

Article

Simplified Recovery Process for Resistive Solder Bond (RSB) Hotspots Caused by Poor Soldering of Crystalline Silicon Photovoltaic Modules Using Resin

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Abstract: When the thickness of the solar cell wafer and the amount of Ag to be used decreases, it is the best method to recover the power of the module after use at a minimum cost and reuse the module itself. Economic recovery technology can be applied to the power degradation, caused by the resistive solder bond (RSB) hotspot by poor soldering, because the recovery process can be simplified compared to the power loss that is often greater than 30%. This study demonstrated a quick recovery of the RSB hotspot with on-site recovery technology applied with resin and verified the performance and long-term reliability of on-site recovery technology, compared to the factory recovery method, where the back sheet is removed and laminated to recover the module. Both the factory and field recovery methods confirmed recovery results closer to the initial rated power output of the samples. Each sample was degraded by the RSB hotspot to ~62–65% of the initial power output, and the recovery process successfully recovered it to ~96–99%. In on-site recovery, verification of the possible EVA solvothermal swelling, which is the effect of organic solvents contained in the resin on EVA, is essential for verifying the long-term reliability of the recovered module. In this study, the power degradations of the on-site recovered samples after a TC 200 cycle test are −2.14% and −0.95%, respectively, which are within the certification test standard of the new manufacturing module. Existing factory recovery costs not only in the recovery process, but also in a total of 22 stages, such as the transfer of the target module. The largest advantage is that the on-site recovery process can be restarted in the field after only eight stages.

Keywords: power degradation; poor soldering; module recovery; RSB hotspot; EVA swelling; on-site recovery



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1. Introduction

The expansion of the energy market has been highly uncertain owing to the continuing pandemic over the past few years, resulting in city blockades, a reduced trade volume, and continued work from home routines. However, the nationwide blockade and decline in trade volumes have resulted in higher prices owing to increased transportation costs and the reduced shipments of fossil fuels, a locally biased resource. Therefore, photovoltaic (PV) energy, a distributed power generation without regional bias, promises to be one of the most competitive means of power generation in the energy market [1–5]. Along with the expansion of the PV market, the inevitable problem is the disposal of the expired PV module waste. Naturally, the amount of waste in PV modules increases in proportion to the amount of installed PV and is expected to increase rapidly from less than 100 tons by 2018 to over 140,000 tons by 2054 [6–8]. The PV module consists of recyclable metals, such as Si, Al, Ag, Cu, and Sn, which are valuable materials, and low-iron glass with a high purity [9–13];

therefore, recognizing PV modules as industrial waste and burying them in landfills is not an ideal option. This paper analyzes the tendency of RSB hotspots that frequently occur in PV power plants and compares the power after recovery with the rated power of the module to focus on a method of reusing the module [14–18]. When a recovered module is restored to 70% or more of its rated output, long-term degradation is crucial to the economic feasibility and long-term reliability of the recovery technology. The simplification of the recovery process is also a factor that has the greatest impact on the economics of technology. Poor soldering occurs intensively at specific sites and models; beginning from 2 to 3 years after a commercial operation, it occurs steadily, and if left unattended, it develops into a hotspot and causes significant power loss; therefore, it is very important to respond quickly with recovery technology rather than replacing modules. However, when recovering the RSB hotspot using the factory recovery process, if the back sheet is removed to reinforce the defective soldering part, and the EVA sheet and the new back sheet are consumed again with the existing technology for the reload layer, an excessive number of parts may be reworked. For commercial power plants, a large amount of power generation loss is expected if all modules with power degradation are stored in the factory to be re-laminated and recovered. This study also verified the long-term reliability of the recovered module by applying on-site recovery technology without removing the back sheet in the field and applying sealing and insulation materials as alternative materials.

Energy recovery, recycling, reuse and minimization, and waste prevention through efficient design are preferred for a sustainable environment [19,20]. For the previous examples of recycling, several studies have been conducted on melting organic materials such as ethylene-vinyl acetate (EVA) and the back sheet of the PV module using a furnace or an organic solvent and then collecting silicon wafers [21–23], and recycling of ribbon metal and low iron glass as raw materials [24–27]. Figure 1 is a schematic of the recycling system of the PV waste module of the Foundation for Advancement of International Science (FAIS) and the procedure for recycling the PV module as raw materials [28].

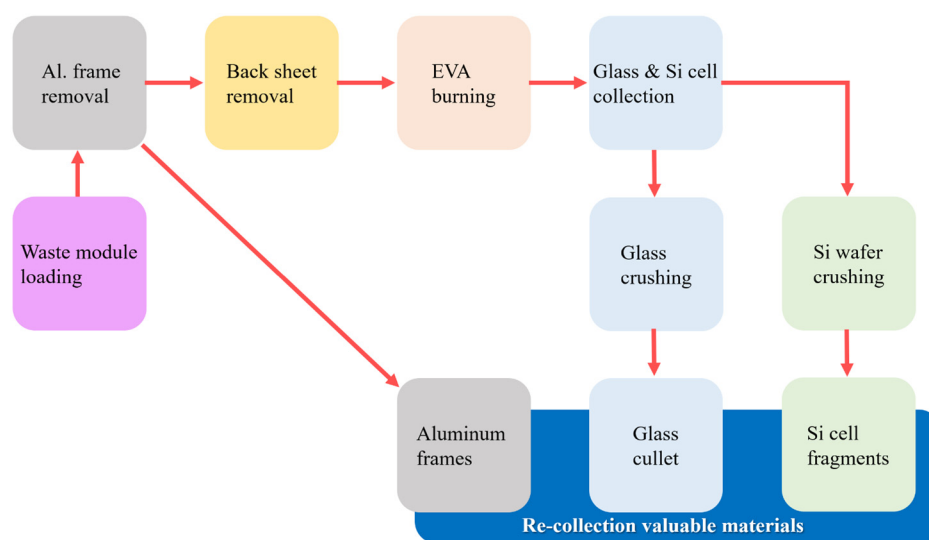


Figure 1. Foundation for Advancement of International Science (FAIS) PV panel recycling system.

However, the recycling technology presented above is not generally activated because the return on investment (ROI) is not economical at approximately -0.25 as of 2022 [29,30]. Moreover, with the continuous development of solar cell manufacturing technology, the thickness of wafers is decreasing, and the quantity of precious metals used in the technology, such as silver, is gradually decreasing [31–33]. Paradoxically, advances in technology will gradually reduce the amount and value of raw materials that can be collected from module recycling. As solar cell technology advances, the thickness of wafers is getting thinner [34–36]. According to the data, the thickness of the wafer in the single-crystal

silicon solar cell M6 grade in 2021 was approximately 165 μm , and it is expected to decrease by more than 15% to 140 μm by 2029. The amount of silver used in the cells has also decreased significantly owing to recent advances in inkjet and screen-printing technology. Additionally, it is expected that the amount of silver used, which was approximately 10 μg per cell in 2021, will be reduced by almost half by 2032 [37]. Therefore, the most desirable method of recycling a PV module is to recover the performance of the module at the end of its commercial life and use it again [38–40]. In particular, a technology to normalize the system by recovering defects in PV modules with severe power degradation in PV power plants, currently operating under the renewable portfolio standard (RPS) subsidy system, is essential. Earlier reports suggest that the performance standard be set to 70% of the initial rated power of the PV module to ensure that the recovered PV module can be reused without being legally classified as waste; it can be also resold as a used module at a discount of about 70% compared with new modules [41].

In general, a crystalline photovoltaic module consists of a string in which each individual solar cell is connected in series, and between each string, there are bypass diodes that can be bypassed when power degradation occurs in individual cells. Accordingly, when the cause analysis of the decrease in output is accurately performed, the recovery of the output may be relatively easy. Several cases with abnormal electrical power degradation in a system-linked photovoltaic power plant were tracked, promoting a considerable rise in the investigations of hotspots. One of the two external causes of hotspots is the occurrence of continuous and repetitive shading caused by structures or foreign substances, which causes power degradation, heat generation at cells or ribbon–bus bar soldering sites at certain locations, and eventually leads to a bypass diode failure [42–46]. The PV module internal factors that cause the second hotspot are cell breakage, internal insulation breakdown of the cell, P–N isolation destruction, poor soldering between the cell and ribbon, and poor soldering in the circuit between the interconnector ribbon and the upper and lower bus bars of the PV module [47–50]. External factors, including shading and burnout of the bypass diodes, will not be addressed in this paper because even if the PV module recovers, it will continue to recur in the same pattern if the cause is not removed. Figure 2 shows an image of forward and reverse biases that occur in the equivalent circuit of the PV module protected by the bypass diode.

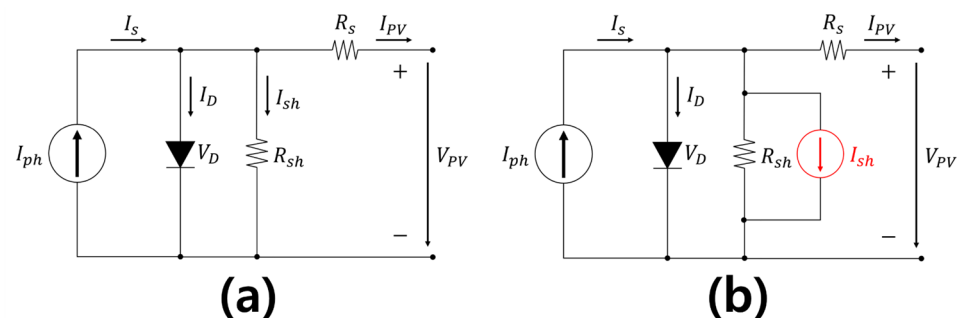


Figure 2. Forward and reverse biases occurring in equivalent circuits in PV modules with bypass diodes. (a) An equivalent circuit in the normal power generation of a photovoltaic module protected by a bypass diode; (b) a circuit where a reverse current occurs if the resistance increases.

Figure 2a shows a typical equivalent circuit in the normal power generation of a photovoltaic module protected by a bypass diode. However, if the resistance increases owing to scenarios such as shading, cell cracks, and poor soldering between the string and module bus bar, a reverse bias is applied to the module, which is shown in Figure 2b. In the figure below, I_{ph} represents the solar irradiance and I_{pv} represents the output current. R_{sh} is the shunt resistance and R_s is the series resistance. The photogenerated electric current is, the current at the diode is I_D , the leakage current is I_{sh} , the output voltage is V_{pv} , and the voltage at the diode terminals is V_D . Although studies have shown that hotspots can be caused by the internal factors of the cell and poor soldering of the ribbon attached to the

cell, the number of these hotspots is small, and the power degradation rate is relatively low. The most significant problem with power degradation is the hotspot caused by the resistive solder bond (RSB) between the interconnector ribbon and the lower bus bar on the module. As a result of investigating a plant, hotspots due to RSB appeared in approximately 4% of all installed solar modules, which was defined as “RSB hotspots.” This term is also used in this paper. The RSB hotspot has different characteristics depending on the production model, even though it can be produced by the same manufacturer, and the power loss is severe. Hotspots in the connection area above the string often cause damage to the bypass diode, causing a large electrical loss of more than 30% of the total module power output [51,52]. The current produced in the cell is connected to the junction box through the interconnector ribbon and the upper and lower bus bars of the module and is connected in series to the next PV module through a cable and connector, which are components of the junction box. Therefore, poor soldering that occurs when manufacturing a module increases its resistance owing to the thermal cycle, etc., eventually develops into an RSB hotspot where the temperature is abnormally high, thereby damaging the bypass diode. Figure 3 shows the current flow diagram of a normally operating cell and module. The PV module is composed of cells suitably in series and parallel to implement the desired electrical performance. As illustrated in Figure 3, a bypass diode is connected between the cell strings optimized to group properly, thereby protecting a part of the module from abnormal operation [53].

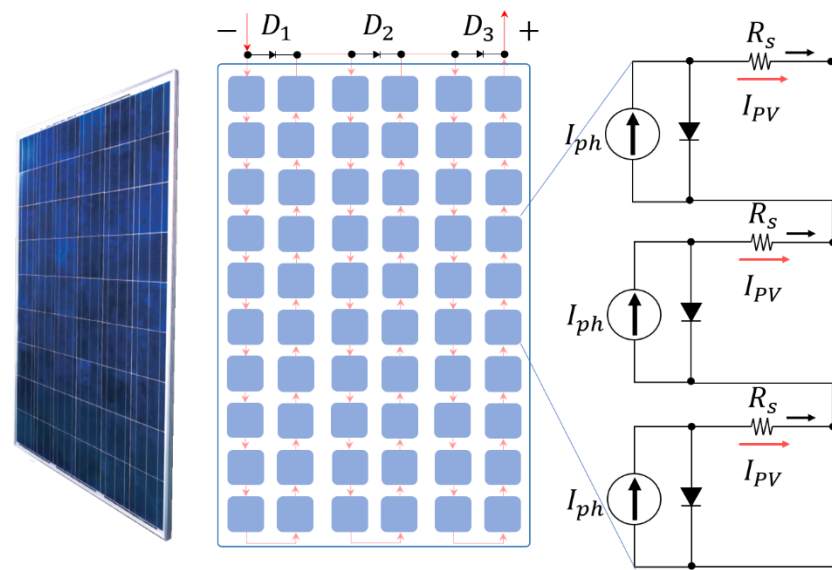


Figure 3. Current flow in PV cells and module. (All bypass diodes D_1 , D_2 , and D_3 are inactive).

Theoretically, the R_{sh} of a solar cell in a normal state is a very large value, and the current cannot flow elsewhere. In addition, R_s such as a cell that transmits electricity, an interconnector, and a silicon wafer that forms the cell, operates in an infinitely small state. The current equation for the PV module in the normal state is given by Equation (1). I_{Rsh} is the current at shunt resistance.

$$I_{PV} = I_{ph} - I_{D1} - I_{D2} - I_{D3} - I_{Rsh} \quad (1)$$

In a normal state, no leakage current occurs in the cell, and the series resistance is infinitely small; thus, no current flows in the bypass diode direction, and thus the power generation current is maximized. I_{D1} , I_{D2} , and I_{D3} are diode characterization currents, q is the electron charge, n_1 , n_2 , and n_3 are ideality factors, k_B is Boltzmann's constant, and T is the temperature. The effect of the diode can be expressed in more detail in Equation (2).

$$I_{PV} = I_{ph} - I_{D1} \left[\exp \frac{q(V + IR_s)}{n_1 k_B T} - 1 \right] - I_{D2} \left[\exp \frac{q(V + IR_s)}{n_1 k_B T} - 1 \right] - I_{D3} \left[\exp \frac{q(V + IR_s)}{n_3 k_B T} - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (2)$$

P_{max} is the maximum power output, I_{sc} is the short-circuit current, V_{oc} stands for open-circuit voltage, I_{mp} is the current at the maximum output, V_{mp} stands for voltage at the maximum output, and the fill factor (FF) is the filling coefficient. If a failure occurs due to a short circuit in the bypass diode of the module, I_{sc} does not change significantly, but V_{oc} decreases, and the most decreases occur in V_{mp} and P_{max} . If the bypass diode fails, a short circuit is configured with other cells, and even when there is no shade in the cell, the current flows to the faulty bypass diode, as shown in Equation (3).

$$I_D = I_{sc} - I \quad (3)$$

The voltage of the solar cells connected to the failed bypass diode is the sum of the current and resistance flowing to the diode. If the bypass diode fails, the power output of the PV module decreases. The current of the PV module, including the failed bypass diode, is shown in Equation (4). The reverse current induced by the mathematical model is proportional to the power degradation of the PV module.

$$I = I_{sc} - I_0 \left[\exp \frac{\frac{V}{2N} + IR_s - \left(\frac{I_D R_D}{2N} \right)}{n V_{th}} - 1 \right] - \frac{\frac{V}{2N} + IR_s - \left(\frac{(I_{sc} - I) R_D}{2N} \right)}{R_{sh}} \quad (4)$$

2. Experiments

Figure 4 shows a factory recovery process diagram of a 6-inch 54-cell 2BB polycrystalline silicon solar cell product, whose power was degraded by poor soldering and was a sample of power degradation caused by the RSB hotspot collected from a commercial power plant. We name 205A the 205-Wp grade sample whose output has been degraded due to poor soldering. The figure below shows the conventional process of removing the EVA and busbar, replacing it with a new busbar, and recovering the output of the 205A sample through a re-soldering process. First, before removing the back sheet of the module, (a) separate the frame and remove adhesive materials such as tape or sealant between the frame and laminated module. After (b) heating and softening the EVA using a hot plate, (c) the back sheet is slowly peeled off from the corner. When the back sheet is completely peeled off, (d) remove the EVA and bus bar in the area damaged by the hotspot and organize the EVA along the interface of the upper and lower cells of the string. The tab of the cell to be connected to the new bus bar is fluxed to re-solder the bus bar, removed from the hot plate, and cooled to room temperature. In a previous study, a study found that there was no damage to the cell and 1st EVA when the back sheet was peeled off from the back using a laser [54].

After cooling the sample module to room temperature, (e) apply flux to the new bus bar to be replaced, (f) add additional soldering to connect the new bus bar, and (g) insert the first EVA between the glass and bus bar. At this time, the error between the EVA and the existing cell should be almost accurate to less than 1 mm, such that the sharp-shaped bubble does not remain after the module is recovered and is perfectly connected to the first EVA of the existing module. (h) The second EVA overlaps with a margin of approximately 5 mm larger than the restored area. Subsequently, (i) fix it using an iron tip so that the EVA is not pushed during the lamination process. (j) If the overlapping width exceeds 5 mm in this process, be careful as signs of repair may occur after lamination. Finally, (k) lay up the EVA and the new back sheet that covers the entire module, (l) check the electrical connection, and place it into the lamination process to finish. As mentioned in the introduction, when the RSB hotspot is recovered owing to poor soldering with the existing technology, an excessive rework is performed compared with the damaged area, thereby reducing the economic feasibility of the recovery process, and recovered module.

Figure 5 schematically shows an electroluminescence (EL) image and a current flow of a module of a 6-inch 54-cell 2BB polycrystalline silicon solar cell product, whose power was degraded by poor soldering and was a sample of power degradation caused by the RSB hotspot collected from a commercial power plant. The rated power of this module was 205 Wp grade; therefore, for convenience, this sample will be denoted as 205A.

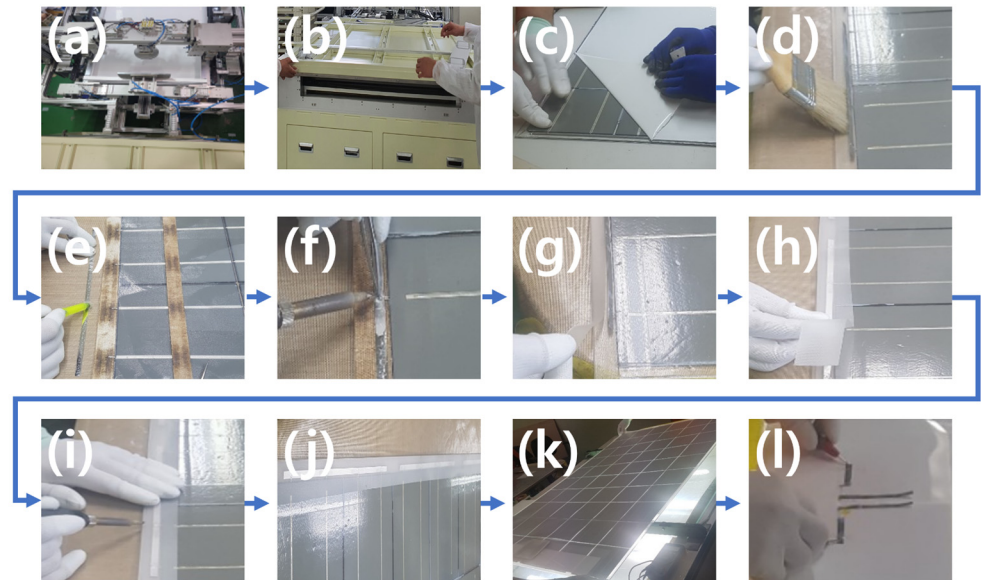


Figure 4. RSB hotspot module recovery process diagram using factory recovery technology. (a) frame disconnection, (b) EVA heating, (c) removing the backsheet completely, (d) removing the busbar, (e) apply flux (f) add soldering, (g) insert first EVA, (h) overlap second EVA, (i) secure EVA, (j) check status, (k) stack new backsheet with EVA covering whole module, (l) check electrical connection and then laminate.

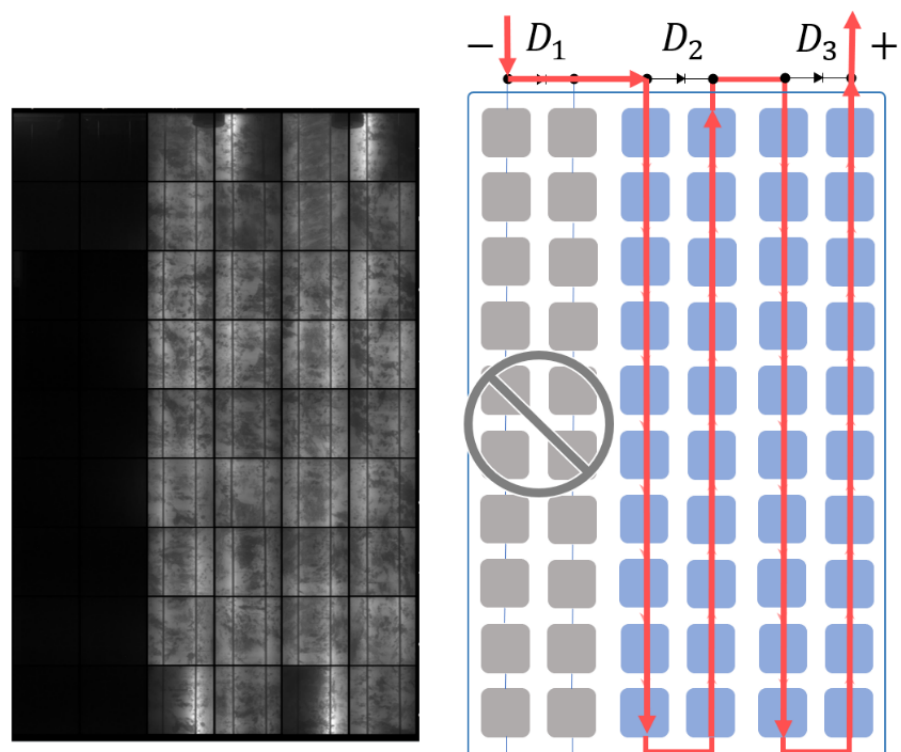


Figure 5. EL image and current flow of RSB hotspot module (205A).

Because strings 1 and 2 are shaded from the left side, the bypass diode was damaged, and the upper and lower interconnectors and bus bars of the other strings were also observed to appear as typical RSB hotspots in the EL image. Table 1 shows the results of measuring the electrical data of the 205A sample that failed owing to the RSB hotspot. In this study, the electrical value before recovery of the recovered sample was experimentally measured using a simulator, but the initial data at the time of module manufacturing were not accurate. Therefore, the electrical value indicated on the rating label attached to the sample was assumed to be an initial value, and P_{max} was calculated from V_{mp} and I_{mp} . In addition, the current–voltage (I–V) curve should be measured after replacing the short-circuited damaged diode with a normally operated diode, because measuring the I–V curve with a small resistance due to diode damage recognizes the six-string module as if it were a four-string module. A detailed explanation will be added later in the results and discussion section.

Table 1. Electrical data deviations of the initial and failed module (205A).

Item			P_{max} (Wp)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	Fill Factor	Tolerance
205A	54 cells	initial	205.39	8.39	33.10	7.78	26.40	0.74	$\pm 3\%$
		failed	130.05	8.40	32.98	7.81	16.65	0.47	-
	Rate of decline		−36.68%	-	−0.36%	-	−36.93%	−36.67%	

As confirmed in the EL image, approximately 33% of the total six strings were dark areas, resulting in a power loss of 36.56% of the EL image by adding a hotspot loss from the bottom of the 3rd and 5th strings and the top of the 4th and 6th strings. As confirmed in the EL image, two strings, which were approximately 33% of the total of six strings, are shown as dark areas. In the basic power loss of 33%, the hotspot loss from the poor soldering part of the bottom of strings 3, 5, 4, and 6 from the left side of the EL image was added, resulting in a power loss of 36.56%. As expected, the main power loss occurred at −36.93% at V_{mp} , and as a result, the fill factor also decreased by −36.67%.

Therefore, in the second experiment, the RSB hotspot module was recovered via field recovery technology using resin material and sealant to replace the lamination process after approaching the hotspot position through punching, without removing the back sheet. Figure 6 shows a process diagram of recovering the hotspot sample with on-site recovery technology without back sheet removal and lamination process. Equipment such as a hot plate or laminator are not required, whereas work lamps, electrical irons for punching and soldering, silicone varnish resin for insulation, and tape fabricated from the back sheet for finishing are used. First, (a) accurately mark the punch location by shining a light source from the bottom of the RSB hotspot part, and then (b) remove the back sheet and EVA of the part with specially manufactured iron. (c) Remove the carbonized EVA around the bus bar and the interconnector ribbon using tweezers and dry it sufficiently at room temperature. Thereafter, (d) apply flux and re-solder using an additional solder and remove the solder smoke cleanly. Instead of the lamination process, (e) a silicon resin that insulates the soldering part was used to fill the re-soldering part and the part from which EVA was removed, and then it was quickly dried at room temperature in a well-ventilated place to remove the organic solvent. Subsequently, a sealant for the PV module, which is widely applied to the junction box of the PV module and insulation inside the box, was applied, and (f) finished with tape made of the same material as the back sheet.

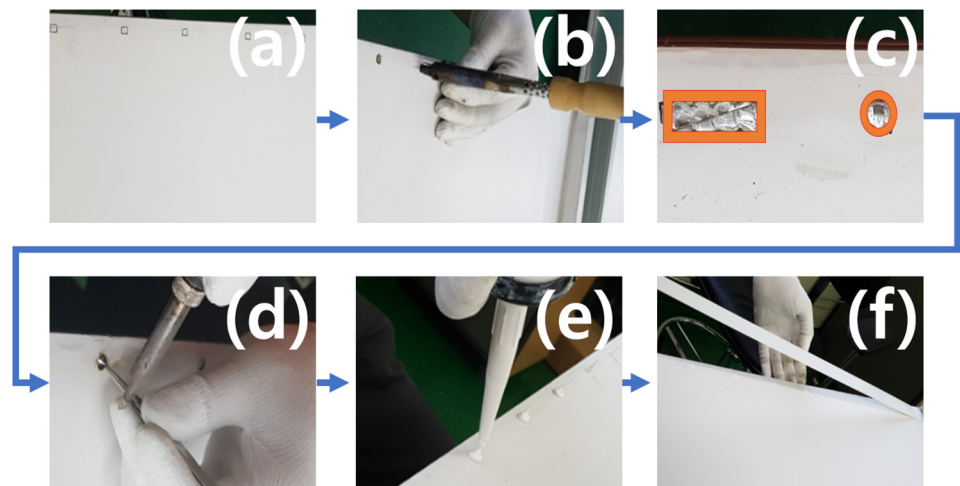


Figure 6. RSB hotspot module recovery process diagram by on-site recovery technology. (a) punching position indication, (b) removing the back sheet and EVA in the repair area, (c) removing the EVA around the busbar and ribbon, (d) re-soldering after application of flux, (e) applying silicone resin and sealant, (f) finishing with back sheet tape.

Figure 7 shows the EL image and current flow of a module of a 6-inch 60-cell 2BB polycrystalline silicon solar cell 240-Wp grade product, whose power was degraded owing to defective soldering. For convenience, this sample was called 240B to distinguish it from the previous 205A sample of 54 cells. Similar to the 205A sample, the third bypass diode from the left was damaged, as strings #5 and #6 were observed in the shade from the left. Assuming that the first cell is #1-1 on the top of the leftmost string and the lowest rightmost cell was #6-10, the upper interconnector–bus bar portion of cells #3-1 and #4-10 was also observed to be an RSB hotspot in the EL image.

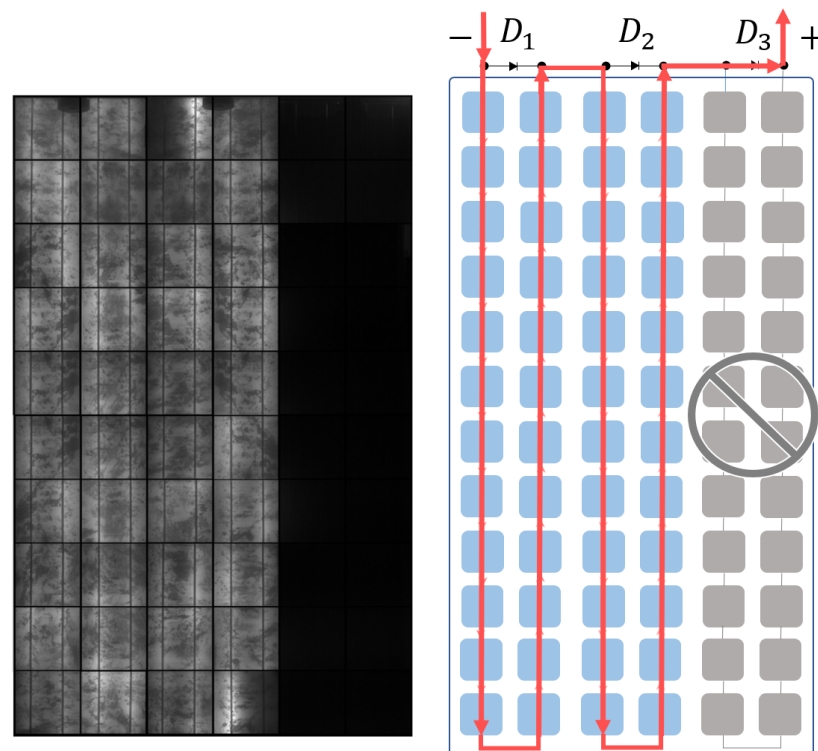


Figure 7. EL image and current flow of RSB hotspot module (240B).

In Table 2, an additional sample of the same model with symptoms, such as the 240B sample, is called the 240C sample. The table summarizes the values for measuring the electrical data of the 240B and 240C samples, whose power was degraded by RSB hotspots.

Table 2. Electrical data deviations of initial and failed modules. (240B, 240C).

Item		P_{max} (Wp)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	Fill Factor	Tolerance
240B	60 cells initial	240.78	8.63	37.40	8.08	29.80	0.75	$\pm 3\%$
	failed	149.25	8.67	37.24	8.07	18.51	0.46	-
	Rate of decline	-38.01%	-	-0.44%	-0.17%	-37.90%	-37.94%	-
240C	failed	157.25	8.64	37.26	8.11	19.39	0.49	-
	Rate of decline	-34.69%	-	-0.374%	-	-34.95%	-34.45%	-

Similarly, in the before-recovery output indicated by the failure above, the damaged diode of the 240B sample was replaced with a normal product and experimentally measured using a simulator. Even if the short-circuit bypass diode is replaced and the power is measured, a reverse current occurs owing to the RSB hotspot, and power degradation occurs equally. Rather, if the diode is short-circuited, V_{oc} and the fill factor can be distorted; therefore, the diode should be replaced, and electrical data should be measured to determine the exact damage state of the module. The details will be covered in the results and discussion section. The initial data described the values in the specification data were provided by the manufacturer, and P_{max} was calculated from I_{mp} and V_{mp} of the initial data. The difference from the previous process is the application of resin, which is widely used in building integrated photovoltaic (BIPV) modules instead of lamination [55]. Resin possesses similar properties as that of EVA or PVB, such as adhesion, strength, transparency, and insulation; thus, it has been widely used as a filler for glass-to-glass modules. However, EVA and resin mixtures are not used together, because organic solvent materials such as toluene, xylene, and ethylbenzene, may partially dissolve or cause swelling of EVA through a chemical reaction with EVA [56].

Table 3 lists the components of the silicon resin, and the contents of various organic solvents in the mixture are roughly indicated. Figure 8 shows the chemical structures of the organic solvents contained in the resin mixture. (a), (b), and (c) show the structures of (a) toluene, (b) xylene, and (c) ethylbenzene, respectively.

Table 3. Silicon resin composition table.

Components	CAS Number	Content (%)	Remarks
Silicone resin compound	-	23–35	Business confidential
Toluene	108-88-3	30–40	
Xylene	1330-20-7	10–20	
Ethylbenzene	100-41-4	10–20	

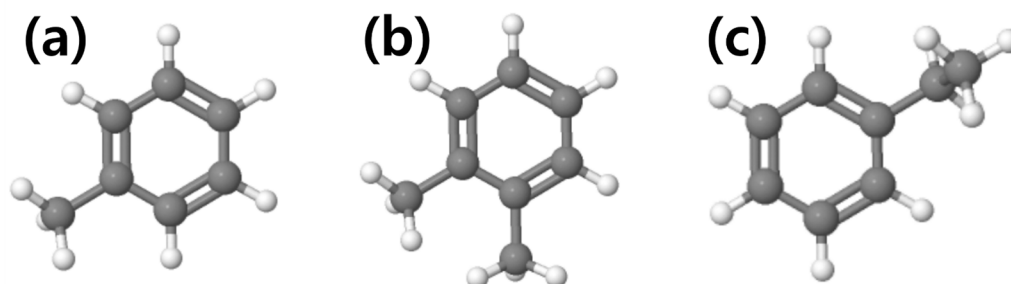


Figure 8. Chemical structures of organic solvents in resin mixtures. (a) toluene, (b) xylene, (c) ethylbenzene.

Among the components, the silicon resin compound cannot be displayed because the manufacturer did not disclose the chemical abstract service number (CAS number) or the specific composition as a trade secret, and the CAS number and chemical structure of the remaining organic solvents were as above. When the resin is cured, insulation is performed using sealant, and in a similar case, a technology for recovering insulation resistance by injecting sealant, synthetic rubber, etc., into a cracked part of the back sheet of a crystalline PV module has been introduced [57,58].

This recovery method can minimize the waste generated during the recovery process of the photovoltaic module and reduce the cost and time. First, the recovery process of the module does not require equipment such as a laminator or hot plate; therefore, on-site recovery can be performed, particularly for plants in operation. The 240B and 240C samples recovered using the above method exhibited long-term reliability through a thermal cycle (TC) 200 test.

3. Result and Discussion

Figure 9 shows an EL image before and after the recovery of the 205A module, where the RSB hotspot occurred due to poor soldering. (a) Among the six strings of the 205A sample, a bypass diode (D_1) connecting the top of the first and second strings from the left was short-circuited, and the first and second strings are shaded in the EL image. In addition, the power was degraded primarily because of RSB hotspots generated between the upper and lower bus bars and the interconnectors such as #3-9, #4-1, #5-9, and #6-1, and we inferred that the short circuit of the bypass diode was intensified or caused by RSB hotspots at the upper or lower ends of the string. (b) As a result of recovering by replacing all bus bars where RSB hotspots occurred with new busbars, other power degradation factors such as cell-in-hotspots were not observed, and the EL image was restored.

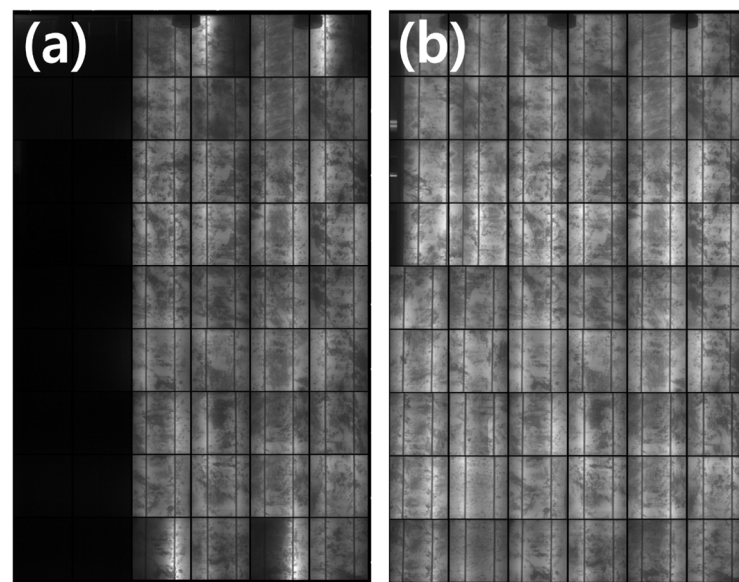


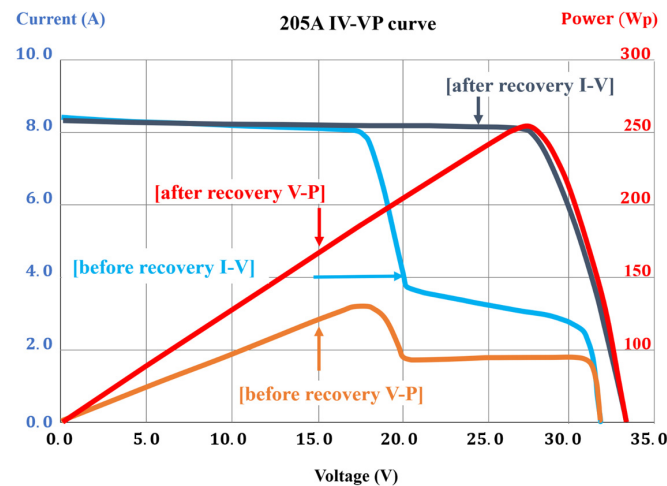
Figure 9. EL images in the module before and after recovery (205A). (a) EL image of 205A sample before RSB hotspot repair, (b) EL image of 205A sample after RSB hotspot repair.

Table 4 compares the electrical data in the initial, failed (before recovery), and after recovery states of the 205A sample. After recovery, the 205A sample recovered close to the initial rated power at 203.718 Wp, far exceeding the level suggested by previous researchers at 70% of the initial rated value of the module, to a level within $\pm 3\%$ of the normal tolerance of the new module.

Table 4. Electrical data deviations of the initial, failed, and recovered module (205A).

Item			P_{max} (Wp)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	Fill Factor	Tolerance
205A	54 cells	initial	205.39	8.39	33.10	7.78	26.40	0.739	$\pm 3\%$
		failed	130.05	8.40	32.98	7.81	16.65	0.468	-
		recovery	203.71	8.38	33.01	7.76	26.25	0.736	-
		Rate of decline (initial)	−0.816%	−0.07%	−0.26%	−2.31%	−0.59%	−0.41%	

Figure 10 shows a comparison of the I–V and voltage–power (V–P) curves before and after the recovery of the 205A sample.

**Figure 10.** I–V and V–P curves in the module before and after recovery (205A).

Earlier, the experiment indicated that the short-circuited bypass diode of the 205A sample should be replaced when measuring power, because the diode was damaged and had a small resistance; the simulator recognized the module as 36 series of four strings, not 54 series of six strings. As a result, even if the electrical power was almost the same during the simulation, V_{oc} appeared differently; thus, the fill factor was distorted as if it were a normal module in the 36 series of four strings. However, it was a module that had a short-circuited diode with six strings. Therefore, it was necessary to convert it to a normally operated bypass diode and measure the electrical data. Figure 11 shows the I–V curve of the 205A sample before and after replacing the short-circuited bypass diode.

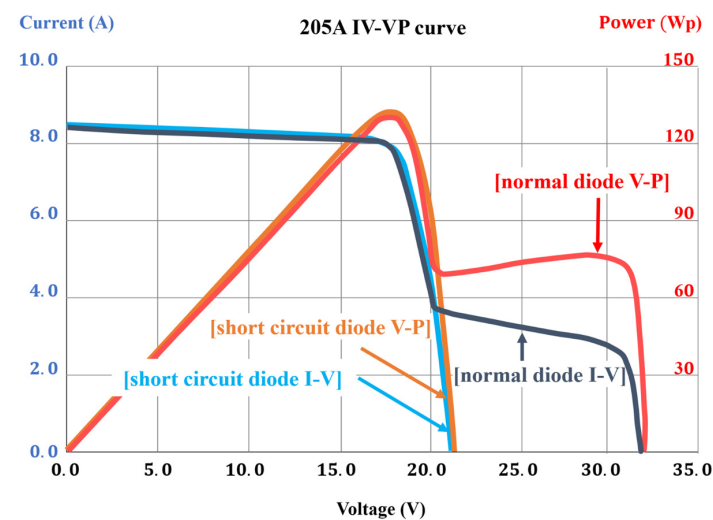
**Figure 11.** I–V and V–P curves before and after replacement of short-circuit diode (205A).

Table 5 shows the electrical data measured when the 205A sample had a short-circuited diode and changed to a normal diode before the above recovery.

Table 5. Electrical data before and after replacement of short-circuit diode (205A).

Item			P_{max} (Wp)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	Fill Factor	Tolerance
205A	54 cells	initial	205.39	8.39	33.10	7.78	26.40	0.74	±3%
		Normal diode	130.05	8.38	32.98	7.81	16.65	0.47	-
		Short circuit diode	131.61	8.28	22.66	7.75	16.98	0.70	-
Deviation (based on normal diode)			+1.20%	+1.35%	−31.29%	−0.77%	+1.98%	+49.79%	

The module power output and current values were almost the same as the two data; however, as mentioned earlier, if the bypass diode is short-circuited, it will not be able to read the V_{oc} of the shorted string. Therefore, V_{oc} was 22.66 V, which was approximately 31.3% lower than the V_{oc} value of 32.98 V in a normal diode. Thus, the fill factor value was 0.701, which did not properly reflect the power decrease in the initial module and is distorted. Therefore, to remove variables outside the module, such as diode failure, and understand the damage characteristics of the module in the state of the module damaged by the RSB hotspot, electrical characteristics should be identified after replacing the damaged diode. This is the same as the #3 diode of the 240B sample, which did not have an EL image of strings #5 and #6. Table 6 compares the initial, failed (before recovery), and electrical data for the 240B and 240C samples.

Table 6. Electrical data deviations of the initial, failed, and recovered modules. (240B and 240C).

Item			P_{max} (Wp)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	Fill Factor	Tolerance
240B	60 cells	initial	240.78	8.63	37.4	8.08	29.8	0.746	$\pm 3\%$
		failed	149.25	8.665	37.235	8.065	18.506	0.463	-
		recovered	233.70	8.57	37.15	7.99	29.24	0.734	-
	Rate of decline (initial)		-2.94%	-0.7%	-0.67%	-1.11%	-1.88%	-1.61%	
240C		failed	157.25	8.637	37.26	8.112	19.385	0.489	-
		recovered	231.9	8.43	37.38	7.90	29.35	0.736	-
	Rate of decline (initial)		-3.69%	-2.32%	-0.05%	-2.23%	-1.51%	-1.34%	

The 240B and 240C samples were recovered at 233.7 and 231.9 Wp, respectively, to 97.38% and 96.63% of the rated power, respectively, and recovered to a level slightly beyond the normal tolerance of $\pm 3\%$ of the new modules. Therefore, we concluded that the recovery results were not significantly different between factory and on-site recovery. Figure 12 shows an EL image before and after the recovery of the 240B sample module where the RSB hotspot occurred owing to poor soldering.

In the recovery process, without removing the back sheet and lamination process, a process of punching and re-soldering a hotspot part using iron, filling the part with silicon resin, and finishing it with sealant and back-sheet tape was used. In this process, the technical difference was that the insulation layer was recovered using punching and resin of iron without a process such as removing the back sheet or re-lamination used to recover the power of the 205 A sample.

Figure 13 shows a comparison of the I-V and V-P curves before and after the recovery of the 240B samples whose output was recovered.

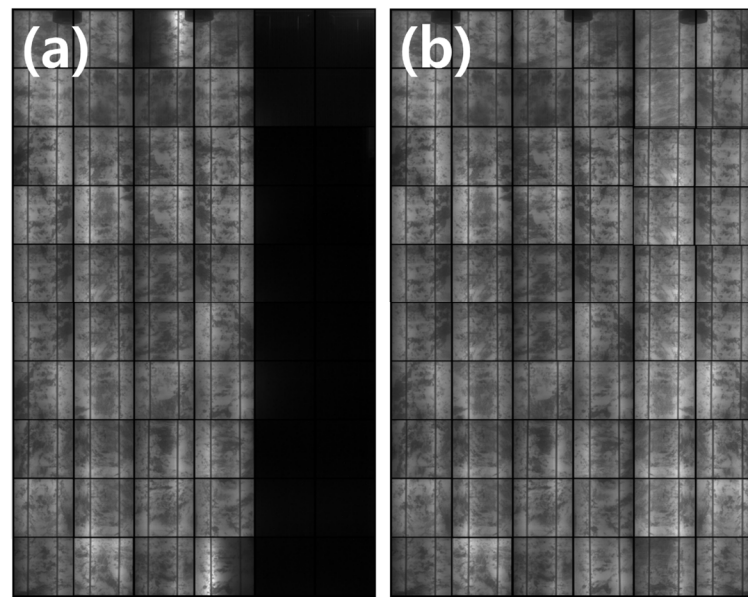


Figure 12. EL images in the module before and after recovery (240B). (a) EL image of 240B sample before RSB hotspot repair, (b) EL image of 240B sample after RSB hotspot repair.

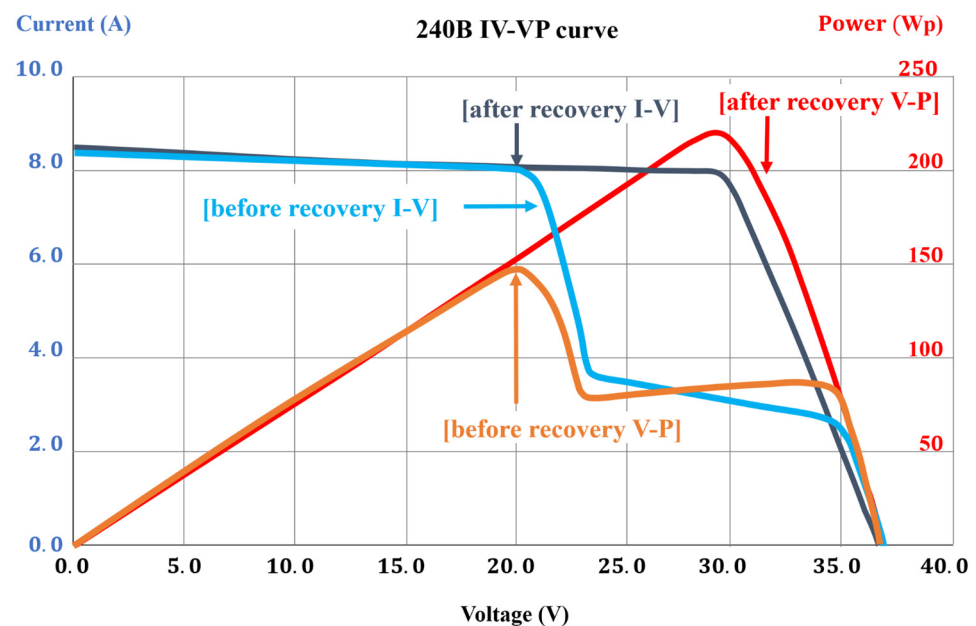


Figure 13. I–V and V–P curves in the module before and after recovery (240B).

Figure 14 schematically shows the factory recovery process used to recover the 205A module. Although the RSB hotspot was recovered close to its rating, approximately 22 processes were consumed from module collection to post-installation inspection, even if the use of the equipment was reduced as much as possible. The lack of recycling plants for waste solar modules has location problems and economic problems, but the economic feasibility caused by the high cost of collecting modules may be the reason [59,60]. The process indicated in red in the figure is one in which equipment must be used, and the equipment is used not only for the recovery process of the module, but also for the logistics transfer, and loading and unloading of the module before and after repair. If RSB hotspots occur in an operating plant, the economic loss is significant, because of the energy and cost required in the recovery process as well as the loss of power generation in the recovery module due to time delay.

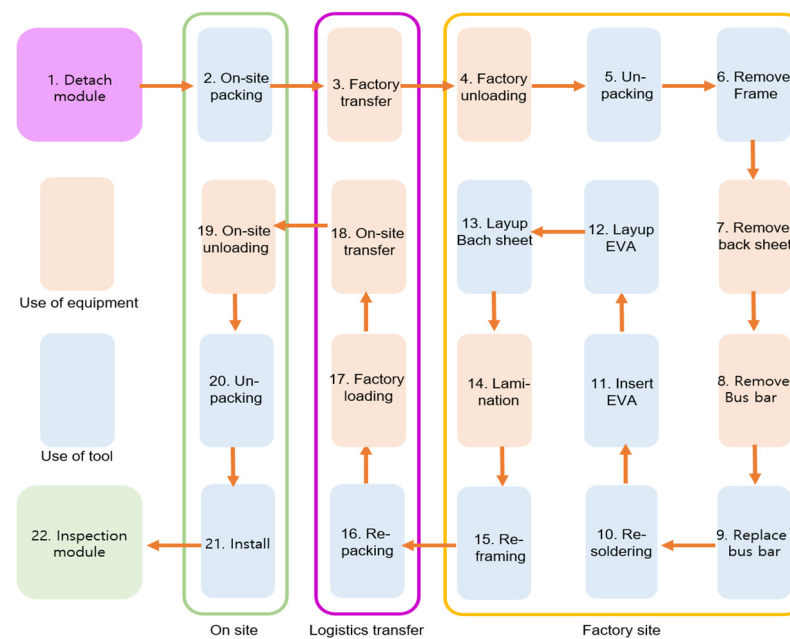


Figure 14. Factory recovery process for RSB hotspot PV module.

In the process shown in Figure 15, only a slight difference occurs in power recovery, even if the equipment is not used in the factory and only tools are used in the field. All processes are performed on-site, and after the module is restored, it can be installed on-site and inspected immediately, without repacking or transfer processes. Overall, the process of reinstalling and inspecting through 22 steps in factory restoration is reduced to eight steps, reducing the time and cost. The greatest advantage of on-site recovery is that the loss of power generation time of the most important modules mentioned above can be minimized if they are recovered by rolling them in the field. After re-soldering the upper and lower bus bars of the 240B module using on-site recovery technology and replacing the bypass diode, the RSB hot spot was also recovered by poor soldering of strings and cells. The 240C module was also recovered using the same process. Through a comparison of the technology completeness owing to the difference between the module factory recovery and on-site recovery process with recovery data, no significant difference was observed. Module 205A recovered almost to the rated level ($<1\%$), but 240B and 240C were slightly different; therefore, we determined that the initial power was assumed to be the rated power and calculated. Because 240B was recovered within the product tolerance value, only a slight power degradation occurred, and the exact initial power was not known, but for 240C, assuming that the actual initial power was 232.8 Wp, which was the lower limit of tolerance, we observed that it recovered close to -0.04% . None of the three samples recovered from the stomach were observed to have remarkable long-term degradation. As a result of the above experiment, no remarkable long-term degradation was observed in any of the three samples. Finally, compared with the reliability of factory recovery technology that has already been verified, the long-term reliability of the on-site recovery process using resin with EVA by punching was verified using a thermal cycle (TC) 200 test. Table 7 presents the results of evaluating the long-term reliability after the TC 200 test. The TC 200 test results after on-site recovery of the 240A and 240B samples indicated a change in values of -5.0 and -2.2 Wp, respectively, which were reduced by -2.14% and -0.95% from the values before the TC 200 test, respectively. After the TC 200 test, the maximum allowable Pmax degradation is -5% , and the experimental results were within the certification test criteria of the new fabrication module.

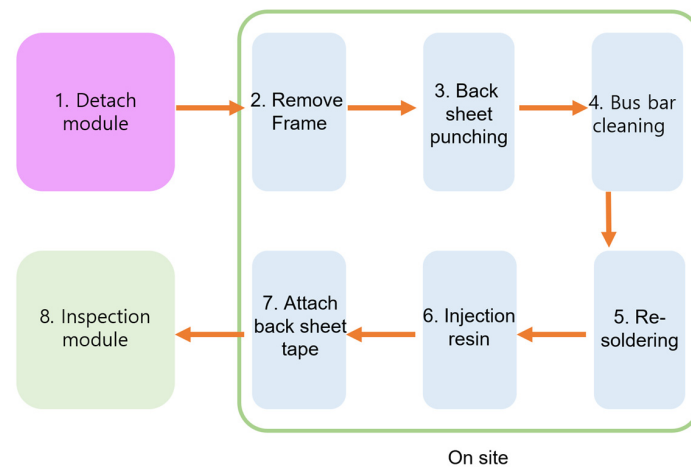


Figure 15. On-site recovery process for RSB hotspot PV module.

Table 7. Long-term reliability assessment after TC 200 test.

Item			P_{max} (Wp)	I_{sc} (A)	V_{oc} (V)	I_{mp} (A)	V_{mp} (V)	Fill Factor	Tolerance
240B	60 cells	recovery	233.70	8.57	37.15	7.99	29.24	0.73	$\pm 3\%$
		after TC 200	228.70	8.55	37.08	7.91	28.92	0.72	-
		Rate of decline	-2.14%	-0.23%	-0.19%	-1.11%	-1.00%	-1.77%	
240C	60 cells	recovery	231.90	8.43	37.38	7.90	29.35	0.74	$\pm 3\%$
		after TC 200	229.70	8.47	37.22	7.91	29.04	0.73	-
		Rate of decline	-0.95%	-	-0.43%	-	-1.06%	-0.95%	

Figure 16 shows a graph of the P_{max} change of the RSB hotspot module using the on-site recovery method. As previously stated, the bypass diode was damaged by the RSB hotspot, and both samples lost power outputs of -38.01% and -34.69% , respectively, compared with the rated power before recovery. Subsequently, the power output was recovered to -2.94% and -3.69% compared with the rated power through re-soldering using a back-sheet punching and recovery process using resin. To verify the long-term reliability of the recovery method, we performed a TC 200 test, and the power output results were measured as -2.14% and -0.95% , which are within -5% .

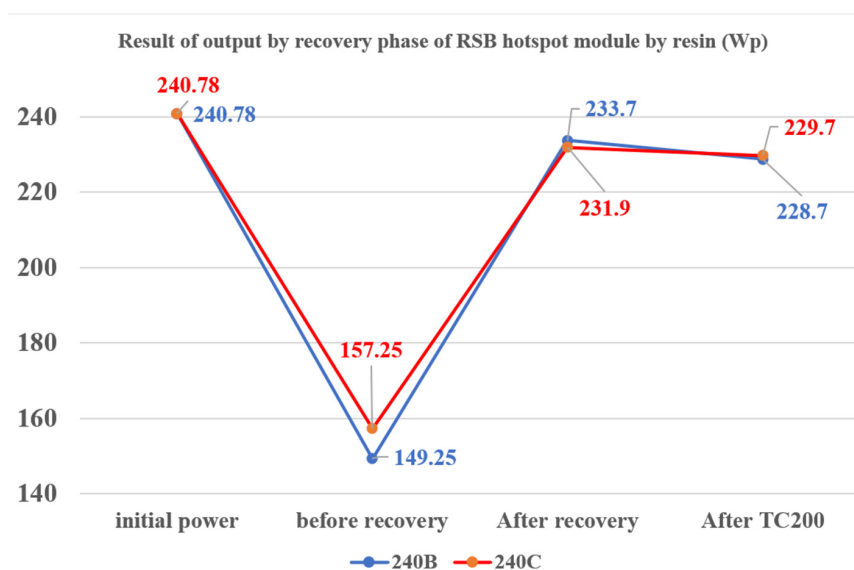


Figure 16. P_{max} change of RSB hotspot module through on-site recovery method.

Figure 17 shows a graph that summarizes the values measured through step-by-step experiments from the initial rated power and compares the power output before and after

recovery and after the TC 200 cycle test with each electrical value. An unusual observation in the recovery steps of the RSB hotspot module was that the I_{sc} values varied only slightly step by step, and the I_{mp} and V_{oc} values exhibited only slight changes when hotspots occurred, after recovery, and after reliability testing, but not to the extent of a power change. The factor directly correlated with the power change was V_{mp} , which accurately matched the power change pattern of the module step by step.

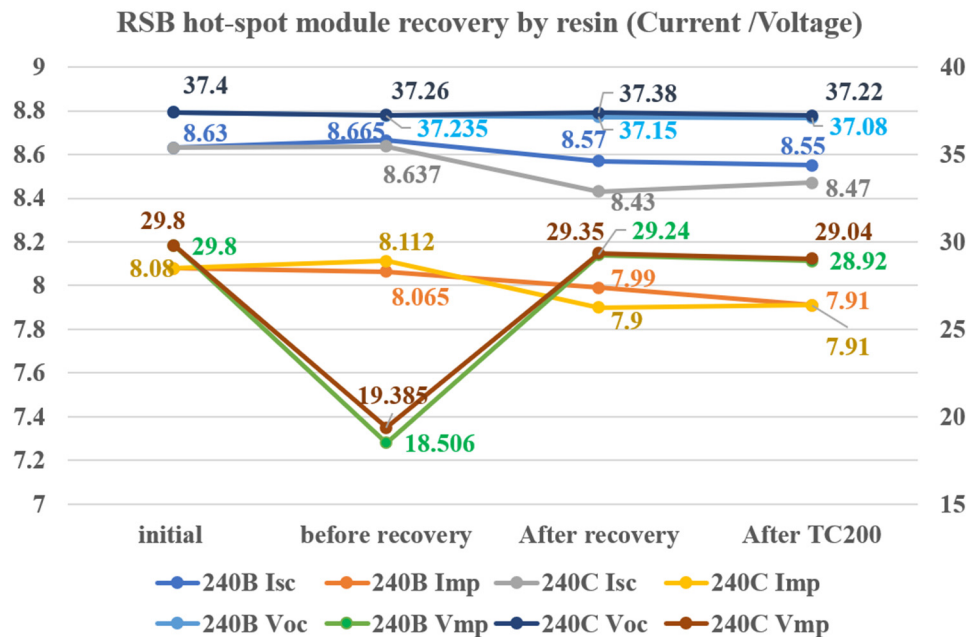


Figure 17. Result of RSB hotspot module recovery by resin. (I_{sc} , I_{mp} , V_{oc} , and V_{mp}).

4. Conclusions

This study analyzed the power loss caused by damage to the bypass diode through the EL image and the I–V and V–P curves of the module as a result of the RSB hotspot caused by poor soldering between the bus bar and the interconnector in the module. The same power as the initial power of the module was recovered. Damage to the bypass diode caused by RSB hotspots results in a large power loss of more than 30% in the unit module, which is one of the most economical module recovery methods owing to its simple recovery technique. The module recovered from the RSB hotspot almost to the rated power level, although it had been operating in a plant for many years. An important change is the application of on-site recovery technology using simple tools to improve the factory recovery technology using various types of equipment. The on-site recovery technology of the back sheet punching method and insulation with resin instead of the back sheet removal and lamination process was verified for reliability through the TC 200 cycle test. Through this process change, a recovered module can be reused after seven steps instead of the current 22-step recovery process. Note that toluene and xylene contained in silicon resin may soften EVA that is not crosslinked, even at room temperature; thus, the influence on EVA should be minimized by removing the organic solvent as quickly as possible under ventilation conditions. The sample used in this experiment was collected at a plant site after heat generation was confirmed using an IR camera, and the power loss occurred in a string of approximately 33%; thus, the power loss was approximately −37% in the 205A sample, −38% in the 240B sample, and approximately −35% in the 240C sample. The 205A sample was recovered using factory recovery, and the 240B and 240C samples were recovered using the on-site recovery method, recovering power to −0.82%, −2.94%, and −3.69%, respectively, compared with the rated power. The 240B and 240C output degradations after the TC 200 cycle test performed for long-term reliability verification of on-site recovery methods were measured at −2.14% and −0.95%, respectively. Note

that I_{sc} exhibited a slight change even when the RSB hotspot occurred and power was degraded, and V_{mp} and I_{mp} exhibited slight changes, but the largest changes were V_{mp} and the fill factor. The reason I_{sc} and V_{oc} are similar is that in the I–V and V–P curves, the starting and ending points of a normal curve are almost similar to those of a curve in which a diode operates owing to the RSB hotspot. Thereafter, the hotspot curve exhibits a small peak at a position faster than a normal curve, and when reverse current occurs, current and power decrease rapidly, and then flatly progress along the voltage axis in the form of a step in the middle and end at a V_{oc} value. Naturally, V_{mp} and the fill factor recovered most prominently after the module power was recovered. When the technology development of photovoltaic modules reduces the valuable resources that can be recycled from waste modules, considering environmentally and economically, the most desirable method of recycling a photovoltaic module at the end of its commercial life is a technology that recovers power to enable the module to be used again.

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