis program (SPSS), which create the I_{SC} distribution based on targeted I_{SC} and σ_{ISC}. The set of I_{SC} values for each PSC is applied to PSM model, consisted of 200 series connected cell. In the model, each PSC is consisted of two resistors, current source, and diode. The series (R_S) and shunt (R_{sh}) resistance of PSC are assumed as 0.1 m and 100 kΩ, respectively. The additional resistance between PSC is ignored in this calculation. Moreover, the I_{SC} of PSC varies following the distribution of I_{SC} achieved through static analysis program. Furthermore, the turn-on voltage of p-n diode for PSC is around 0.9 V under dark condition. Lastly, it is assumed that the bypass diode, parallel connected to equivalent circuit model of PSC, is a Schottky diode, whose turn-on voltage is ~ 0.3 V. To avoid misunderstanding of results from specific case, this process was repeatedly (30 times) conducted. Finally, the distribution of normalized power can be achieved through this process at each σ_{ISC} values.

3. Local heating of PSM with non-uniform I_{SC}

We experimentally investigated the reverse bias behavior in a lab-scale perovskite solar module (PSM) under conditions of non-uniform short-circuit current (I_{SC}). The PSM consisted of 10 series-connected PSCs, each with dimensions of 5 × 0.3 cm^2. The device architecture of PSC was ITO/ MeO-2PACZ/ $FAPbI_3$ /CH_3/C_{60}/Bathocuproine/Al. In addition, the large-area PSCs were fabricated into a module using laser scribing to define cell interconnections. Under AM 1.5 condition without shading, the I_{SC} and V_{OC} of the PSM were 25.6 mA (corresponding to 16.3 mA/cm^2 × 1.5 cm^2) and 10.7 V (1.07 V per cell × 10 cells), respectively. The PCE of module was 11.5%, which is lower than that of single cell. This reduction is attributed to losses introduced during the laser cutting process and non-optimized fabrication procedure for large area films.

To stimulate specific variations in I_{SC} (σ_{ISC}), we intentionally modulated the I_{SC} of individual cells within the module through black tape. As the I_{SC} of the PSCs was deliberately varied, a distinct kink appeared in the I–V characteristics of the PSM, as shown in Figure S3 (b). For example, a sharp drop in the I–V curve was observed near 4 V in modules containing a cell applying 10% or 20% shading. When a cell is shaded, I_{SC} of the PSM decreases, potentially driving it into reverse bias operation. In our 10-cell module, it is energetically more favorable to sacrifice the maximum power point current (I_{MPP}) rather than maintain the voltage at the maximum power point (V_{MPP}). In contrast, for commercial PV power plants, which consist of strings with more than 1,000 cells, maintaining a high I_{MPP} by sacrificing V_{MPP} is more beneficial. Under such conditions, the lowest-performing cell consistently operates in reverse bias, which accelerates the degradation of the module having large σ_{ISC}. However, the heating of poor performance cell from the reverse bias is not distinctive in the PSM due to different encapsulation method. In this work, the PSM was demonstrated on the 0.7 mm sodium free glass and all measurement was taken without encapsulation. Thus, the heating from reverse bias was well dissipated, leading to different experimental result compared to c-Si PV module cases. However, we believe that field installed PSM will be heated due to reverse bias shown in this work, because thick glass and encapsulation layers are mandatory in commercialized PSM for improving mechanical robustness.

Our experimental results from both lab-scale c-Si PV modules and PSMs demonstrate that significant I_{SC} mismatches among PV cells not only reduce the overall power output but also contribute to premature aging of the module. This degradation is primarily driven by localized heating effects in underperforming cells operating under reverse bias.

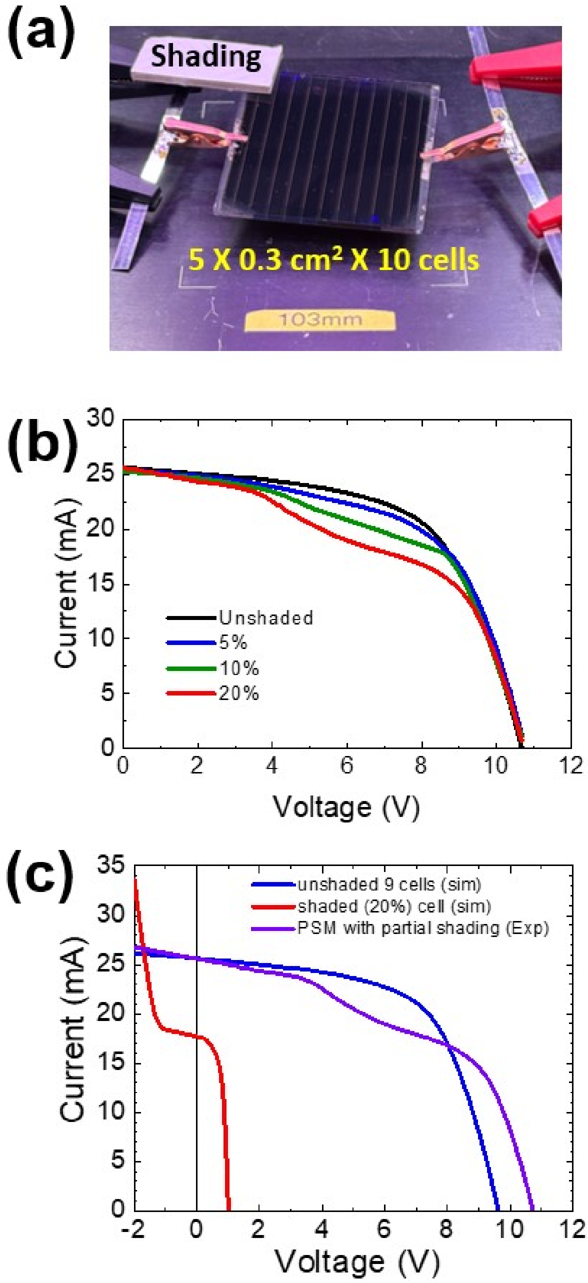

Fig S3. (a) Photograph of the PSM under a solar simulator. The module consists of 10 sub-cells, each with dimensions of ($5 \times 0.3\ cm^2$). We deliberately applied shading to a single cell to mimic non-uniform I_{SC}. (b) Empirically measured I-V characteristics of the PSM with and without partial shading. As 5, 10, and 20% of an individual PSC is shaded, the overall I–V curve of the PSM shows a progressive decrease, and a distinct kink appears. This kink serves as experimental evidence that a shaded cell can enter reverse bias operation. Due to the small number of cells in the PSM, it is more advantageous to maintain the voltage at V_{MPP}, even at the cost of reducing I_{MPP}. In contrast, in large-scale PV power plants, it is generally more efficient to bypass the shaded cell in order to sustain a high I_{MPP} under conditions of significant σ_{ISC}. (c) Simulated I-V characteristics of a single shaded PSC and series connection of unshaded 9 PSCs, based on experimental data shown in (b). The current mismatch forces the shaded cell into reverse bias, which leads to continuous temperature rise and potential thermal degradation.

4. Comparison of c-Si and perovskite solar module with σ_{ISC}

The responses of two different types of PV modules—c-Si PV modules and PSMs—without bypass diodes were compared under identical σ_{ISC}. The c-Si PV cell model used in this study exhibits an I_{SC} of 39 mA/cm², an V_{OC} of 0.74 V, a FF of 80.0%, and a PCE of 23.0%, which is comparable to that of conventional heterojunction c-Si PV cells. To match the PCE of the c-Si PV module with the PSM, the I_{SC} of the c-Si PV module was adjusted downward compared to its state-of-the-art performance (> 40 mA/cm^2). Each module consisted of 200 series-connected cells. The V_{OC} of the c-Si PV module (148.4 V) is lower than that of the PSM (225 V); however, the decreased V_{OC} can be compensated by an increased I_{SC} (25.5 -> 39 mA/cm^2).

Subsequently, the PCE of the c-Si PV module was calculated under various values of σ_{ISC}, as summarized in Table S2 and illustrated in Figure S3. To avoid any misinterpretation of the results, we used average value of the I_{SC}, V_{OC}, and PCE from six different cases, each with the same σ_{ISC}. As previously mentioned, the reverse breakdown voltage (V_{BR}) of each cell plays a role in determining the PCE of both PSMs and c-Si PV modules. Therefore, V_{BR} values were also considered in each scenario. For clarity, the simulations of the c-Si PV module were conducted with V_{BR} values of 5, 15, and 30 V, which correspond to those used for the PSM cases presented in Figure S1 and Table 1.

When σ_{ISC} is zero, both modules exhibit identical PCEs. As σ_{ISC} increases, the PCE of the c-Si PV module declines. A lower V_{BR} is beneficial for both module types in terms of maintaining higher PCE, consistent with the trends observed for PSMs. The degradation in PCE due to σ_{ISC} was found to be comparable between the PSM and c-Si PV modules, indicating that performance losses caused by non-uniform ISC are largely independent of cell type.

Although the c-Si PV module shows a slightly higher PCE than the PSM under large σ_{ISC} conditions (6–10%)—primarily due to reduced voltage loss—the performance gap is less than

0.2%. In PSMs, the voltage loss from sacrificing a single cell with low I_{SC} is approximately 1.1 V, while this loss is reduced to about 0.7 V in the case of c-Si PV modules. This may contribute to the slightly different PCE behavior under large σ_{ISC} conditions. However, in large-scale PV power plants composed of over 1000 cells per string, the impact of sacrificing a low-I_{SC} cell on voltage loess becomes less significant due to the increased number of cells per string. Consequently, the difference in PCE between c-Si PV modules and PSMs under the same σ_{ISC} becomes negligible. Overall, these results highlight the importance of controlling σ_{ISC} in PV modules, regardless of cell type.

Table S2. The average I_{SC}, V_{OC}, FF, I_{MPP}, V_{MPP}, and PCE of c-Si PV module having different V_{BR}. Here, the average value is achieved from 6 different cases having the same σ_{ISC}.

V_{BR}	σ_{ISC} (%)	I_{SC} (mA)	V_{OC} (V)	FF (%)	I_{MPP} (mA)	V_{MPP} (V)	PCE (%)
5 V	0	39.0	148.4	79.6%	36.5	126.3	23.0 (-)
	2	38.2	148.4	81.0%	36.2	126.7	22.9 (-0.4 %)
	4	37.1	148.4	81.4%	34.4	130.5	22.4 (-2.7 %)
	6	36.3	148.4	80.8%	32.7	133.2	21.7 (-5.6 %)
	8	35.5	148.4	79.1%	31.2	133.8	20.9 (-9.5 %)
	10	34.2	148.3	75.5%	28.6	133.9	19.1 (-17.0 %)
15 V	0	39.0	148.4	79.6%	36.5	126.3	23.0 (-)
	2	38.0	148.4	81.3%	36.2	126.7	22.9 (-0.4 %)
	4	36.6	148.4	82.6%	34.4	130.5	22.4 (-2.7 %)
	6	35.5	148.4	82.5%	32.7	133.2	21.7 (-5.6 %)
	8	34.3	148.4	81.6%	30.7	135.3	20.8 (-9.9 %)
	10	32.3	148.3	79.0%	27.5	137.8	18.9 (-17.9 %)
30 V	0	39.0	148.4	79.6%	36.5	126.3	23.0 (-)
	2	38.0	148.4	81.3%	36.2	126.7	22.9 (-0.4 %)
	4	36.5	148.4	82.8%	34.4	130.5	22.4 (-2.7 %)
	6	35.3	148.4	83.0%	32.7	133.2	21.7 (-5.6 %)
	8	33.9	148.4	82.5%	30.7	135.3	20.8 (-9.9%)
	10	31.7	148.3	80.5%	27.5	137.8	18.9 (-17.9 %)

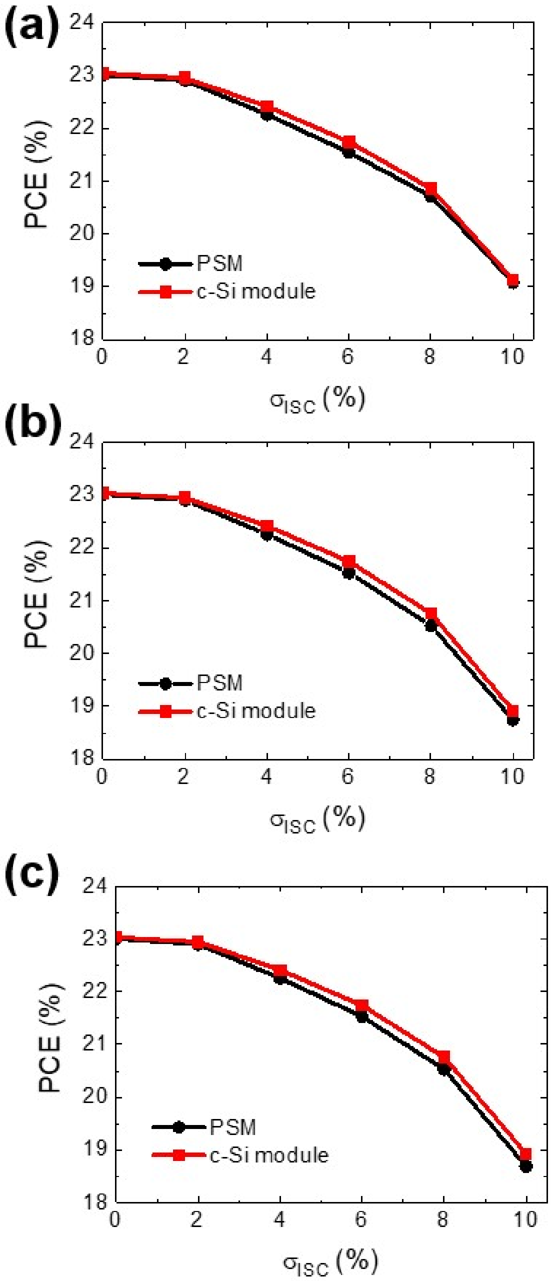

Fig S4. PCE comparison between PSM and c-si PV module under different σ_{ISC}, when V_{BR} of each cell is (a) 5, (b) 15, and (c) 30 V.

5. Minimum and maximum PCE of PSM with different configurations under various σ_{ISC}

Table S3. Minimum and maximum values of PSM-0's PCE under various σ_{ISC} conditions. Values in parentheses represent the corresponding normalized values.

PSM-0				
σ_{ISC}(%)	Average PCE	Median of PCE	Maximum PCE	Minimum PCE
0	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)
2	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)	22.8% (0.99)
4	22.3% (0.97)	22.3% (0.97)	22.8% (0.99)	21.6% (0.94)
6	21.2% (0.92)	21.4% (0.93)	22.1% (0.96)	19.6% (0.85)
8	20.2% (0.88)	20.2% (0.88)	21.6% (0.94)	18.2% (0.79)
10	18.9% (0.82)	19.1% (0.83)	20.0% (0.87)	16.3% (0.71)

Table S4. Minimum and maximum values of PSM-20's PCE under various σ_{ISC} conditions. Values in parentheses represent the corresponding normalized values.

PSM-20				
σ_{ISC}(%)	Average PCE	Median of PCE	Maximum PCE	Minimum PCE
0	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)
2	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)	22.8% (0.99)
4	22.3% (0.97)	22.3% (0.97)	22.8% (0.99)	21.6% (0.94)
6	21.4% (0.93)	21.4% (0.93)	22.1% (0.96)	19.6% (0.85)
8	20.2% (0.88)	20.2% (0.88)	21.6% (0.94)	19.3% (0.84)
10	19.1% (0.83)	19.3% (0.84)	20.0% (0.87)	18.2% (0.79)

Table S5. Minimum and maximum values of PSM-40's PCE under various σ_{ISC} conditions. Values in parentheses represent the corresponding normalized values.

PSM-40				
σ_{ISC}(%)	Average PCE	Median of PCE	Maximum PCE	Minimum PCE
0	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)
2	22.8% (0.99)	23.0% (1.00)	23.0% (1.00)	22.8% (0.99)
4	22.3% (0.97)	22.3% (0.97)	22.8% (0.99)	21.9% (0.95)
6	21.4% (0.93)	21.4% (0.93)	22.1% (0.96)	20.0% (0.87)
8	20.5% (0.89)	20.2% (0.88)	21.6% (0.94)	19.1% (0.83)
10	19.3% (0.84)	19.3% (0.85)	20.2% (0.88)	17.9% (0.78)

Table S6. Minimum and maximum values of PSM-100's PCE under various σ_{ISC} conditions. Values in parentheses represent the corresponding normalized values.

PSM-100				
σ_{ISC}(%)	Average PCE	Median of PCE	Maximum PCE	Minimum PCE
0	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)	23.0% (1.00)
2	22.8% (0.99)	22.8% (0.99)	23.0% (1.00)	22.5% (0.98)
4	22.3% (0.97)	22.3% (0.97)	22.8% (0.99)	21.9% (0.95)
6	21.6% (0.94)	21.6% (0.94)	22.1% (0.96)	20.7% (0.90)
8	20.7% (0.90)	20.7% (0.90)	21.6% (0.94)	19.6% (0.85)
10	20.0% (0.87)	20.0% (0.87)	20.7% (0.90)	18.9% (0.82)

6. Comparison of power output of PSM different configurations under various σ_{ISC}

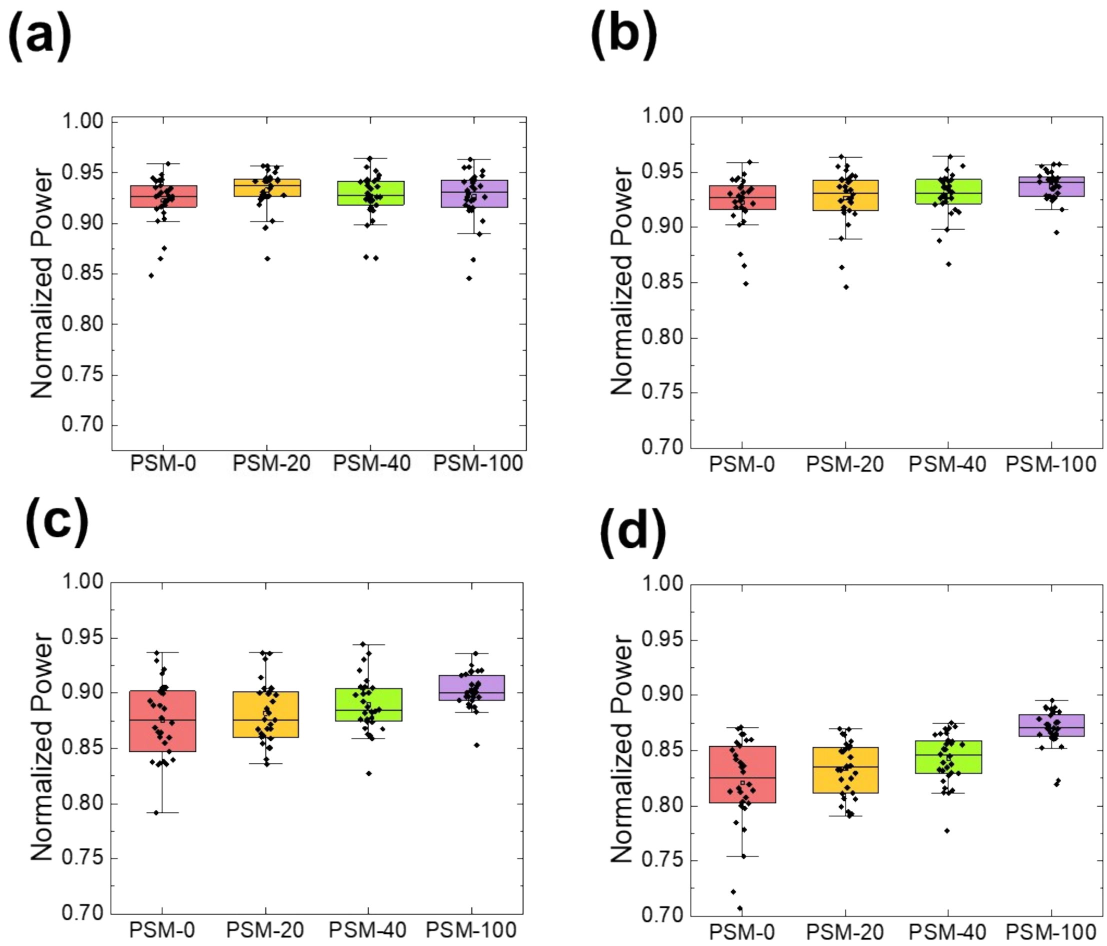

Fig S5. Normalized power distribution of PSM with σ_{ISC} of (a) 4, (b) 6, (c) 8, and (d) 10%. The graph shows that the impact of bypass diode is more pronounced at the PSM with high σ_{ISC}.