RESEARCH ARTICLE

Annual degradation rates of recent crystalline silicon photovoltaic modules

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ABSTRACT

Long-term reliability and durability of recently installed photovoltaic (PV) systems are currently unclear because they have so far only been operated for short periods. Here, we investigated the quality of six types of recent crystalline silicon PV modules to study the viability of PV systems as dispersed power generation systems under operating conditions connected to an electric power grid. Three indicators were used to estimate the annual degradation rates of the various crystalline silicon PV modules: energy yield, performance ratio, and indoor power. Module performance was assessed both with indoor and outdoor measurements using electric measurements taken over a 3-year period. The trends in the results of the three indicators were almost consistent with each other. Although the performance of the newly installed PV modules decreased by over 2% owing to initial light-induced degradation immediately after installation, little to no degradation was observed in all the PV modules composed of p-type solar cells over a 3-year operation period. However, the PV modules composed of n-type solar cells clearly displayed performance degradation originating from the reduction of open-circuit voltage or potential-induced degradation. The results indicate that a more continuous and detailed outdoor actual investigation is important to study the quality of new, high-efficiency solar cells, such as heterojunction, interdigitated back contact solar cells, and passivated emitter rear cells, which are set to dominate the PV markets in the future. © 2017 The Authors. Progress in Photovoltaics: Research and Applications published by John Wiley & Sons Ltd.

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1. INTRODUCTION

The total cumulative photovoltaic (PV) installation capacity worldwide had reached 223 GW by the end of 2015, with the majority installed in China, the USA, Germany, Japan, and Italy [1]. In 2014 and 2015, Japan was the second largest PV market in the world; in each of those years, PV installation ranged between 9 and 10 GW in Japan [2]. Thus, the total cumulative PV capacity in Japan was over 30 GW at the beginning of 2016. This large market indicates that PV systems are being recognized as reliable power generation systems. Therefore, the reliability and durability of PV systems are very important aspects of these PV power generation systems that provide electricity to the national electric power grid. Moreover, the reliability and durability of PV systems are two of the main factors that determine the bankability of PV projects because the lifetime of a PV system has a large impact on the cost of energy production.

Against such a background, many researches have been conducted to investigate the reliability and durability of PV modules [3–6]. Performance analyses have been conducted for bulk crystalline silicon (c-Si) PV modules, which have provided electric power as PV systems for around 20 years [7–13]. Numerous studies on the degradation rates of PV modules conducted around the world over the past 40 years have been reviewed, suggesting that the average degradation rates of bulk c-Si and thin-film technologies were 0.7 and 1.5%/year, respectively [14].

Most existing PV modules in the world have been installed recently. Therefore, there are obviously no long-term performance records yet for the most recently developed PV modules. Consequently, the quality of recently developed PV modules has necessarily been
judged based on accelerated stress tests [15–24]. However, these accelerated stress tests tended to be conducted under various stress types and stress strength conditions. Based on these investigations, the requirements of design and safety qualification for terrestrial PV modules have been established by the International Electrotechnical Commission (IEC) standards IEC 61215 [25] and IEC 61730 [26] in 2016. Working Group 2 of the IEC Technical Committee 82 on PV and the International PV Quality Assurance Task Force developed these international standards to ensure that PV modules meet a minimum acceptable quality [27]. However, it turns out that the methodologies in these IEC standards may be better suited for filtering out PV modules that cause early failure, because a review paper on accelerated stress testing concluded that standard module qualification tests cannot be used to determine the lifetimes of PV modules [28]. Therefore, it is very important to investigate the quality—and the actual degradation rates—of recently developed PV modules under actual operating conditions, even if the operating period so far is short. In particular, recently developed PV cells tend to have higher efficiencies than conventional PV cells owing to the development of numerous novel technologies to enhance PV cell efficiencies; however, it is unknown whether these enhancements may actually impact device quality in the long term.

The purpose of this study was to investigate the quality of six types of c-Si PV modules, including their degradation rates. The investigation used not only outdoor current–voltage (I–V) curves of the PV strings measured using an I–V curve tracer for PV arrays but also indoor I–V curves of the PV modules measured using a pulse-type solar simulator. In addition, electroluminescence (EL) images of all the c-Si PV modules were taken with a digital camera under forward bias conditions. In this study, we estimated the annual degradation rate of six types of c-Si PV technologies using three different methods. Furthermore, we evaluated the mechanisms of the performance degradation based on non-destructive testing procedures, such as the EL images as well as indoor and outdoor I–V curves.

### 2. EXPERIMENTAL AND METHODS

#### 2.1. Measurement location and schedule

The National Institute of Advanced Industrial Science and Technology (AIST) has been measuring the performance of PV arrays composed of two types of c-Si PV modules at the AIST Kyushu Center located in Saga Prefecture in Japan (33.2°N and 130.3°E) since October 2010. Additional PV arrays consisting of four types of c-Si PV modules were installed in December 2012. Figure 1 shows an aerial photograph of the outdoor PV measurement system at the AIST Kyushu Center, which has nine sectors. Table I explains the configuration of the six types of PV arrays located in the E-1, E-2, and W-2 sections marked by red color. [Colour figure can be viewed at wileyonlinelibrary.com]

![Aerial photograph using a camera on a drone taken by the Remote Sensing Technology Center of Japan showing the outdoor measurement system at the National Institute of Advanced Industrial Science and Technology Kyushu Center. The outdoor field is divided into nine sectors. The width of one sector is 20 m as suggested by the scale. In this study, we investigate the photovoltaic modules that are located in E-1, E-2, and W-2 sections marked by red color. [Colour figure can be viewed at wileyonlinelibrary.com]](image-url)

| Kinds | Total $P_{\text{MAX}}$ [kW] | Array configuration | Installation month/year |
|-------|-----------------|---------------------|------------------------|
| E-1A  | sc-Si           | 5.04                | 7S × 1P × 4A           | October/2010           |
| E-1B  | sc-Si           | 4.90                | 5S × 1P × 4A           | December/2012          |
| E-2A  | mc-Si           | 5.00                | 6S × 1P × 4A           | October/2010           |
| E-2B  | mc-Si           | 5.00                | 5S × 1P × 4A           | December/2012          |
| W-2A  | SHJ             | 4.80                | 5S × 1P × 4A           | December/2012          |
| W-2B  | IBC             | 4.68                | 6S × 1P × 4A           | December/2012          |

S, P, and A stand for “series,” “parallel,” and “array” in the array configuration column, respectively.
of four kinds (13 types) of thin-film PV modules in other locations, including M-1, M-2, M-3, and W-3, as of January 2016. The total of the nominal power outputs of all the PV systems is approximately 62 kW. These PV arrays are connected to multi-string power conditioning systems (PCS) with isolation transformers. The PV systems are used as grid-connected PV systems. Figure 2 shows the schedule of the indoor and outdoor measurements. Outdoor $I-V$ curves measured over the course of 3 years (from 2013 to 2015) were used in this study. Indoor measurements of all the c-Si PV modules were conducted four times, as indicated in Figure 2.

### 2.2. Types of investigated photovoltaic modules

In this study, we use location codes in order to identify the various PV module types. Two types of PV modules composed of p-type front-junction single c-Si (sc-Si) solar cells with aluminum-back surface field (Al-BSF) were located in sector E-1, namely, in E-1A and E-1B, respectively. PV modules composed of p-type front-junction multi-c-Si (mc-Si) solar cells with Al-BSF were located in sector E-2, namely, in E-2A and E-2B, respectively. The final two types of PV modules consisting of n-type front-junction sc-Si heterojunction (SHJ) and n-type rear-junction interdigitated back contact (IBC) sc-Si solar cells were located in sector W-2, namely, in W-2A and W-2B, respectively. Photographs of all the investigated PV arrays taken from the ground are shown in Figure 3. It should be noted that E-1A and E-2A modules were installed in October 2010, while the other modules were installed in December 2012 (Figure 2).

### 2.3. Configuration and wiring diagram of photovoltaic systems

Figure 4 shows the configuration and wiring diagram of an E-1 PV system. The PV arrays in both E-1A and E-1B were composed of four strings. Furthermore, all the c-Si PV arrays consisted of four strings, which were composed of
five to seven PV modules in series, as shown in Table I. The PCS used in this investigation was a multi-string PCS with eight maximum power point trackings (MPPTs). The eight MPPTs could track each maximum power point of the eight strings (E-1A and E-1B) independently. Similarly, the eight strings in E-2 (E-2A and E-2B) and the eight strings in W-2 (W-2A and W-2B) were also tracked independently by the MPPTs in the multi-string PCS. The nominal power output of one PV string was between 1.17 and 1.26 kW. Therefore, the nominal power output of each array was between 4.68 and 5.04 kW (Table I). The results were corrected to just 5 kW using the nominal power output defined by the manufacturers to correctly evaluate the relative performance of each array.

2.4. Measurement systems of outdoor current–voltage curves of photovoltaic strings

The outdoor I–V curves of the PV strings were measured using I–V curve tracers for outdoor PV arrays. The method for measuring the I–V curves of eight strings using only one I–V curve tracer is as follows. The first string is separated from the grid and connected to the I–V curve tracer first. After measuring its I–V curve, the first string is reconnected to the grid through the PCS. Then, the second string is separated from the grid and connected to the I–V curve tracer. By repeating the same procedure for all remaining strings, we can obtain the I–V curves of the eight strings. Such cycle measurements were conducted every 10 min. The sweep time of one I–V curve was approximately 500 ms. The direction of the I–V sweep was from open-circuit voltage ($V_{OC}$) to short circuit current ($I_{SC}$).

2.5. Measurement systems of meteorological parameters

Meteorological parameters, such as in-plane solar irradiance, direct solar irradiance, solar spectrum, air temperature, wind velocity, wind direction, and relative humidity, were measured by meteorological measuring instruments. All the instruments were manufactured by EKO Instruments Co., Ltd., Tokyo, Japan and compiled as a measuring system by Climatec Inc., Tokyo, Japan. In this study, we use solar in-plane irradiance and solar spectra measured by a pyranometer (MS-802) and spectroradiometers (MS-710 and MS-712), respectively. The meteorological station is operated by the Japan Weather Association. Japan Weather Association has operated meteorological stations with the same components at five locations in Japan including the AIST Kyushu Center since 2008 [29,30]. In addition, the backsheets temperature of every array was measured as module temperature using t-type thermocouples. We selected a solar cell near the center of each PV module. The t-type thermocouple was fixed to the backsheet at the position of the center of the selected solar cell with aluminum tape.
2.6. Method A: estimation based on annual energy production

In the first method, we calculated the monthly energy production of every PV array composed of four strings, based on the total of the maximum power outputs \( P_{\text{MAX}} \) derived from the outdoor \( I-V \) curves of the four strings. For example, the monthly energy production (1 kWh/1 kW) of a PV array from 1 to (n) January 2013 is given by

\[
\text{Monthly energy production} = \sum_{i=1}^{31} \frac{P_{\text{MAX},i}}{6} \frac{\text{kWh}}{\text{kW}} \tag{1}
\]

where \( P_{\text{MAX(NOM)}} \) is the nominal power output of the PV array shown in Table I and \( P_{\text{MAX},i} \) is the calculated from the outdoor \( I-V \) curves of the four strings measured on the day “i”. In Eqn (1), the right term must be divided by 6, because outdoor \( I-V \) curves have been measured six times for an hour.

Then, the annual energy production was calculated from the total of the monthly energy production for each year. In general, the main factors that influence the performance of PV systems are the solar irradiance, module temperature, solar spectrum, and angle of incidence. The effects of the module temperature, solar spectrum, and angle of incidence vary with the seasons. Because these seasonal variations occur again every year, their effects on PV performance could be neglected when determining differences in the yearly energy yield. However, the total yearly solar irradiation, which directly affects the PV performance, is different each year and varies throughout the year. In this study, the annual energy yield of E-1A (sc-Si) was used as a reference to normalize the annual energy yield of the other PV arrays because the PV modules in E-1A showed quite a stable performance and little to no degradation over the measurement period, as will be described in Section 3. It should be noted that method A could not be used to estimate the annual degradation rates of PV systems without such a stable reference system.

As such, the degradation rate of every PV array was estimated based on the change in each array’s annual energy production. There are many missing outdoor \( I-V \) curves because of power outages, issues with the measurement systems, and removal of the modules for indoor measurements. Therefore, a data filtering method was used in order to compare every array’s relative energy production suitably. We selected only the \( I-V \) curves of which all the strings were normally measured without any missing values in the relevant time interval. The selected \( I-V \) curves were further picked out by a filtering condition that all the \( P_{\text{MAX}} \) calculated from the selected \( I-V \) curves were more than 0 W in the relevant time interval. All the missing data could be removed using this filtering method.

2.7. Method B: estimation based on the performance ratio

In the second method, the performance ratio (PR) of each PV array was used to evaluate its degradation rates. PR is frequently used to investigate the soundness of PV systems. An array’s PR is given by

\[
\text{PR} = \frac{P_{\text{MAX}}}{P_{\text{MAX(NOM)}}} \cdot \frac{G}{G_{\text{STC}}} \tag{2}
\]

where \( G \) is the measured solar irradiance and \( G_{\text{STC}} \) is the solar irradiance of 1000 W/m² as defined by standard test conditions (STCs). PR is generally calculated under high and stable solar irradiance conditions [31,32]. Therefore, we used only outdoor \( I-V \) curves that were measured under solar irradiances of 700 W/m² or greater. Additionally, we selected only \( I-V \) curves measured under the condition that the difference in the solar irradiance between the start and end of each 10-min time interval was 5% or less. Furthermore, we selected only \( I-V \) curves measured under the condition that such time intervals occurred six times or more in a row in order to select stable solar irradiance conditions. This filtering method could select only the periods in which the solar irradiance was continuously both high and stable over 60 min.

An array’s PR is converted into \( \text{PR}_{T=25} \), that is, PR at a temperature of 25 °C as defined by STC. The correction equation is given by

\[
\text{PR}_{T=25} = \text{PR} \times \frac{1}{1 + \gamma(T - 25)} \tag{3}
\]

where \( \gamma \) is the temperature coefficient for PR and \( T \) is the measured module Celsius temperature. The temperature coefficient (\( \gamma \)) for every type of PV module is defined from the slope value of the least squares regression line for the relationship between the filtered PR and \( T \).

The monthly averages PR and \( \text{PR}_{T=25} \) of each PV array were estimated from the averages of the filtered PR and \( \text{PR}_{T=25} \) values, respectively, for each month. Then, the monthly average \( \text{PR}_{T=25} \) was further averaged over each year, which resulted in the annual average \( \text{PR}_{T=25} \). The degradation rate of each PV array was estimated from the change in the annual average \( \text{PR}_{T=25} \).

2.8. Method C: estimation based on indoor module performance

All the PV modules were removed from the mounting systems once a year to investigate their indoor \( I-V \) characteristics under STC and EL images of the modules. So far, we have measured the indoor \( I-V \) curves four times and taken EL images of each PV module twice, as demonstrated in Figure 2. A pulse-type solar simulator (PVS 1222i made by Nissinbo Mechatronics Inc., Tokyo, Japan) was used for the indoor \( I-V \) curve measurements. The direction of the \( I-V \) sweep was from \( I_{\text{SC}} \) to \( V_{\text{OC}} \). \( P_{\text{MAX}} \) was evaluated from the measured indoor \( I-V \) curves.

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The annual degradation rate was estimated from the change in the average $P_{\text{MAX}}$ of every PV module.

The solar simulator used here is classified as a class AAA device (spectral content, spatial uniformity, and temporal stability) according to the IEC 60904-9 standard [33]. Xenon arc lamps were used as light sources. The repeatability of the $I$–$V$ curve measurements of the pulsetype solar simulator is within ±0.25% according to the manufacturer’s specifications. In this study, we do not discuss the uncertainty of the measurement because the purpose of the study is to investigate the yearly performance changes of the recent PV modules. In this case, the excellent repeatability (not the reproducibility) is more important than the uncertainty of the measurement.

As such, we estimate the annual degradation rates of the PV modules by the three methods. The methods A and B are based on the outdoor $I$–$V$ of the PV arrays. The reference PV arrays (E-1A) and pyranometer were used as the reference in the methods A and B, respectively. Conversely, method C is based on the indoor $I$–$V$ curves with excellent repeatability. In this case, a calibrated sc-Si PV module was used as the reference.

3. RESULTS

3.1. Annual degradation rates estimated by method A

The nominal power output values of E-1A, E-1B, W-2A, and W-2B are not each 5 kW, as stated in Table I. This is because we wanted to compare their performances properly; therefore, the monthly energy production of each c-Si PV array measured in direct current (DC) (shown in Figure 5) was normalized to 5 kW by the nominal power output values specified by the manufacturers, as described in Section 2.3. The highest monthly energy yields were observed in May each year. This is because spring includes many sunny days each year in Saga Prefecture.

At first glance, the relative monthly energy production of each array shown in Figure 5 does not seem to change throughout the measurement period. However, we can identify in more detail that the monthly energy production of W-2A (SHJ) gradually decreases by a slight amount. The monthly energy yield of the c-Si PV arrays was further averaged for each year to evaluate the changes in the annual energy production. We can observe a clear performance degradation of W-2A in Figure 6, which shows the normalized annual energy production. Table II summarizes the annual degradation rate of each type of PV array. The annual degradation rate of W-2A was approximately 1.5%/year. The annual energy yield of E-2A (mc-Si) and E-2B (mc-Si) seems to be almost constant, suggesting that no to little degradation occurred. The normalized annual energy production of W-2B (IBC) decreased gradually (0.5%/year), although that of E-1B increased (~0.4%/year).

Figure 5. Monthly direct current energy production of each photovoltaic array normalized to 5 kW. The cause of the low energy yield in November 2013 is because of some issues with the measurement systems. The low or absent energy production in December 2014 and 2015 was caused by the removal of the photovoltaic modules from the mounting to conduct the indoor measurements. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 6. Annual energy yield normalized by that of E-1A (method A). Therefore, the value of E-1A is always 1. [Colour figure can be viewed at wileyonlinelibrary.com]
3.2. Annual degradation rates estimated by method B

Figure 7 (a) shows the monthly average PR of the c-Si PV arrays. All the PRs show higher values in winter and lower values in summer. This is mostly caused by seasonal variations in module temperature. Therefore, the monthly PR was corrected to 25 °C (PR$_{25}$) using equation (1), the results of which are shown in Figure 7 (b). The monthly average PR$_{25}$ was further averaged over each year as described in Section 2.7.

Figure 8 shows the annual average PR$_{25}$ values of the c-Si PV arrays. The overall trend shown in Figure 8 is quite similar to that in Figure 6. We can also observe a distinct performance degradation of the W-2A (SHJ) array. In addition, the annual average PR$_{25}$ of W-2B (IBC) also visibly decreases. As shown in Table II, the annual degradation rates of W-2A and W-2B were approximately 1.4 and 0.5%/year, respectively. The annual average PR$_{25}$ of E-1B (sc-Si) also increased by approximately 0.4%/year (i.e., the degradation rate was 0.4%/year). The annual degradation rates of the other arrays were quite low, which is consistent with the results of method A. The results indicate that E-1A, which does not show any performance change, is suitable to be used as the reference array in method A.

Table II. Summary of the annual degradation rates in %/year of the investigated c-Si PV modules estimated by methods A, B, and C.

| Method   | E-1A (sc-Si) | E-1B (sc-Si) | E-2A (mc-Si) | E-2B (mc-Si) | W-2A (SHJ) | W-2B (IBC) |
|----------|--------------|--------------|--------------|--------------|------------|------------|
| (A) Energy yield | 0.0 | -0.4 | 0.0 | 0.1 | 1.5 | 0.5 |
| (B) Outdoor PR | 0.0 | -0.4 | -0.1 | 0.0 | 1.4 | 0.5 |
| (C) Indoor PR$_{max}$ | 0.1 | -0.3 | 0.2 | 0.0 | 0.7 | 0.6 |

Positive and negative values indicate degradation and recovery, respectively.

3.3. Annual degradation rates estimated by method C

Figure 9 shows the average indoor power outputs (W) of the PV modules normalized by the nominal power outputs (W) specified by the manufacturers. The arrows shown in Figure 9 indicate the initial light-induced degradation (LID) [34, 35]. The performance of E-1B (sc-Si) and E-2B (mc-Si) decreased by about 2.6 and 2.2%, respectively, between December 2012 and January 2014. However, such a distinct performance degradation cannot be observed in the results of the outdoor measurements shown in Figures 6 and 8. Therefore, we propose that any LID occurred just after outdoor exposure. In order to omit the effect of the LID, the annual degradation rates of E-1B...
and E-2B were estimated while excluding the values measured in December 2012.

Table II shows that the annual degradation rates of W-2A (SHJ) and W-2B (IBC) were about 0.7 and 0.6%/year, respectively. The annual degradation rate of E-1B was −0.3%/year. The annual degradation rates of the other arrays were very low. Hence, the annual degradation rates estimated by the indoor measurements (method C) are consistent with those estimated by the outdoor measurements (methods A and B), with the exception of the degradation rates of W-2A.

A degradation rate of 0.7%/year was estimated for W-2A based on the indoor measurements, while rates of 1.5 to 1.4%/year were estimated based on the outdoor measurements. We speculate that the difference in the degradation rates may result from a decrease in the spectral response (or quantum efficiency) in the long wavelength region because the spectrum intensity of the solar simulator is much lower than that of the natural solar irradiance or the Air Mass 1.5 Global standard spectrum [36,37] in the region above 1000 nm. Furthermore, it should be noted that the solar simulator with pulse width shorter than 100 ms used in this study cannot measure the absolute...
power outputs of high-efficiency modules such as SHJ modules with high capacitance. For example, the energy production and PR of W-2A in 2013 show the highest values (Figures 6 and 8), although the indoor power output of W-2A shows the lowest value (Figure 9). The power outputs from PV arrays are actually extracted not by an $I-V$ curve tracer but by a MPPT system incorporated into PCS. We confirmed that the values of the DC power at the PCS are consistent with those of the outdoor measurements. Therefore, the degradation rates based on the outdoor measurements would be close to the true values. Anyway, the inconsistency of the W-2A modules' indoor and outdoor measurements will be the topic of future research.

4. DISCUSSION

In this section, we discuss the degradation mechanisms, based on the measured indoor $I-V$ curves, their $I-V$ curve parameters, and the EL images of the PV modules.

4.1. Degradation mechanisms inferred from indoor current-voltage curves of photovoltaic modules

Figure 10 shows the measured indoor $I-V$ parameters normalized by the nominal parameters specified by the manufacturers. All the normalized $I-V$ parameters of E-1A (sc-Si) and E-2A (mc-Si) show little variation (Figure 10 (a) and (c)), which is in agreement with the annual degradation rates discussed in the previous section. This is also consistent with the indoor $I-V$ curves of 1-1 module in E-1A and E-2A, shown in Figure 11. In particular, the $I-V$ curves around $V_{OC}$ in Figure 11 (a) and (b) overlap almost perfectly.

4.2. Light-induced degradation and regeneration of p-type solar cells

Figure 10 (b) and (d) shows the normalized indoor $I-V$ parameters of E-1B (sc-Si) and E-2B (mc-Si) modules, respectively. As described in Section 3.3, the performance of these PV modules initially decreased owing to LID. The performance degradation of E-1B results from decreases in both $I_{SC}$ and $V_{OC}$, whereas that of E-2B originates almost exclusively from a decrease in $I_{SC}$. These results are in agreement with the shapes of the indoor $I-V$ curves shown in Figure 12. Moreover, the magnified inset in Figure 12 (a) indicates that part of the $I-V$ curves, where $P_{MAX}$ is obtained, certainly recovered from December 2014 to December 2015.

LID is generally ascribed to boron–oxygen (B–O) complexes in the bulk of p-type Czochralski sc-Si with high oxygen content [38–41]. However, there have been few studies on the LID of mc-Si solar cells with low oxygen content [42]. The B–O complexes act as recombination centers thereby reducing the minority carrier lifetime. The LID originating in B–O complexes can be recovered by thermal annealing. The temperature and time for thermal annealing are generally set to 200 °C and 30 min, respectively. Moreover, it has been recently demonstrated that B–O complexes can be permanently deactivated under the combined action of temperature and illumination [43–45]. This phenomenon is known as light-induced regeneration (LIR), which improves the performance of solar cells, in particular that of high-efficiency passivated emitter and rear cell [46,47]. LIR may explain the performance recovery observed in the PV modules in E-1B, because the module temperature increases near 70 °C in summer and an activation energy for LIR of 0.61 ± 0.01 eV is reported [44].
Figure 13 shows the EL images of module 4-5 in E-2B taken in December 2014 (Figure 13 (a)) and December 2015 (Figure 13 (b)). The number of cell cracks observed in E-2B modules is by far the largest among the six types of PV modules. We compared the EL image of each PV module in E-2B taken in December 2014 with those taken in December 2015. No increase in the number of large-sized cell cracks was observed. However, it is highly possible that the performance of the E-2B modules may reduce in the near future.

Figure 12. Indoor current-voltage (I-V) curves of module 4-5 in (a) E-1B and (b) E-2B. The magnified inset in (a) indicates that the I-V curves of the sc-Si module recovered between December 2014 and December 2015, although the I-V curve initially decreased because of light-induced degradation. As indicated by black arrows, the performance degradation of E-1B resulted from decreases in both I_{SC} and V_{OC} (a), whereas I_{SC} was the main factor for the performance reduction of E-2B (b). [Colour figure can be viewed at wileyonlinelibrary.com]
4.3. \( V_{OC} \) reduction of sc-Si heterojunction solar cells

Figure 10 (e) shows the normalized indoor \( I-V \) parameters of the W-2A (SHJ) modules. The gradual performance degradation mostly originates from the decrease in \( V_{OC} \). The shapes of the \( I-V \) curves also show a gradual decrease in \( V_{OC} \), as shown in Figure 14. In this study, we conducted only electrical characterizations and no destruction inspections. However, it is generally considered that a decrease in \( V_{OC} \) may imply some deterioration of the surface passivation layers composed of hydrogenated amorphous Si, the transparent conductive oxide coating, or their interfaces.

4.4. Potential-induced degradation of interdigitated back contact solar cells

Figure 10 (f) shows the average values of the normalized indoor \( I-V \) parameters for the 24 modules contained in the four strings in W-2B (IBC). One string is composed of six modules under floating potential conditions because grounding is not conducted in DC circuits. Therefore, it is presumed that three modules are at negative potentials, and the other three modules are at positive potentials. Figure 15 shows the indoor \( I-V \) curves of modules 2-1 and 2-6 in W-2B installed at the lowest potential and the highest potential, respectively. No performance degradation is indicated by the indoor \( I-V \) curves shown in Figure 15 (a). Conversely, a large performance degradation is seen in the indoor \( I-V \) curves shown in Figure 15 (b). Decreases in both \( I_{SC} \) and \( V_{OC} \) result in this performance degradation shown in Figures 10 (f) and 15 (b). The \( P_{MAX} \) of module 2-6 decreased by about 4.8% from December 2012 to December 2015. Figure 16 shows the EL images of modules 2-1 and 2-6 in W-2B taken in December 2015. The EL image of module 2-1 is bright and homogeneous (Figure 16 (a)), although that of module 2-6 is a little bit darker; in particular, the peripheral cells near the frame show a lower brightness (Figure 16 (b)).

The three modules would be at negative potentials showed no degradation, while the other three modules would be at positive potentials showed clear signs of degradation.
The magnitude of the degradation increases with increasing electrical potential. We refer to this phenomenon literally as “PID” of n-type IBC solar cells. Only the performance of the PV modules in W-2B was influenced by the electrical potential, whereas the performance of those in W-2A was almost homogeneous and does not seem to be influenced by the electrical potential.

This PID of the n-type IBC solar cells coincides with that mentioned in SunPower’s report, in which the degradation was referred to as “surface polarization” [48]. They proposed the following mechanism. First, the surface of IBC solar cells at positive potentials is negatively charged by leakage currents because the electrical resistivity of the hydrogenated silicon nitride layer is very high. The hydrogenated silicon nitride layer, which is charged negatively, thus attracts photoexcited holes, which results in recombination. Consequently, the diffusion length of minority carriers (holes) in the n-layer is shortened [48].

The mechanism of the PID of p-type solar cells is considered to be different from that of n-type technologies. The PID of p-type Si technologies has been vigorously investigated [49–55] since the discovery of this phenomenon around 2010 [56,57]. The most probable mechanism is cation transport to the p–n junction region [49–53], although one study suggests that sodium ion diffusion is not a sufficient condition for PID occurrence [55].

5. CONCLUSIONS

In this study, we investigated the annual degradation rates of six types of the recent PV modules using outdoor I–V curves of PV strings over a 3-year period and four times indoor I–V curve measurements for all PV modules. In addition, the mechanisms of the degradation of the PV modules were discussed on the basis of the changes of the I–V curve parameters and shapes as well as their EL images.

The performances of the sc-Si and mc-Si modules, which were newly installed in December 2012, decreased by over 2% because of initial LID. Since the initial LID, the performances have been stable, as have the performances of the already installed sc-Si and mc-Si modules. Their annual degradation rates were estimated as 0 ± 0.2%. As such, no significant degradation could be observed in the investigated PV modules composed of p-type front-junction Si solar cells with Al-BSF. Exceptionally, the performance of the newly installed sc-Si modules recovered after the initial LID. This recovery may be caused by the LIR phenomenon.

Conversely, the SHJ modules and IBC modules consisting of n-type Si solar cells showed clear performance degradation. For the SHJ modules, Voc is the main I–V parameter influencing performance degradation. The decrease in Voc may result from damage to the passivation layers. The IBC modules were degraded under positive potential conditions.

The PV modules of the latest types of solar cells, such as SHJ, IBC, and passivated emitter and rear cell, are set to dominate the PV markets in the near future. However, their long-term reliability has not been investigated adequately. The changes or additions of the manufacturing processes to enhance the conversion efficiency result in that the degradation rates of these high-efficiency PV modules might be higher than those of conventional c-Si PV modules. Therefore, enhancing the reliability and durability of PV modules is quite important for PV systems to be authorized as dispersed power generation systems.

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REFERENCES

1. Zeng P, Wen J. Foreword for the special section on sustainable power network planning. CSEE Journal of Power and Energy Systems 2016; 2(1): 1–2. https://doi.org/10.17775/CSEEJPES.2016.00002.
2. Annual Report 2015 - The International Energy Agency Photovoltaic Power Systems Programme (IEA PVPS), 2016; ISBN: 978-3-906042-41-1.
3. King DL, Quintana MA, Kratochvil JA, Ellibee DE, Hansen BR. Photovoltaic module performance and durability following long-term field exposure. Progress in Photovoltaics: Research and Applications 2000; 8(2): 241–256. https://doi.org/10.1002/(SICI)1099-159X(200003/04)8:2<241::AID-PIP290>3.0.CO;2-D.
4. Gxasheka AR, van Dyk EE, Meyer EL. Evaluation of performance parameters of PV modules deployed outdoors. Renewable Energy 2005; 30(4): 611–620. https://doi.org/10.1016/j.renene.2004.06.005.
5. Osterwald CR, Adelstein J, del Cueto JA, Sekulic W, Trudell D, McNutt P, Hansen R, Rummel S, Anderberg A, Moriarty T. Resistive loading of photovoltaic modules and arrays for long-term exposure testing. Progress in Photovoltaics: Research and Applications 2006; 14(6): 567–575. https://doi.org/10.1002/pip.693.
6. Ishii T, Takashima T, Otani K. Long-term performance degradation of various kinds of photovoltaic modules under moderate climatic conditions. Progress in Photovoltaics: Research and
1. Jordan DC, Kurtz SR. Photovoltaic degradation rates
2. McMahon TJ. Accelerated testing and failure of thin-
3. DOI: 10.1002/pip.627.
4. Skoczek A, Sample T, Dunlop ED. The results of
5. Chamberlin C. E., Rocheleau M. A., Marshall M. W.,
6. Lorenzo E, Zilles R, Moretón R, Gómez T, de Olcoz
7. Davis KO, Kurtz SR, Jordan DC, Wohlgemuth JH,
8. Skoczek A, Sample T, Dunlop ED. The results of
9. Chamberlin C. E., Rocheleau M. A., Marshall M. W.,
10. Davis KO, Kurtz SR, Jordan DC, Wohlgemuth JH,
11. Polverini D, Field M, Dunlop E, Zaaiman W. Polycrystalline silicon PV modules performance and degradation over 20 years. Progress in Photovoltaics: Research and Applications 2013; 21(4): 702–712. https://doi.org/10.1002/pip.2154.
12. Lorenzo E, Zilles R, Moretón R, Gómez T, de Olcoz AM. Performance analysis of a 7-kW crystalline silicon generator after 17 years of operation in Madrid. Progress in Photovoltaics: Research and Applications 2014; 22(12): 1273–1279. https://doi.org/10.1002/pip.2379.
13. Pozza A, Sample T. Crystalline silicon PV module degradation after 20 years of field exposure studied by electrical tests, electroluminescence, and LBIC. Progress in Photovoltaics: Research and Applications 2016; 24(3): 368–378. https://doi.org/10.1002/pip.2717.
14. Jordan DC, Kurtz SR. Photovoltaic degradation rates—an analytical review. Progress in Photovoltaics: Research and Applications 2013; 21(1): 12–29. https://doi.org/10.1002/pip.1182.
15. McMahon TJ. Accelerated testing and failure of thin-film PV modules. Progress in Photovoltaics: Research and Applications 2004; 12(2–3): 235–248. https://doi.org/10.1002/pip.526.
16. Jørgensen GJ, McMahon TJ. Accelerated and outdoor aging effects on photovoltaic module interfacial adhesion properties. Progress in Photovoltaics: Research and Applications 2008; 16(6): 519–527. https://doi.org/10.1002/pip.826.
17. Sample T, Skoczek A, Field M, Köhl M, Geyer D., Herrmann W., Accelerated ageing of seven different thin-film module types by sequential exposure to damp heat or damp heat with either additional applied voltage or ultraviolet light, Proceedings of the 24th European Photovoltaic Solar Energy Conference and Exhibition 2009; 3241–3247, Hamburg, Germany, https://doi.org/10.4229/24thEUPVSEC2009-4CO.2.6.
18. Reil F., Althaus J., Vaaljen W., Herrmann W., Strohke M., The effect of transportation impacts and dynamic load tests on the mechanical and electrical behaviour of crystalline PV modules, Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion 2010; 3989–3992, Valencia, Spain, https://doi.org/10.4229/25thEUPVSEC2010-4AV.3.9.
19. Kajari-Schröder S, Kunze I, Etner U, Köntges M. Spatial and orientational distribution of cracks in crystalline photovoltaic modules generated by mechanical load tests. Solar Energy Materials and Solar Cells 2011; 95(11): 3054–3059. https://doi.org/10.1016/j.solmat.2011.06.032.
20. Koehl M, Heck M, Wiesmeier S. Modelling of conditions for accelerated lifetime testing of humidity impact on PV-modules based on monitoring of climatic data. Solar Energy Materials and Solar Cells 2012; 99: 282–291. https://doi.org/10.1016/j.solmat.2011.12.011.
21. Wohlgemuth J. H., Kempe M. D., Equating damp heat testing with field failures of PV modules, Proceedings of the 39th IEEE Photovoltaic Specialists Conference 2013; 126–131, Tampa, Florida, USA, DOI: https://doi.org/10.1109/PVSC.2013.6744113.
22. Hacke P, Smith R, Terwilliger K, Glick S, Jordan D, Johnston S, Kempe M, Kurtz S. Testing and analysis for lifetime prediction of crystalline silicon PV modules undergoing degradation by system voltage stress. IEEE Journal of Photovoltaics 2013; 3(1): 246–253. https://doi.org/10.1109/JPHOTOV.2012.2222351.
23. Kraft A, Labusch L, Enslen T, Dür I, Bartsch J, Glatthaar M, Glunz S, Reinecke H. Investigation of acetic acid corrosion impact on printed solar cell contacts. IEEE Journal of Photovoltaics 2015; 5(3): 736–743. https://doi.org/10.1109/JPHOTOV.2015.2395146.
24. Masuda A, Uchiyama N, Hara Y. Degradation by acetic acid for crystalline Si photovoltaic modules. Japanese Journal of Applied Physics 2015; 54(8): 04DR04-1-04DR04-5. https://doi.org/10.7567/JJAP.54.04DR04.
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25. International Electrotechnical Commission, Terrestrial photovoltaic (PV) modules—design qualification and type approval, IEC 61215 series Ed. 1.0, 2016.

26. International Electrotechnical Commission, Photovoltaic (PV) module safety qualification, IEC 61730 series Ed. 2.0, 2016.

27. Kurtz S., Sample T., Wohlgemuth J., Zhou W., Bosco N., Althaus J., Phillips N., Deceglie M., Flueckiger C., Hacke P., Miller D., Kempe M., Yamamichi M., Kondo M., Moving toward quantifying reliability—the next step in a rapidly maturing PV industry, Proceedings of the 42nd Photovoltaic Specialists Conference 2015; 1–8, New Orleans, Louisiana, USA, https://doi.org/10.1109/PVSC.2015.7355814.

28. Osterwald CR, McMahon TJ. History of accelerated and qualification testing of terrestrial photovoltaic modules: a literature review. Progress in Photovoltaics: Research and Applications 2009; 17 (1): 11–33. https://doi.org/10.1002/pip.861.

29. Ishii T, Otani K, Itagaki A, Utsunomiya K. A methodology for estimating the effect of solar spectrum on photovoltaic module performance by using average photon energy and a water absorption band. Japanese Journal of Applied Physics 2012; 51(10S):10NF05-1-10NF05-4. https://doi.org/10.1143/JJAP.51.10NF05.

30. Ishii T, Otani K, Itagaki A, Utsunomiya K. A simplified methodology for estimating solar spectral influence on photovoltaic energy yield using average photon energy. Energy Science & Engineering 2013; 1(1): 18–26. https://doi.org/10.1002/ese3.3.

31. Ishii T, Otani K, Takashima T. Effects of solar spectrum and module temperature on outdoor performance of photovoltaic modules in round-robin measurements in Japan. Progress in Photovoltaics: Research and Applications 2011; 19(2): 141–148. https://doi.org/10.1002/pip.995.

32. Ishii T, Otani K, Takashima T, Ikeda K. Change in I–V characteristics of thin-film photovoltaic (PV) modules induced by light soaking and thermal annealing effects. Progress in Photovoltaics: Research and Applications 2014; 22(9): 949–957. https://doi.org/10.1002/pip.2346.

33. International Electrotechnical Commission, Photovoltaic devices—part 9: solar simulator performance requirements, IEC 60904–9 Ed. 2, 2007.

34. Fischer H, Pschunder W. Investigation of photon and thermal induced changes in silicon solar cells. In Proceedings of the 10th IEEE Photovoltaic Specialists Conference. Palo Alto: California, USA, 1973; 404–411.

35. Weizer VG, Brandhorst HW, Broder JD, Hart RE, Lamneck JH. Photon-degradation effects in terrestrial silicon solar cells. Journal of Applied Physics 1979; 50(6): 4443–4449. https://doi.org/10.1063/1.326437.

36. International Electrotechnical Commission, Photovoltaic devices—part 3: measurement principles for terrestrial photovoltaic (PV) solar devices with reference spectral irradiance data, IEC 60904–3 Ed. 2, 2008.

37. Gueynard CA, Myers D, Emery K. Proposed reference irradiance spectra for solar energy systems testing. Solar Energy 2002; 73(6): 443–467. https://doi.org/10.1016/S0038-092X(03)00005-7.

38. Schmidt J, BERGE C, Aberle AG. Injection level dependence of the defect-related carrier lifetime in light-degraded boron-doped Czochralski silicon. Applied Physics Letters 1998; 73(15): 2167–2169. https://doi.org/10.1063/1.122411.

39. Glunz SW, Rein S, Lee JY, Warta W. Minority carrier lifetime degradation in boron-doped Czochralski silicon. Journal of Applied Physics 2001; 90(5): 2397–2404. https://doi.org/10.1063/1.1389076.

40. Vu TK, Ohshita Y, Araki K, Yamaguchi M. Generation and annihilation of boron–oxygen related defects in boron-doped Czochralski-grown Si solar cells. Journal of Applied Physics 2002; 91(8): 4853–4856. https://doi.org/10.1063/1.1459609.

41. Schmidt J, Bothe K. Structure and transformation of the metastable boron- and oxygen-related defect center in crystalline silicon. Physical Review B 2004; 69(2): 024107-1-024107-8. https://doi.org/10.1103/PhysRevB.69.024107.

42. Damiani B, Nakayashiki K, Kim DS, Yelundur V, Ostapenko S, Tarasov I, Rohtagi A. Light induced degradation in promising multi-crystalline silicon materials for solar cell fabrication. In Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion. IEEE: Osaka, Japan, 2003; 927–930.

43. Herguth A., Schubert G., Kaes M., Hahn G., A new approach to prevent the negative impact of the metastable defect in boron doped CZ silicon solar cells, Proceedings of the 4th World Conference on Photovoltaic Energy Conversion 2006; 940–943, Waikoloa, Hawaii, USA. https://doi.org/10.1109/WCPEC.2006.279611.

44. Herguth A, Schubert G, Kaes M, Hahn G. Investigations on the long time behavior of the metastable boron-oxygen complex in crystalline silicon. Progress in Photovoltaics: Research and Applications 2008; 16(2): 135–140. https://doi.org/10.1002/pip.779.

45. Fertig F, Greulich J, Broisch J, Biro D, Rein S. Stability of the regeneration of the boron-oxygen complex in silicon solar cells during module integration. Solar Energy Materials and Solar Cells
46. Lee K., Kim M., Lim J.-K., Ahn J.-H., Hwang M.-I., Cho E.-C., Natural recovery from LID: Regeneration under field conditions?, *Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition 2015;* 1835–1837, Hamburg, Germany, https://doi.org/10.4229/EUPVSEC2015-5CO.16.6.

47. Walter DC, Lim B, Schmidt J. Realistic efficiency potential of next-generation industrial Czochralski-grown silicon solar cells after deactivation of the boron–oxygen-related defect center. *Progress in Photovoltaics: Research and Applications* 2016; 24 (7): 920–928. https://doi.org/10.1002/pip.2731.

48. Swanson, R., Cudzinovic M., DeCeuster D., Desai V., Jürgens J., Kaminar N., Mulligan W., Rodrigues-Barbarosa L., Rose D., Smith D., Terao A., Wilson K., The surface polarization effect in high-efficiency silicon solar cells, *Proceedings of the 15th International Photovoltaic Science & Engineering Conference 2005;* Shanghai, China, 410–411.

49. Naumann V, Lausch D, Hähnel A, Bauer J, Breitenstein O, Graff A, Werner M, Swatek S, Großer S, Bagdahn J, Hagendorf C. Explanation of potential-induced degradation of the shunting type by Na decoration of stacking faults in Si solar cells. *Solar Energy Materials and Solar Cells* 2014; 120(Part A): 383–389. https://doi.org/10.1016/j.solmat.2013.06.015.

50. Lausch D, Naumann V, Breitenstein O, Bauer J, Graff A, Bagdahn J, Hagendorf C. Potential-induced degradation (PID): introduction of a novel test approach and explanation of increased depletion region recombination. *IEEE Journal of Photovoltaics* 2014; 4(3): 834–840. https://doi.org/10.1109/JPHOTOV.2014.2300238.

51. Hara K, Ichinose H, Murakami TN, Masuda A. Crystalline Si photovoltaic modules based on TiO2-coated cover glass against potential-induced degradation. *RSC Advances* 2014; 4: 44291–44295. https://doi.org/10.1039/c4ra06791f.

52. Hacke P, Terwilliger K, Glick S, Tamizhmani G, Tatapudi S, Stark C, Koch S, Weber T, Berghold J, Hoffmann S, Koehl M, Dietrich S, Ebert M, Mathiak G. Interlaboratory study to determine repeatability of the damp-heat test method for potential-induced degradation and polarization in crystalline silicon photovoltaic modules. *IEEE Journal of Photovoltaics* 2015; 5(1): 94–101. https://doi.org/10.1109/JPHOTOV.2014.2361650.

53. Kapur J, Stika KM, Westphal CS, Norwood JL, Hamzavtyehram B. Prevention of potential-induced degradation with thin ionomer film. *IEEE Journal of Photovoltaics* 2015; 5(1): 219–223. https://doi.org/10.1109/JPHOTOV.2014.2365465.

54. Jonai S, Hara K, Tsutsui Y, Nakahama H, Masuda A. Relationship between cross-linking conditions of ethylene vinyl acetate and potential induced degradation for crystalline silicon photovoltaic modules. *Japanese Journal of Applied Physics* 2015; 54(8S1):08KG01-1-08KG01-5. https://doi.org/10.7567/JJAP.54.08KG01.

55. Masuda A, Hara Y, Jonai S. Consideration on Na diffusion and recovery phenomena in potential-induced degradation for crystalline Si photovoltaic modules. *Japanese Journal of Applied Physics* 2016; 55(2S): 02BF10-5. https://doi.org/10.7567/JJAP.55.02BF10.

56. Berghold J., Frank O., Hoehne H., Pingel S., Richardson B., Winkler M., Potential induced degradation of solar cells and panels. *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion 2010;* 3753–3759, Valencia, Spain, https://doi.org/10.4229/25thEUPVSEC2010-4BO.9.5.

57. Hacke P., Kempe M., Terwilliger K., Glick S., Call N., Johnston S., Kurtz S., Bennett I., Kloos M., Characterization of multicrystalline silicon modules with system bias voltage applied in damp heat, *Proceedings of the 25th European Photovoltaic Solar Energy Conference and Exhibition / 5th World Conference on Photovoltaic Energy Conversion 2010;* 3760–3765, Valencia, Spain, https://doi.org/10.4229/25thEUPVSEC2010-4BO.9.6.