Solar cell cracks within a photovoltaic module: Characterization by AC impedance spectroscopy

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Abstract

Various cell crack modes (with or without electrically inactive cell areas) can be induced in crystalline silicon photovoltaic (PV) cells within a PV module through natural thermomechanical stressors such as strong winds, heavy snow, and large hailstones. Although degradation in the performance of PV modules by cell cracks has been reported occasionally, the mode-dependent evolutions in the electrical signatures of cracks have not yet been elucidated. In this study, we propose that the reduction of the time constant in the AC impedance spectra, which is caused by the elevation of minority-carrier recombination in the p–n junction of a PV cell, is a ubiquitous signature of cracked PV cells encapsulated in a commercially available PV module. Several other characteristics derived from the illuminated current-voltage (I–V) and dark I–V data significantly evolved only in PV cells with inactive cell areas. We also propose that the evaluation by carrier recombination is a crucial diagnostic technique for detecting all crack modes, including microcracks, in wafer-based PV modules.

1. Introduction

As of the end of 2021, the global photovoltaic (PV) market had grown by over 940 GW owing to the annual installation of over 100 GW for the fifth successive year [1]. Further expansion of the PV market will be facilitated by advances in PV module technologies, including the development and implementation of innovative designs and materials. Within the bills of materials of the PV module, a decrease in the crystalline silicon (c-Si) wafer thickness could be a key factor leading to cost savings through the efficient use of silicon. Presently, it has reached approximately 170 μm, and a minimum thickness of 125 μm is projected to be achieved in 2032 [2]. However, the tendency to decrease the wafer thickness of PV cells could lead to a worst-case scenario with a significant reduction in the PV module/system performance owing to the initiation/propagation of cell cracks from extreme weather events (e.g., strong winds from tropical cyclones, heavily accumulated snow, and frequent hailstorms). In fact, over 20% power loss caused by cell cracks (including those attributed to hailstorms) has been occasionally reported
in PV modules deployed outdoors [3–6]. Therefore, we determined the proper inspection principles for cell cracks to contribute to proactive measures in the design and manufacturing processes of PV cells/modules, as well as the appropriate operation and maintenance of PV systems.

Various detection and inspection methods for cell cracks have been proposed based on optical/imaging technologies [7–14] and electroluminescence (EL) has been the gold standard for crack detection [15]. Recently, photoluminescence (PL) and ultraviolet fluorescence (UVF) methods have been applied for the explicit identification of cell cracks in field-aged PV modules [16–18]. These techniques can provide superior qualitative information; however, quantitative data associated with the electrical characteristics of PV cells/modules are difficult to collect. Particularly, the resolution/accuracy of signals in these images is decreased in PV modules owing to their large size and interference with the encapsulant and glass within the PV modules.

As thoroughly reviewed in [9, 10, 13], numerous electrical signatures attributed to cell cracks have been reported, such as the elevations of series resistance (R_s) [19–27] and saturation current densities of the second diode (J_{02}) in the two-diode model of the PV cell/module [28–31], reduction in the short-circuit current (I_{sc}) [19, 22, 26], shunt resistance (R_{sh}) [30, 32–35], and fill factor (FF) [20, 36], depending on the development of cell cracks. However, the extent of power loss in PV modules with cell cracks (particularly, with microcracks) is quite small. In one study [19], the PV module power loss did not exceed 2.5%, unless all cracks were electrically isolated. It is therefore common for the degree of evolution in the electrical signatures of PV modules with cracks to be quite small. Even when obvious cell cracks with electrical isolation were identified in a commercially available PV module, the reduction in the power generated by this PV module was less than 3% [26].

In the IEC standard [15], cell cracks are rated as follows: a) Mode A (microcracks): cracks that can be detected as line defects in EL images (no electrically inactive cell regions), b) Mode B: cracks that generate at partially disconnected region from the rest of the electrical circuit, and c) Mode C: cracks that produce regions that are essentially isolated from the electrical circuit, according to the nomenclature proposed by Köntges et al. [19]. In this study, for the concurrent determination of indicators of the initiation and propagation of various crack modes, we aimed to statistically identify the evolution of the respective electrical signatures in individual PV cells with two different crack behaviors (PV cells with Mode B and C cracks and those with Mode A cracks), which are in a commercially available PV module degraded by sequential mechanical loading tests. Thus, we demonstrated that the elevation of minority-carrier recombination in cracked cells could be a universal indicator for all modes of cell cracks (including Mode A cracks), as discussed in detail in Section 4. Additionally, it is suggested that only this signature is evolved even in PV cells with microcracks because those in other signatures could not be detected in the PV cells. We also suggest that the identification of this evolution by AC impedance spectroscopy is more effective than conventional current–voltage (I–V) analyses for these PV cells. These consequences are highly likely to be equivalent to the electrical evolutions due to cell cracks in the PV modules exposed in fields because they can be obtained in individual PV cells encapsulated in a commercially available PV module.

This article is organized as follows: In Section 2, the experimental procedures for the cell-crack formation, electrical isolation of the individual PV cells within a PV module, and characterization of these PV cells are presented. In Section 3, the electrical characteristics of the individual PV cells are summarized, including the elevation of the minority carrier recombination, which is determined by the AC impedance parameters. Additionally, we discuss not only the detection mechanisms of microcracks but also the applications to practically evaluate PV modules and systems, in Section 4.
2. Materials and methods

2.1 Cell-crack formation in a PV module with nonuniform mechanical loading

A sequential mechanical loading test was conducted on a commercially available PV module (1970 × 993 × 35 mm) assembled with 72 mono-c-Si PV cells (156 × 156 mm², four busbars) to form cell cracks reflecting non-uniform wind loads during a strong typhoon, as described in our previous report [37]. The I–V parameters—maximum power ($P_{\text{max}}$), $I_{\text{sc}}$, open-circuit voltage ($V_{\text{oc}}$), and FF—in the PV module before this sequential mechanical loading test were assessed as 359.8 W, 9.88 A, 45.6 V, and 76.5%, respectively. Thus, the mean $P_{\text{max}}$ of the individual PV cells was 4.997 W/cell, and the mean $V_{\text{oc}}$ was 0.66 V/cell. In this module, no cell cracks were detected in the EL image prior to the mechanical loading test. After the non-uniform static mechanical loads with a combination of pressure load (1 h) and suction load (1 h) were applied seven times, non-uniform dynamic mechanical loads (10 cycles/min for 6 h) were applied to the PV module. The uneven mean surface pressure pattern (MSPP) used in the non-uniform static/dynamic mechanical loading can be found in the S1 Fig. The EL image was obtained at a forward bias current of 8 A. In accordance with IEC standards [15], the EL images of the respective PV cells were evaluated by the human eye with respect to the presence and severity of cell cracks.

2.2 Electrical isolation of the individual PV cells within the PV module

To assess the electrical characteristics of the individual PV cells within the PV module, the interconnector ribbons located in the intercell spaces of each cell string were exposed to the backsheet peeling of the corresponding portions (Fig 1), as reported in our previous article [38]. Briefly, the backsheets of the PV modules were peeled off with a micro grinder and a small wire brush to expose the interconnector ribbons between the PV cells, as can be found in S2A Fig. Copper solder leads were soldered to the exposed interconnector ribbons (S2B Fig) and connected with another set of wide copper solder ribbons at each side of the respective PV cells to evaluate the electrical characteristics of the individual PV cells, as shown in Fig 1B and 1C.

2.3 Electrical characterization of isolated PV cells

The I–V characteristics of the PV cells were individually assessed using a surface mask with an aperture area on an object PV cell, through the leads of the respective PV cells, under the standard test conditions of 1,000 W/m², 25˚C, and AM 1.5G [38]. Dark I–V data were collected at 23.3–23.9˚C in the dark, by the connection of the leads of an object PV cell to a source measurement unit (Keysight B2901a). The I–V parameters, including $R_s$, $R_{\text{sh}}$, saturation current densities ($J_{01}$ and $J_{02}$), and ideality factors of diodes ($n_1$ and $n_2$), were extracted from the respective I–V data obtained under illuminated or dark conditions by fitting to two-diode equivalent circuit models as presented in (1) and (2) according to [39, 40]:

$$I_i = I_{\text{ph}} - \frac{V + IR}{R_{\text{sh}}} - J_{01}A\left\{\exp\left[\frac{q(V + IR)}{n_1k_BT}\right] - 1\right\} - J_{02}A\left\{\exp\left[\frac{q(V + IR)}{n_2k_BT}\right] - 1\right\},$$  \hspace{1cm} (1)

$$I_{\text{dark}} = 0 - \frac{V + IR}{R_{\text{sh}}} - J_{01}A\left\{\exp\left[\frac{q(V + IR)}{n_1k_BT}\right] - 1\right\} - J_{02}A\left\{\exp\left[\frac{q(V + IR)}{n_2k_BT}\right] - 1\right\},$$  \hspace{1cm} (2)

where $I_i$ is the current under illumination, $I_{\text{ph}}$ is the photo current, $q$ is the elementary charge, $k_B$ is Boltzmann’s constant, $T$ is the temperature, $A$ is the cell area, and $I_{\text{dark}}$ is the current in...
Fig 1. Electrical isolation of individual PV cells in a PV module with cell cracks. Front (a), rear (b), and an enlarged view of the rear (c) of the PV module are shown.

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the dark. The median root mean square error (RMSE) in the illuminated $I-V$ fittings was 0.015, and that of the root mean square logarithmic error (RMSLE) in the dark $I-V$ fittings was 0.040, as shown in Fig 2. These results indicate that these $I-V$ parameters can be estimated with sufficient accuracy. In the dark $I-V$ fitting, $n_1$ values in the individual PV cells fell within the range of $1.18 \pm 0.05$, whereas the $n_2$ values fell within the range of $1.97 \pm 0.04$. These values indicated that each $I_{01}$ in the dark $I-V$ parameters estimated from the individual PV cells corresponds to the current density, owing to the recombination current in the respective PV cells. To accurately quantify the total series resistance of each PV cell within the PV module, the lumped series resistance was calculated as $R_{s-ld}$ from the respective illuminated and dark $I-V$ data (3) in accordance with the procedure described by Spataru et al. [26]:

$$R_{s-ld} = \frac{V_{d-mp} - V_{mp}}{I_{mp}} |_{I_{dark} = I_{sc} - I_{mp}},$$

where $I_{mp}$ and $V_{mp}$ are the current and voltage at the maximum power point under the illuminated conditions, respectively. $V_{d-mp}$ is the voltage corresponding to $I_{dark} = I_{sc} - I_{mp}$ on the dark $I-V$ curve.

The AC impedance data of the individual PV cells were acquired by connecting the four-point probes of an LCR meter (Keysight 4284a with 001 DC bias option) at 22.3–24.0°C in the dark, under the condition that a 10-mV-amplitude AC voltage with various intensities of DC bias voltage was applied. According to [41], the voltage across the p–n junction ($V_j$) of the PV

Fig 2. Histograms of (a) RMSE and (b) RMSLE in the illuminated and dark $I-V$ curve fittings, respectively.
cell is defined as \( V_i = V - IR_s \), where \( V \), \( I \), and \( R_s \) are the applied DC bias voltage, applied DC current, and series resistance, respectively (cf. \( R_s \) or \( R_1 \) in Fig 5A-1–5A-3). From the AC impedance (amplitude \( |Z| \) and argument \( \theta \)) collected at each frequency in the range of 20 Hz to 10 kHz, the real \( (Z') \) and imaginary \( (Z'') \) impedances were calculated, and the AC impedance parameters in the postulated AC equivalent circuits (cf., Fig 5A-1–5A-3) were determined using a Web-based impedance-fitting application (Elchemea Analytical) [42].

2.4 Statistical evaluation

The Steel–Dwass test is a statistical procedure for evaluating the stochastic equality among multiple sample groups, utilizing the pairwise ranking non-parametric method. Because the distribution of the respective parameters adopted in this study is not corresponding to the normal distribution, we applied this non-parametric test to assess the difference among the distributions of these parameters, using the pSDCFlig function (Monte Carlo method with 10,000 iterations) in the NSM3 package [43] embedded into the R software [44]. Statistically significant differences were judged by the \( p \)-value limit (\( p < 0.05 \)). Particularly, the multi-endpoints issue arising from post hoc definitions were not considered, since this study aimed to evaluate distinguished electrical characteristics attributed to cell cracks. The discretization of the cumulative frequency distribution to a multimodal distribution was performed using the normalmixEM function in the mixtools package [45] built into the R software.

3. Results

3.1 Power losses in the cracked PV cells

As presented in our previous report [46], various types of cell cracks were observed in the PV module after the nonuniform mechanical loading test, which included Mode B/C cracks (with inactive cell area(s) detectable in the EL image) and Mode A cracks (without any inactive cell area) [15, 19], as shown in Fig 3A. Based on the rating criteria, the individual PV cells with cell cracks were divided into two groups, particularly, the cracked cells with or without the inactive cell area were categorized as hard-cracked (HC) or minorly cracked (MC) cells, respectively. In these HC cells, the inactive areas were identified in the central region of the respective PV cells (e.g., C08 cell), as well as at the edges of the PV cells (e.g., C07 cell). The PV cells without cracks were referred to as non-cracked (NC) cells. The spatial distributions of these cell groups in the PV module are shown in Fig 3B, accompanied by the cell address, defined by the location of the respective PV cells within the PV module. Although the distribution of these cracked cells (HC and MC cells) within the PV module did not sufficiently coincide with that of the MSPP applied to the PV module, these cells are likely to be located in steep regions in the applied MSPP [46]. To quantitatively assess the extent of power loss attributed to the cell cracks, the respective maximum powers of the individual PV cells were measured and indicated in the cell matrix of the PV module (Fig 3C) as values normalized with the pristine \( P_{\text{max}} \) in individual PV cells (4.997 W/cell). It is recognized that obvious power loss occurred the HC cells, although that in the MC cells was not detectable at a glance, as reported in the PV module with only Mode A cracks [19].

A histogram of the actual \( P_{\text{max}} \) values in each PV cell is shown in Fig 4, with the mean \( P_{\text{max}} \) in the pristine PV cells (4.997 W/cell). A broad distribution with a long tail in the low \( P_{\text{max}} \) range is observed, and the median of the entire PV cell is 4.586 W/cell. Almost all HC cells were in this long tail with a low \( P_{\text{max}} \), although those in the MC cells were completely overlaid with those in the NC cells. This power-loss behavior was statistically confirmed by non-parametric multiple comparison analysis (see the inset figure of Fig 4); particularly, the significant decrease in \( P_{\text{max}} \) of HC cells from those in other cell groups was clearly demonstrated,
### (a) Solar cell cracks within a photovoltaic module

| HC | Hard Cracked Cell | MC | Minor Cracked Cell | NC | Noncracked Cell |
|----|-------------------|----|--------------------|----|-----------------|
| A01 | A02 | A03 | A04 | A05 | A06 | A07 | A08 | A09 | A10 | A11 | A12 |
| B01 | B02 | B03 | B04 | B05 | B06 | B07 | B08 | B09 | B10 | B11 | B12 |
| C01 | C02 | C03 | C04 | C05 | C06 | C07 | C08 | C09 | C10 | C11 | C12 |
| D01 | D02 | D03 | D04 | D05 | D06 | D07 | D08 | D09 | D10 | D11 | D12 |
| E01 | E02 | E03 | E04 | E05 | E06 | E07 | E08 | E09 | E10 | E11 | E12 |
| F01 | F02 | F03 | F04 | F05 | F06 | F07 | F08 | F09 | F10 | F11 | F12 |

### (b) Table of data

|               | 0.934 | 0.897 | 0.899 | 0.930 | 0.927 | 0.892 | ND   | ND   | 0.927 | 0.901 | 0.933 | 0.892 |
|---------------|-------|-------|-------|-------|-------|-------|------|------|-------|-------|-------|-------|
|               | 0.896 | 0.915 | 0.911 | 0.898 | 0.888 | 0.893 | ND   | ND   | 0.892 | 0.892 | 0.931 | 0.619 |
|               | 0.901 | 0.910 | 0.791 | 0.844 | 0.876 | 0.876 | 0.831 | 0.750 | 0.928 | 0.934 | 0.913 | 0.863 |
|               | 0.928 | 0.933 | 0.946 | 0.947 | 0.937 | 0.943 | 0.857 | 0.808 | 0.948 | 0.936 | 0.948 | 0.897 |
|               | 0.897 | 0.943 | 0.920 | 0.921 | ND   | ND   | 0.848 | 0.916 | 0.927 | 0.921 | 0.948 | 0.913 |
|               | 0.934 | 0.920 | 0.920 | 0.954 | ND   | ND   | 0.939 | 0.952 | 0.951 | 0.928 | 0.924 | 0.771 |
although a substantial difference between the respective power losses in the MC cells was not proven.
3.2 AC impedance characteristics of the cracked PV cells

As a potential electrical signature for cell cracks, it has been reported that the intensity of the parallel resistance ($R_p$; cf. Fig 5A-1) in the AC equivalent circuit of a PV cell/module is reduced by cell cracks that are intentionally introduced in the PV cell/module [33–35]. We then examined whether this parameter could be crucial for cell cracks (particularly, MC cells). Generally, the locus of AC impedance for a PV cell/module is expressed as a semicircle in the Nyquist plot when the AC equivalent circuit for a PV cell with a single p–n junction is assumed to be composed of a series resistance ($R_s$) and a parallel circuit including a resistor and capacitor (Fig 5A-1: $R_s$-$R_p$|$C_p$ model). Fig 5B shows the AC impedance locus observed in the PV cell

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**Fig 5. AC impedance characteristics of PV cells.** (a) Postulated AC equivalent circuits for the $R_s$-$R_p$|$C_p$ model (a-1), $R_1$-$R_2$|$CPE_2$ model (a-2), and $R_1$-$Z_2$-$Z_3$ model (a-3). (b-d) The Nyquist plots for AC impedance (open circles) measured at various forward DC bias voltages for F08 cell. The dashed and solid curves in black color indicate the model curves based on the $R_s$-$R_p$|$C_p$ model (a-1) and $R_1$-$R_2$|$CPE_2$ model (a-2), respectively. In (d), the blue, green, and thick-orange curves denote the model curves derived from each component ($Z_2$, $Z_3$) and the entire $R_1$-$Z_2$-$Z_3$ model, respectively. In (e), the capacitor factor ($\phi$) in the $R_1$-$R_2$|$CPE_2$ model (a-2) for the F08 cell is indicated as a function of $V_j$. Each reduced $\chi^2$ at various $V_j$ is plotted in (f). Reduced $\chi^2$ from the $R_1$-$R_2$|$CPE_2$ model (a-2) is shown as the open circle when $V_j < 0.3$ V, although those obtained at $V_j \geq 0.3$ V are indicated as closed circles. Additionally, each reduced $\chi^2$ from the $R_1$-$Z_2$-$Z_3$ model (a-3) is plotted as the orange triangle.

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without any cell cracks (F08 cell) under the conditions that the bias voltage is not applied. Although the AC impedance spectra could not be sufficiently fitted to the $R_s-R_{p||}C_p$ model with a perfect semicircle curve (dashed curve), a satisfactory value ($1.32 \times 10^{-4}$) for the goodness of fit (also known as the reduced $\chi^2$) was obtained in the $R_1-R_3||CPE_2$ model (Fig 5A-2), as can be observed in the depressed semicircle (solid curve) of Fig 5B. In this $R_1-R_3||CPE_2$ model, because the impedance of the constant-phase element (CPE) is given by $Z_{CPE} = 1/(Q(j\omega)^\phi)$ \cite{47}, that of the $R||CPE$ component can be described as $Z_{R||CPE} = 1/[(1/R) + Q(j\omega)^\phi]$, and the effective capacitance ($C_\varepsilon$) for the $R||CPE$ component can be defined as $C_\varepsilon = [(QR)^1/\phi]/R$ \cite{48}. Where $j$ and $\omega$ are the imaginary operator and angular frequency, respectively. Moreover, $\phi$ is the capacitor factor for the phase angle $[\theta = -(90 \times \phi)$, where $\theta$ is expressed in degrees unit] of the CPE impedance, with a value of 0 to 1. If $\phi = 1$, the capacitance parameter ($Q$) indicates the capacitance of an ideal capacitor, that is, $C_\varepsilon = Q$. When $V_j$ was applied at less than 0.3 V, a similar behavior in the AC impedance spectra was observed (Fig 5C), and $\phi$ estimated under these conditions was almost always over 0.95 (Fig 5E). Therefore, we deduce that the $R_1-R_3||CPE_2$ model can be effectively applied into the estimation of AC impedance parameters in PV cells under these DC-bias conditions. At $V_j > 0.3$ V, however, we were not able to obtain a sufficient value of the reduced $\chi^2$ by fitting the measured AC impedance data to the $R_1-R_2||CPE_2$ model (Fig 5F), and $\phi$ fell below 0.95 (Fig 5E). Because the effects of the low–high interface (p–p\textsuperscript{+} junction in the back surface field) observed in the high forward bias voltage range (at $V_j > 0.3$ V) should be considered, these AC impedance data were fitted to the $R_1-Z_2-Z_3$ model (Fig 5A-3 and 5D), according to previous reports \cite{49, 50}. The entire AC impedance curve (indicated by the thick curve in orange) calculated from the parameters for this model had very small values in the reduced $\chi^2$ (indicated by the orange triangles in Fig 5F) and was clearly divided into two curves comprising $Z_2$ (AC impedance derived from the p–n junction) and $Z_3$ (that from the p–p\textsuperscript{+} junction) in Fig 5D. Thus, to identify the critical parameters attributed to the cell cracks in individual PV cells, we used the $R_1-R_3||CPE_2$ or $R_1-Z_2-Z_3$ models, depending on the applied bias voltage. In all the estimated parameters of these models, the standard errors were almost always within 10%.

The dependency of the parallel resistances ($R_2$) extracted from the AC impedance spectra of the individual PV cells on the bias voltage is shown in Fig 6A. As reported previously \cite{51}, a nearly constant resistance was estimated in the reverse bias voltage range, although drastic reductions were observed when the forward bias was applied, irrespective of the cell groups.

**Fig 6.** (a) Estimated $R_2$ as a function of $V_j$ and (b) multicomparison chart for the categorized PV cells on $R_{sh-R_2}$ ($R_{sh}$ determined from $R_2$). In (a), the orange, blue, and black symbols correspond to those from the two PV cells representing HC, MC, and NC cells, respectively. In (b), the open circles represent the outliers.
categorized as the crack mode. The extent of $R_{sh}$ derived from $R_2$ (hereafter, this $R_{sh}$ is referred as $R_{sh-R2}$) in the individual PV cells was numerically calculated as the mean value of $R_2$ at $-0.6$ to $-0.3$ V in the bias voltage range [51], and their distributions in the respective PV cell categories were not significantly segregated, as shown in Fig 6B and Table 1. Although these extents are widely spread in all categories, $R_{sh-R2}$ was over $1 \times 10^4 \text{ cm}^2$ even in the HC cells (Fig 6B), and the $R_{sh-R2}$ level was considerably higher than that proposed as the industrial $R_{sh}$ criteria of the PV cell ($0.8–2.4 \times 10^3 \text{ cm}^2$) [30, 52–54]. Furthermore, because it is well known that the power loss attributed to potential-induced degradation (PID) with an obvious reduction in $V_{oc}$ occurs when $R_{sh}$ in the degraded cells/modules is below a critical value ($2–3 \times 10^3 \text{ cm}^2$) [55], we can conclude that the $R_{sh}$ extents indicated in Fig 6B would not be a crucial cause of $V_{oc}$ reduction. In previous studies [34, 35], the extent of parallel resistance ($R_p$) was estimated from the AC impedance data collected at $V_j=0$, and those in the cracked cells and modules with cracked cells were maintained at $4.86 \times 10^4 \text{ cm}^2$ and ca. $6 \times 10^7 \text{ cm}^2$, respectively; however these extents were decreased by approximately 40–50% of those in the pristine PV cell/module. A similar reduction in $R_2$ measured at $V_j=0$ was observed in the HC cells in our results (Fig 6A); however, a significant decrease in the MC cells was not observed compared to that in the NC cells, judging from the statistical analysis ($p=0.933$). From these results, we conclude that the reduction in the parallel resistance ($R_p/R_2$) does not directly correlate with the occurrence of cell cracks, including microcracks.

### 3.3 Elevation of minority-carrier recombination in cracked PV cells

To identify a specific electrical signature of the cracked PV cells (particularly, for the MC cells), we compared the time constants for minority-carrier recombination among these cell categories on cracks through the evaluation of the $R_2$ and $C'/C_2$ parameters that reflected the electrically dynamic behavior in the p–n junction of a PV cell. In the $V_j$ range over 0.2 V, the
intensity of $R_2$ changed in a logarithmic linear manner, depending on the applied bias voltage (Fig 7A), and these data could be completely traced by the proposed relationship on the diffusion resistance in the p–n junction [41, 56]. For $C^*/C_2$, their intensities were drastically elevated in the same range as $V_j > 0.2$ V), and the theoretical curve for the diffusion capacitance entirely coincided with the trends of these data [41, 56, 57], as shown in Fig 7B. For both parameters ($R_2$ and $C^*/C_2$), we deduced that the parameters in the PV cell with complex cell cracks (in C08 and C03 cells) have a different dependency on the bias voltage from those in other PV cells. In fact, the intensities of $R_2$ and $C^*/C_2$ were lower than those measured in other PV cells, whereas those at a higher forward bias voltage ($> 0.45$ V) could not be measured. This is because their comparably lower $R_{sh}$ contributes to the apparent reduction of the $R_2$ value in the forward bias voltage range, and the loading of a higher forward bias voltage ($> 0.45$ V) to these PV cells was difficult with the impedance spectrometer used in this study, as also suggested by Yeow et al. [58]. However, for the bias voltage dependencies of $R_2$ and $C^*/C_2$ in other cells, there were small but definite differences among the crack categories. Because
the time constant of the carrier recombination in the p-n junction can be simply calculated as a multiplication of the parallel resistance ($R_2$) and capacitance ($C'/C_2$), their bias voltage dependency in the representative cells of the respective crack categories is shown in Fig 7C. Reflecting the difference in $R_2$ and $C'/C_2$ among the crack categories, the time constant over the 0.3 V forward bias voltage range was distinguished between the PV cells with and without cell cracks. That is, the minimum time constants in all the cracked PV cells [including the MC cells (F03 and F01 cells)] were considerably smaller than those in the NC cells (F08 and F10 cells) at approximately 0.4 V forward bias voltage. To confirm the significant differences among these time constants observed in the respective crack categories, we statistically compared these values estimated at 0.4 V forward DC bias voltage using the nonparametric multiple comparison test (Fig 7D). A nearly significant reduction in the time constant was identified between the NC and MC cells ($p = 0.072$), which was not confirmed in other electrical signatures examined in this study, as discussed in Section 4. Simultaneously, critical reductions in the HC cells from other crack categories were also observed. These results suggest that the enhancement of the carrier recombination, which is observed through the reduction of the time constant measured by AC impedance spectroscopy, is common to cracked PV cells, regardless of the crack categories.

To clarify whether the reduction in the time constant of the MC cells compared to that of the NC cells is meaningful, the time constants of all the cells were plotted as a cumulative frequency profile (Fig 8). In this profile, two major breakpoints were observed at approximately $5 \times 10^{-5}$ s (−4.3 in logarithmic scale) and $1 \times 10^{-4}$ s (−4.0 in logarithmic scale), with a nearly flat leaning between them. This inflected profile comprises at least two distributions of the time constant. That is, there was one distribution below $1 \times 10^{-4}$ s (lower time-constant range) and the other spread at the higher part of the time constant (higher time-constant range). This cumulative frequency profile can be almost entirely fitted to the bimodal distribution consisting of two lognormal distributions (RMSE = 3.93), as also shown in Fig 8. The parameters of the lognormal distributions are listed in Table 2. The significant difference between the population means of these distributions was confirmed by the unequal variances $t$-test (Welch’s $t$-test) with $p < 0.001$. Remarkably, the time constants of almost all cracked cells (HC- and MC-cells) located in the lower time-constant range, especially those of the HC cells were concentrated near the lower end (Fig 8). Meanwhile, a major portion of the time constants in the NC cells spread in the higher time-constant range, although some of them were in the lower time-constant range. When the statistical multiplicity arising from the post hoc analysis was considered, we confirmed that the median value (−4.308) of the time-constant distribution in the cracked cells (HC- and MC-cells) was significantly lower than that (−3.968) in the NC cells (Table 1: footnote 3) using a nonparametric statistical test (Brunner–Munzel test) for stochastic differences between two samples [59]. The mean/median values in both distributions (lognormal and real data distribution) were comparable in the respective time-constant ranges. These results suggest that the distributions located in the lower and higher time-constant ranges correspond to the electrical characteristics of the cracked (HC and MC) and non-cracked (NC) cells, respectively. Moreover, the sizes of the PV cells with cracks (including microcracks) were estimated to be 25 out of 72 (cells) when all the PV cells with cell cracks were assumed to be distributed in the lower time-constant range (Table 2). This indicates that the recall rate in our rating was 64% [= 16 cells (consisting of nine HC cells and seven MC cells) / 25 cells]. Because this rate is comparable to those (67 ± 15%) reported in a previous article [60], there is no contradiction between the cracked cell sizes estimated from the bimodal distribution of the time constants and those presumed by the actual inspection. Consequently, we deduce that the remarkable decrease in the time constant of the carrier recombination
should be recognized as a specific electrical signature for all cracked PV cells (including MC cells).

3.4 $I$–$V$ characteristics of the cracked PV cells

The $I$–$V$ parameters of the individual PV cells within the PV module subjected to the nonuniform mechanical loading test (Fig 3) were extracted from their $I$–$V$ curves obtained under the illuminated and dark conditions (hereafter referred to as flash $I$–$V$ and dark $I$–$V$, respectively); these are summarized in Fig 9, and all $p$-values estimated by the Steel–Dwass test are added to Table 1. As potential electrical signature for cell cracks, the critical reduction $I_{mp}$ in the Mode B and C cells laminated in the mini-PV modules has been recently reported [61]; however the

![Image](https://doi.org/10.1371/journal.pone.0277768.g008)

**Fig 8.** Cumulative frequency profile of the time constant determined at $V_j = 0.40$ V for all PV cells (left axis). Orange, blue, and open circles correspond to those in the HC, MC, and NC cells, respectively. The dashed-dotted line indicates the curve fitted to the bimodal distribution, which comprises two lognormal distributions drawn in the solid and dashed lines (right axis).

| Parameter                  | Mean (s)   | Standard Deviation (s) | Estimated Size (Cells) | $p$-values |
|----------------------------|------------|------------------------|------------------------|------------|
|                            | Low        | High                   |                         |            |
| Mean (s)                   | $4.51 \times 10^{-5}$ | $1.21 \times 10^{-4}$ |                         |            |
| Standard Deviation (s)     | $-4.345^a$ | $-3.953^a$             |                         |            |
| Estimated Size (Cells)     | 0.0953     | 0.0842                 |                         |            |

* These values indicate the logarithm of the respective means.

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authors did not mention the evolution in the Mode A cells. In this study (Table 1), a significant decrease in the $I_{mp}$ was confirmed in the HC cells (Mode B and C cells), although no significant difference between the MC (Mode A cells) and NC cells was verified. There was also a significant difference in the $I_{mp}$ between the MC and HC cells. Del Prado Santamaria et al. demonstrated that the decrease in the $I_{sc}$ was a specific feature in Mode C cells [61], and it was also confirmed in our study that $I_{sc}$ was decreased in the HC cells (Fig 9A and Table 1), but not in the MC cells. Based on the combination of two independent observations (in [61] and this study), we infer that $I_{mp}$ reduction is a common signature in HC cells, and the crucial reduction of $I_{sc}$ could be attributed to the occurrence of an electrically inactive area within the HC cells. Furthermore, $I_{mp}$ reduction cannot be regarded as a distinguishing feature of MC cells. Similar to the $I_{sc}$ case, obvious decreases in $V_{oc}$, $V_{mp}$, and FF were statistically identified in their distributions in the HC and NC cells. For the MC cells, substantial reductions against the NC cells were not statistically detected. Thus, for the $I-V$ parameters extracted from the flash $I-V$ curves, we did not identify any common feature(s) caused by the microcracks (3rd column in Table 1).

Among the flash $I-V$ parameters indicated in Fig 9A–9C, the most intense decrease in the HC cells was observed in the FF case. Because FF reduction depends on the evolution of $R_s$ and/or $R_{sh}$, we statistically analyzed the correlation between the crack behavior and the extent
estimated from the dark $I–V$ data. No significant deviation was observed among all cell groups in the $R_{sh}$ case ($d\cdot R_{sh}$ in Table 1), as well as those estimated from the AC impedance data ($R_{sh}$, $R_2$ in Table 1). The significant elevation of $R_s$ ($p = 0.049$) in the HC cells was validated, as shown in Fig 9D; however, the obvious evolution of $R_s$ was not confirmed in the MC cells ($p = 0.765$). To critically assess the contribution of $R_s$ elevation in the MC cells, we estimated the total $R_s$ value ($R_{s,ld}$) in these cell groups (Figs 10 and 11), which was suggested as the lumped $R_s$ around the maximum power point [26, 62].

In Fig 10A–10F, the ($I_L−I_{dark})$–$V_{dark}$ curves are drawn with the flash $I–V$ curves for the respective PV cells, in accordance with a previous report [26]. Here, $I_L$, $I_{dark}$, and $V_{dark}$ are the maximum currents determined from $I_c$ in the flash $I–V$ data, and the current and voltage on the dark $I–V$ curve, respectively. The $R_{s,ld}$ was calculated using (3). Although the values of $I_{mp}$, $V_{mp}$, and $V_{d,mp}$ were nearly equal between the NC cells (F08 and F10 cells) and MC cells (F03 and F01 cells), $I_{mp}$ and $V_{mp}$ decreased in the HC cells (C07 and C08 cells). Hence, because an increase in $V_{d,mp}$ was also observed in the HC cells, $R_{s,ld}$ was drastically elevated only in the HC cells (Fig 11). A significant elevation in $R_{s,ld}$ was not detected in the MC cells with obvious microcracks. As shown in Fig 10E and 10F, the divergence between the flash and dark $I–V$ curves at the low voltage range (0 to 0.4 V) is clearly demonstrated in the HC cells with high $R_{s,ld}$; this phenomenon is known as “Fake Shunt” which is caused by the spatial inhomogeneous distribution of $R_s$ in a PV cell/module [63, 64]. Because this “fake shunt” was not recognized in the MC cells, it was confirmed that a noticeable non-uniform elevation in the $R_s$ did not occur in the individual MC cells.

The elevation of $J_{02}$ was reported as a crucial electrical signature for a PV cell with microcracks, which can be observed in the global $I–V$ curve, as well as in the local $I–V$ image obtained in the microcrack region [29]. The values of $J_{01}$ and $J_{02}$ were estimated from the dark $I–V$ data of the individual cells, and are indicated as cumulative frequency profiles (Fig 12). Both frequencies monotonically proliferated with an increase in the respective saturation current densities, and no obvious flection was observed. Additionally, an uneven distribution owing to the difference in the crack categories was not observed in the $J_{01}$ and $J_{02}$ cases. Accordingly, $J_{02}$-elevation in both the HC and MC cells was not significantly identified in our data (Table 1), and $J_{01}$-elevation in both cell groups was not statistically evident. In this subsection, when PV cells are encapsulated as a PV module, we demonstrate that the peculiar electrical signatures of the individual PV cells with microcracks cannot be practically identified by the electrical parameters derived from the conventional $I–V$ curve analyses, but those of the PV cells with an electrically inactive area can be recognized easily.

### 4. Discussion

For PV cells encapsulated in a PV module, we demonstrated the evolution of various electrical signatures in PV cells with (MC and HC cells) or without (NC cells) cell cracks. In this study, the evolution from the pristine state of the respective PV cells has not been directly shown because we applied a typical destructive analysis (the electrical isolation of each cell from the electrical circuit of a PV module); the confounding factor(s) may affect the evolution of these signatures. However, we can presume that the evolutions identified in this study are attributed to cell cracks for following three reasons: 1) Each electrical signature of all the PV cells within a commercially available PV module can be presumed to have similar values with a certain deviation range, similar to a normal distribution, because the latest PV modules are manufactured under good quality control conditions. In fact, the saturation current densities ($J_{01}$ and $J_{02}$) of all PV cells have their respective monomodal distributions with a small variation range, and those of the cracked PV cells cannot be distinguished from those in the noncracked PV cells.
2) Although there is a bias in the distribution of the electrical signature of the respective PV cells within a pristine PV module, it is unlikely that the PV cells in the biased positions of the distribution would meaningfully correspond to the PV cells with cracks induced by mechanical stress. However, the time constant in the cracked PV cells is confined to one side of the distribution (Fig 8). 3) Significant evolutions of the electrical signatures ($P_{\text{max}}$, $I_{\text{sc}}$, $I_{\text{mp}}$, FF, and $d$-$R_s$) were observed in the cracked PV cells with electrically inactive regions, coinciding with the results reported in previous publications (in particular, in [61]). Therefore, we
conclude that the evolution of these electrical characteristics, which were observed in this study, should be predominantly used to study cell cracks.

As recently reported in [60], the recall rates for crack detection by conventional ELs, PLs, and high-resolution EL were $67 \pm 15\%$, $74 \pm 18\%$, and $84 \pm 3\%$, respectively, even for plain PV cells prior to encapsulation to assemble a PV module. This suggests that these methods fail to detect 16–33% of the actual cracks placed in the PV cells and that the miss rate is likely to be higher when targeting cracks in the PV cells within the PV module because of the reduced resolution of the images. Furthermore, the inspection method for cell cracks should have a broad spectrum to detect various types of crack modes because the cells with different crack modes are mixed within a PV module damaged by thermomechanical stress. Within this context, Spataru et al. clearly identified the distinguishing evolutions of electrical signatures in PV modules depending on the initiation/propagation of cell cracks [26]; the combined evolution (slight reductions in $I_{sc}$, $V_{oc}$, and FF, accompanied by drastic elevations in $R_{s,ld}$ and $J_{loss}$) was a unique signature of cell-crack development. Although this criterion is valuable for determining the specific degradation modes (cell damage) from various failure modes, it has not yet been proven whether this criterion can cover all cell-crack modes, especially microcracks. In fact, although this combined evolution was clearly confirmed in PV modules with a large power loss, it can be observed that the evolution of the dark $I-V$ curve in the PV module with a small power loss was considerably smaller [26, 65]. Moreover, it was suggested in their recent report that these evolutions have limitations when applied in cell-crack analysis [61]. This implies that microcracks could not be clearly detected by the evolutions of the dark $I-V$ parameters (particularly, $J_{01}$ and $J_{02}$) when they occurred in the PV cells encapsulated in a PV module, as shown in Fig 12. In this study, because the electrical characteristics were individually
assessed in the respective PV cells with various crack modes, we can conclude that the evolution of the carrier recombination is a universal electrical signature throughout all the cell-crack modes. In other words, it is suggested that microcracks can be practically detected only by this signature, but not by other electrical signatures. Furthermore, the evolution of other signatures (including the obvious decrease in output power) can be detected, depending on the cell-crack propagation (e.g., the emergence and expansion of electrically inactive cell area) due to further thermomechanical stress [31, 66].

So far, various electrical signatures attributed to cell cracks have been reported, such as a possible decrease in $I_{sc}$ owing to the development of an inactive cell area [19, 22, 26], an increase in $R_s$ [19–27], and a reduction in $R_{sh}/R_p$ [30, 32–35]. The $J_{02}$ elevation, which reflects the increase in carrier recombination occurring at the p-n junction, has been clearly demonstrated at the PV cell level [28–31]; however, at the PV module level, it may not necessarily apply to all cell-crack modes (including microcracks) [26, 61, 65], as discussed above. At the PV cell level, it is suggested that the evolution of these signatures (excluding carrier recombination and its relevant ones) depends on the progression of the crack modes, that is, the signatures (such as $R_s$-elevation) would appear if the cracks reached the rear side from the front surface of the PV cells [30, 31]. Our findings are consistent with this suggestion. Even in the PV cells within a PV module, a clear tendency toward elevated carrier recombination was observed in all cracked PV cells, although those in the other characteristics could not be
significantly recognized in the PV cells with only microcracks. Thus, this increase in carrier recombination is caused by the newly generated recombination centers in the microcracks [28–30]. Particularly, because the occurrence of microcracks is equivalent to the generation of a new edge in the PV cell, the non-passivated surface of silicon should be exposed. An increase in carrier recombination was observed when PV cells were cut with laser scraping equipment [67, 68], and it was deduced that this elevation predominantly proceeds in the depletion layer of an edge in the PV cells [69]. Additionally, the debris accumulated within the cracks of the PV cells would also act as a recombination center [70]. Therefore, we presume that this elevation is identified in all crack modes, not just in microcracks that have not yet propagated.

For the accurate detection of carrier recombination occurring at the depletion layer located within a PV cell, AC impedance spectroscopy should be selected from various methods, because the diffusion/transition capacitances can be satisfactorily estimated when the forward or reverse DC bias voltage is applied concurrently for the estimation of dynamic/shunt resistances [71]. Moreover, using this approach, the AC impedance parameters in the p–n junction can be independently extracted from those in the p–p+ junction placed at the interface between the Si bulk (p) and rear Al-BSF (p+) [50]. The evolution of electrical signatures caused by cell cracks has been evaluated by AC impedance spectroscopy analysis [33–35]; however, because AC impedance parameters (Cp/Rp/Rs in the AC equivalent circuit, cf. Fig 5A-1) were extracted from the AC impedance spectra obtained under DC biasless conditions, it has been advocated that the drastic reduction of Rs might correlate with the extent of the cracks. In this study, we applied a forward/reverse DC bias voltage at several voltage levels when the AC impedance data were acquired to estimate the AC impedance parameters in the p–n junction. Consequently, although the increase in the carrier recombination was not confirmed in the evolutions of J01 and J02 in the cracked PV cells, we statistically demonstrated that a trend toward significance in the reduction of the time constant is a critical signature of cell cracks through the estimation of their evolutions occurring in the p–n junction from those in an entire PV cell (including the p–p+ junction).

Because microcracks can be propagated through their penetration into the deeper bulk layer of PV cells by the thermomechanical stress experienced in laboratory tests and on-site (including transportation, installation, and/or operation stages) [10, 72], the evolution of carrier recombination, as a favorable signature of microcracks, is a crucial indicator/predictor to proactively maintain PV modules, even when the microcracks cannot be detected in their EL images. Because the data acquisition in AC impedance spectroscopy has been performed on PV modules [34, 73–75], the measurement accomplished using a DC bias voltage can be conducted effortlessly. Therefore, the diagnosis of failures with cell cracks at both the PV module and string levels, which is based on our conclusions, could be practically implemented for the assessment of the condition of a PV plant, the estimation of needed repairs, and asset transfer, although further verification in actual PV modules and strings is necessary. Moreover, this diagnostic indicator could also be a pass/fail criterion for quality assurance in processes including the manufacturing, transportation, and installation of PV modules.

5. Conclusions
In this study, we observed a remarkable reduction in the AC impedance spectroscopy time constant for all cell-crack modes including microcracks, although the evolutions in other
electrical signatures were not meaningfully related to microcracks in the PV cells within a PV module. Because this reduction reflects the elevation of the minority-carrier recombination at the p-n junction in the c-Si PV cell, we deduced that cell cracks located in a PV cell can be quantitatively assessed using this electrically measurable signature. This work is the first attempt to comprehensively elucidate the electrical behavior of cracks located in individual PV cells encapsulated in a PV module mimicking wind-load damage, by AC impedance spectroscopy with various DC bias voltages. Therefore, the signature identified in this procedure could be a valuable indicator and beneficial technique for assessing the health of PV modules and systems through practical verification.

Supporting information
S1 Fig. MSPP (in Pa) for the pressure load (a) or the suction load (b). Alphanumeric characters outside the box indicate the PV cell address shown in Fig 3.

S2 Fig. Interconnector ribbons exposed using a micro-grinder (a) and the attached electrical leads (b).

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References
1. Snapshot of global PV markets 2022. Paris, France: International Energy Agency; 2022. Available: https://iea-pvps.org/snapshot-reports/snapshot-2022/
2. International technology roadmap for photovoltaic (ITRPV): 2021 results. 13th ed. Frankfurt am Main, Germany: VDMA; 2022.
3. Jordan DC, Silverman TJ, Sekulic B, Kurtz SR. PV degradation curves: Non-linearities and failure modes. Prog Photovoltaics Res Appl. 2017; 25:583–591. https://doi.org/10.1002/pip.2835
4. Dhimish M, Holmes V, Dales M, Mehrdadi B. Effect of micro cracks on photovoltaic output power: Case study based on real time long term data measurements. Micro Nano Lett. 2017; 12:803–807. https://doi.org/10.1049/mnl.2017.0205

5. Mühliesen W, Hirschl C, Brantegger G, Neumaier L, Spielberg M, Sonnleitner H, et al. Scientific and economic comparison of outdoor characterisation methods for photovoltaic power plants. Renew Energy. 2019; 134:321–325. https://doi.org/10.1016/j.renene.2018.11.044

6. Dhimish M. Micro cracks distribution and power degradation of polycrystalline solar cells wafer: Observations constructed from the analysis of 4000 samples. Renew Energy. 2020; 145:466–477. https://doi.org/10.1016/j.renene.2019.06.057

7. Abdelhamid M, Singh R, Omar M. Review of microcrack detection techniques for silicon solar cells. IEEE J Photovoltaics. 2014; 4:514–524. https://doi.org/10.1109/JPHOTOV.2013.2285622

8. Karimi AM, Fada JS, Hossain MA, Yang S, Peshke TJ, Braid JL, et al. Automated pipeline for photovoltaic module electroluminescence image processing and degradation feature classification. IEEE J Photovoltaics. 2019; 9:1324–1335. https://doi.org/10.1109/JPHOTOV.2019.2920732

9. Ennemri A, Logebais PO, Balistrou M, Durastanti JF, Belaidi I. Cracks in silicon photovoltaic modules: A review. J Optoelectron Adv Mater. 2019; 21:74–92. Available: https://joam.inoe.ro/articles/cracks-in-silicon-photovoltaic-modules-a-review/

10. Papargyri L, Theristis M, Kubicek B, Krametz T, Mayr C, Papanastasiou P, et al. Modelling and experimental investigations of microcracks in crystalline silicon photovoltaics: A review. Renew Energy. 2020; 145:2387–2408. https://doi.org/10.1016/j.renene.2019.07.138

11. David PW, Murugan MS, Elavarasan RM, Pugazhendhi R, Jeba Singh O, Murugesan P, et al. Solar PV’s micro crack and hotspots detection technique using nn and svm. IEEE Access. 2021; PP: 1–1. https://doi.org/10.1109/ACCESS.2021.3111904

12. Goudelis G, Lazaridis PI, Dhimish M. A review of models for photovoltaic crack and hotspot prediction. Energies. 2022; 15:4303. https://doi.org/10.3390/en15124303

13. Koester L, Lindig S, Louwen A, Astigarraga A, Manzolini G, Moser D. Review of photovoltaic module degradation, field inspection techniques and techno-economic assessment. Renew Sustain Energy Rev. 2022; 165:112616. https://doi.org/10.1016/j.rser.2022.112616

14. Jiang Y, Zhao C. Attention classification-and-segmentation network for micro-crack anomaly detection of photovoltaic module cells. Sol Energy. 2022; 238:291–304. https://doi.org/10.1016/j.solener.2022.04.012

15. Photovoltaic devices—part 13: electroluminescence of photovoltaic modules. IEC TS 60904–13; 2018.

16. Bhoopathy R, Kunz O, Juhi M, Trupke T, Hameiri Z. Outdoor photoluminescence imaging of photovoltaic modules with sunlight excitation. Prog Photovoltaics Res Appl. 2018; 26:69–73. https://doi.org/10.1002/pip.2946

17. Bhoopathy R, Kunz O, Juhi M, Trupke T, Hameiri Z. Outdoor photoluminescence imaging of solar panels by contactless switching: Technical considerations and applications. Prog Photovoltaics Res Appl. 2020; 28:217–228. https://doi.org/10.1002/pip.3216

18. Köntges M, Morlier A, Eder G, Fleis E, Kubicek B, Lin J. Review: Ultraviolet fluorescence as assessment tool for photovoltaic modules. IEEE J Photovoltaics. 2020; 10:616–633. https://doi.org/10.1109/JPHOTOV.2019.2961781

19. Köntges M, Kunze I, Kajari-Schröder S, Breitenmoser X, Bjernemklett B. The risk of power loss in crystalline silicon based photovoltaic devices due to micro-cracks. Sol Energy Mater Sol Cells. 2011; 95:1131–1137. https://doi.org/10.1016/j.solmat.2010.10.034

20. Khatri R, Agarwal S, Saha I, Singh SK, Kumar B. Study on long term reliability of photovoltaic modules and analysis of power degradation using accelerated aging tests and electroluminescence technique. Energy Procedia. 2011; 8:396–401. https://doi.org/10.1016/j.egypro.2011.06.156

21. Kajari-Schröder S, Kunze I, Köntges M. Criticality of cracks in PV modules. Energy Procedia. 2012; 27:658–663. https://doi.org/10.1016/j.egypro.2012.07.125

22. Paggi M, Corrado M, Rodriguez MA. A multi-physics and multi-scale numerical approach to microcracking and power-loss in photovoltaic modules. Compos Struct. 2013; 95:630–638. https://doi.org/10.1016/j.compstruct.2012.08.014

23. Berardone I, Corrado M, Paggi M. A generalized electric model for mono and polycrystalline silicon in the presence of cracks and random defects. Energy Procedia. 2014; 55:22–29. https://doi.org/10.1016/j.egypro.2014.08.005

24. Käsewiete J, Haase F, Larrodé MH, Köntges M. Cracks in solar cell metallization leading to module power loss under mechanical loads. Energy Procedia. 2014; 55:469–477. https://doi.org/10.1016/j.egypro.2014.08.011
25. Käsewieter J, Haase F, Köntges M. Model of cracked solar cell metallization leading to permanent module power loss. IEEE J Photovoltaics. 2016; 6:28–33. https://doi.org/10.1109/JPHOTOV.2015.2487829

26. Spataru SV, Sera D, Hacke P, Kerekes T, Teodorescu R. Fault identification in crystalline silicon PV modules by complementary analysis of the light and dark current–voltage characteristics. Prog Photovoltaics Res Appl. 2016; 24:517–532. https://doi.org/10.1002/pip.2571

27. Seigneure H, Ogtman K, Schneller E, Davis KO, Schoenfeld W V. Effect of cracks on spatially resolved c-Si solar cell parameters. 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC). IEEE; 2016. pp. 0704–0707. https://doi.org/10.1109/PVSC.2016.7749692

28. van Mölen J, Yusufoğlu UA, Safiei A, Windgassen H, Khandewal R, Pletzer TM, et al. Impact of micro-cracks on the degradation of solar cell performance based on two-diode model parameters. Energy Procedia. 2012; 27:167–172. https://doi.org/10.1016/j.egypro.2012.07.046

29. Pletzer TM, van Mölen J, Rilland S, Breitenstein O, Knoch J. Influence of cracks on the local current-voltage parameters of silicon solar cells. Prog Photovoltaics Res Appl. 2015; 23:428–436. https://doi.org/10.1002/pip.2443

30. Demant M, Welschhold T, Kluska S, Rein S. Microcracks in silicon wafers II: implications on solar cell characteristics, statistics and physical origin. IEEE J Photovoltaics. 2016; 6:136–144. https://doi.org/10.1109/JPHOTOV.2015.2465172

31. Kikelj M, Lipovšek B, Bokalič M, Topič M. Spatially resolved electrical modelling of cracks and other inhomogeneities in crystalline silicon solar cells. Prog Photovoltaics Res Appl. 2021; 29:124–133. https://doi.org/10.1002/pip.3348

32. Breitenstein O, Rakotoniaina JP, Al Rifai MH, Werner M. Shunt types in crystalline silicon solar cells. Prog Photovoltaics Res Appl. 2004; 12:529–538. https://doi.org/10.1002/pip.544

33. Osawa S, Nakano T, Matsumoto S, Katayama N, Saka Y, Sato H. Fault diagnosis of photovoltaic modules using AC impedance spectroscopy. 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA). IEEE; 2016. pp. 210–215. https://doi.org/10.1109/ICRERA.2016.7884539

34. Symonowicz J, Riedel-Lyngskær N, Thorsteinsdottir S, Sera D, Poulsen PB. New method of silicon photovoltaic panel fault detection using impedance spectroscopy. 33rd European Photovoltaic Solar Energy Conference and Exhibition. Amsterdam, Netherland; 2017. pp. 1831–1835. https://doi.org/10.4229/EUPVSEC2017-2017-SDV.3.40

35. Katayama N, Osawa S, Matsumoto S, Nakano T, Sugiyama M. Degradation and fault diagnosis of photovoltaic cells using impedance spectroscopy. Sol Energy Mater Sol Cells. 2019; 194:130–136. https://doi.org/10.1016/j.solmat.2019.01.040

36. Chaturvedi P, Hoex B, Walsh TM. Broken metal fingers in silicon wafer solar cells and PV modules. Sol Energy Mater Sol Cells. 2013; 108:78–81. https://doi.org/10.1016/j.solmat.2012.09.013

37. Hsu S-T, Lin W-Y, Wu S-J. Environmental factors for non-uniform dynamic mechanical load test due to wind actions on photovoltaic modules. Energy Procedia. 2018; 150:50–57. https://doi.org/10.1016/j.egypro.2018.09.008

38. Tanahashi T, Sakamoton N, Shibata H, Masuda A. Corrosion-induced AC impedance elevation in front electrodes of crystalline photovoltaic solar cells within field-aged photovoltaic modules. IEEE J Photovoltaics. 2019; 9:741–751. https://doi.org/10.1109/JPHOTOV.2019.2893442

39. Suckow S, Pletzer TM, Kurz H. Fast and reliable calculation of the two-diode model without simplifications. Prog Photovoltaics Res Appl. 2014; 22:494–501. https://doi.org/10.1002/pip.2301

40. Lugo-Muñoz D, Muci J, Ortiz-Conde A, García-Sánchez FJ, Souza M de, Pavanello MA. An explicit multi-exponential model for semiconductor junctions with series and shunt resistances. Microelectron Reliab. 2011; 51:2044–2048. https://doi.org/10.1016/j.microrel.2011.06.030

41. Crain DJ, Rock SE, Garland JE, Roy D. Comparison of D.C. and A.C. electro-analytical methods for measuring diode ideality factors and series resistances of silicon solar cells. Curr Appl Phys. 2013; 13:2087–2097. https://doi.org/10.1016/j.cap.2013.09.012

42. Koch S, Graves C, Hansen KV. Elchema analytical. Kongens Lyngby, Denmark: Technical University of Denmark; 2013 [cited 8 Apr 2022]. Available: https://www.elchema.dk/

43. Schneider G, Chicken E, Becvarik R. Functions and datasets to accompany hollander, wolfe, and chicken—nonparametric statistical methods, third edition. 2020 [cited 8 Apr 2022]. Available: https://cran.r-project.org/web/packages/NSM3/

44. R Development Core Team. R: the R project for statistical computing. 2020 [cited 8 Apr 2022]. Available: https://www.r-project.org/
45. Young D, Benaglia T, Chauveau D, Hunter D, Elmore R, Hettmansperger T, et al. Tools for analyzing finite mixture models. 2020 [cited 8 Apr 2022]. Available: https://cran.r-project.org/web/packages/mixtools/index.html

46. Hsu S-T, Lien C. Evaluations of wind effect on PV module by non-uniform mechanical loads system and mean-surface pressure pattern. 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC). IEEE; 2018. pp. 0405–0408. https://doi.org/10.1109/PVSC.2018.8547493

47. Macdonald JR, Johnson WB. Fundamentals of impedance spectroscopy. 2nd ed. In: Barsoukov E, Macdonald JR, editors. Impedance Spectroscopy Theory, Experiment, and Applications. 2nd ed. Hoboken, NJ: John Wiley & Sons, Inc., Publication; 2005. pp. 1–26.

48. Proskuryakov YY, Durose K, Al Turkestani MK, Mora-Seró I, García-Belmonte G, Fabregat-Santiago F, et al. Impedance spectroscopy of thin-film CdTe/CdS solar cells under varied illumination. J Appl Phys. 2009; 106:044507. https://doi.org/10.1063/1.3204484

49. Garland JE, Crain DJ, Zheng JP, Sulyma CM, Roy D. Electro-analytical characterization of photovoltaic cells by combining voltammetry and impedance spectroscopy; Voltage dependent parameters of a silicon solar cell under controlled illumination and temperature. Energy Environ Sci. 2011; 4:485–498. https://doi.org/10.1039/C0ES00307G

50. Yadav P, Pandey K, Bhatt V, Kumar M, Kim J. Critical aspects of impedance spectroscopy in silicon solar cell characterization: A review. Renew Sustain Energy Rev. 2017; 76:1562–1578. https://doi.org/10.1016/j.rser.2016.11.205

51. Herrmann W, Adrian M, Wiesner W. Operational behaviour of commercial solar cells under reverse biased conditions. 2nd World Conference on Photovoltaic Solar Energy Conversion. Vienna, Austria; 1998. pp. 2357–2359.

52. Lopez-Escalonante MC, Martin F, Ramos-Barrado J. Grouping by bulk resistivity of production-line monocrystalline silicon wafers and its influence on the manufacturing of solar cells modules. Sol Energy. 2016; 131:61–70. https://doi.org/10.1016/j.solener.2016.02.023

53. López-Escalonante MC, Jiménez FM, Pérez MG, Leinen D, Barrado JRR. Shunt resistance criterion: Design and implementation for industrial silicon solar cell production. Sol Energy. 2020; 206:269–278. https://doi.org/10.1016/j.solener.2020.05.092

54. Taubitz C, Schütze M, Koenstopp MB. Towards a kinetic model of potential-induced shunting. 27th European Photovoltaic Solar Energy Conference and Exhibition. Frankfurt, Germany: WIP-Munich; 2012. pp. 3172–3176. https://doi.org/10.4229/27thEUPVSEC2012-4DO.6.6

55. Yeow T, Sun J, Yao Z, Jaubert J-N, Musselman KP. Evaluation of impedance spectroscopy as a tool to characterize degradation mechanisms in silicon photovoltaics. Sol Energy. 2019; 184:52–58. https://doi.org/10.1016/j.solener.2019.03.088

56. Gastwirth JL, Gel YR, Hallacek WL, Lyubachich V, Miao W, Noguchi K. Lawstat: Tools for biostatistics, public policy, and law. 2020 [cited 8 Apr 2022]. Available: https://cran.r-project.org/web/packages/lawstat/index.html

57. Greulich JM, Demant M, Kunze P, Dost G, Ramspeck K, Vetter A, et al. Comparison of inline crack detection systems for multicrystalline silicon solar cells. IEEE J Photovoltaics. 2020; 10:1389–1395. https://doi.org/10.1109/JPHOTOV.2020.2996750

58. Del Prado Santamaria R, Dos Reis Benatto GA, Lancia AAS, Garaj M, Thorsteinsson S, Poulsen PB, et al. Characterization of electrical parameters of cracked crystalline silicon solar cells in photovoltaic modules. 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). IEEE; 2021. pp. 0846–0853. https://doi.org/10.1109/PVSC43889.2021.9519081

59. Hacke P, Meier DL. Analysis of fill factor losses using current-voltage curves obtained under dark and illuminated conditions. Conference Record of the Twenty-Ninth IEEE Photovoltaic Specialists Conference, 2002. IEEE; 2002. pp. 462–464. https://doi.org/10.1109/PVSC.2002.1190559

60. Bowden S, Rohatgi A. Rapid and accurate determination of series resistance and fill factor losses in industrial silicon solar cells. 17th European Photovoltaic Solar Energy Conference and Exhibition. 2001. pp. 1802–1805.
64. Asadpour R, Sun X, Alam MA. Electrical signatures of corrosion and solder bond failure in c-Si solar cells and modules. IEEE J Photovoltaics. 2019; 9:759–767. https://doi.org/10.1109/JPHOTOV.2019.2896898

65. Spataru S, Hacke P, Sera D. In-situ measurement of power loss for crystalline silicon modules undergoing thermal cycling and mechanical loading stress testing. Energies. 2020; 14:72. https://doi.org/10.3390/en14010072

66. Paggi M, Berardone I, Infuso A, Corrado M. Fatigue degradation and electric recovery in silicon solar cells embedded in photovoltaic modules. Sci Rep. 2015; 4:4506. https://doi.org/10.1038/srep04506 PMID: 24675974

67. Bertrand D, Manuel S, Pirot M, Kaminski-Cachopo A, Veschetti Y. Modeling of edge losses in Al-BSF silicon solar cells. IEEE J Photovoltaics. 2017; 7:78–84. https://doi.org/10.1109/JPHOTOV.2016.2618603

68. Gérenton F, Eymard J, Harrison S, Clerc R, Muñoz D. Analysis of edge losses on silicon heterojunction half solar cells. Sol Energy Mater Sol Cells. 2020; 204:110213. https://doi.org/10.1016/J.SOLMAT.2019.110213

69. Fell A, Schön J, Müller M, Wöhrl N, Schubert MC, Glunz SW. Modeling edge recombination in silicon solar cells. IEEE J Photovoltaics. 2018; 8:428–434. https://doi.org/10.1109/JPHOTOV.2017.2787020

70. Silverman TJ, Bliss M, Abbas A, Betts T, Walls M, Repins I. Movement of cracked silicon solar cells during module temperature changes. 2019 IEEE 46th Photovoltaic Specialists Conference (PVSC). IEEE; 2019. pp. 1517–1520. https://doi.org/10.1109/PVSC40753.2019.8981150

71. Chenvidhya D, Kirtikara K, Jivacate C. PV module dynamic impedance and its voltage and frequency dependencies. Sol Energy Mater Sol Cells. 2005; 86:243–251. https://doi.org/10.1016/j.solmat.2004.07.005

72. Küntges M, Kurtz S, Packard C, Jahn U, Berger KA, Kato K, et al. Review of failures of photovoltaic modules. Paris, France,: International Energy Agency; 2014. Available: https://iea-pvps.org/key-topics/review-of-failures-of-photovoltaic-modules-final/

73. Johnson J, Schoenwald D, Kuszmaul C, Strauch J, Bower W. Creating dynamic equivalent PV circuit models with impedance spectroscopy for arc fault modeling. 2011 37th IEEE Photovoltaic Specialists Conference. IEEE; 2011. pp. 002328–002333. https://doi.org/10.1109/PVSC.2011.6186419

74. Oprea MI, Spataru S V., Sera D, Poulsen PB, Thorsteinsson S, Basu R, et al. Detection of potential induced degradation in c-Si pv panels using electrical impedance spectroscopy. 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC). IEEE; 2016. pp. 1575–1579. https://doi.org/10.1109/PVSC.2016.7749885

75. Guejia-Burbano RA, Petrone G, Piliouge M. Impedance spectroscopy for diagnosis of photovoltaic modules under outdoor conditions. IEEE J Photovoltaics. 2022. https://doi.org/10.1109/JPHOTOV.2022.3195003