Degradation and longevity of solar photovoltaic modules—An analysis of recent field studies in Ghana

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Abstract
Solar photovoltaic (PV) technology has attracted an enormous amount of attention and investment in recent years—translating to record deployment levels. This is due to in part to its potential role as a cleaner energy source in the emissions-constrained development agenda that is currently being pursued at both global and national levels. Solar PV has also been propelled to the forefront of today’s menu of technological options by virtue of its attributes such as scalability, fast deployment lead times, and low operating cost. Substantial investments are needed in the coming years in order to accomplish climate targets and other goals set by various countries and regional/subregional blocs. In support of informed investment decision-making and ultimately, improved outcomes of solar PV projects, there has been an uptick in studies on operational performance of fielded PV systems across the globe. These studies are, however, geographically unbalanced, and there is the need for data from under-represented regions. This paper presents a synthesis of results obtained from recent seminal field studies on PV module performance degradation in Ghana. The studies altogether analyzed sixty-five (65) modules (mono- and polycrystalline silicon) from twenty-nine (29) installations across the country (1118 module-years). The field-aged modules were characterized in situ using current-voltage (I-V) curves, visual inspection checklists, and thermal imaging. Annual module performance degradation rates (peak power) of 0.8%-7%, 0.55%-2.07%, and 1.1%-2.4% were found for modules located in various climate subcategorizations.

KEYWORDS
degradation, Ghana, module, performance, photovoltaic

1 | INTRODUCTION
As the deployment of solar photovoltaic (PV) systems continues to rise at record pace on an annual basis, module reliability and durability have taken on added importance, as investors and prospective system owners desire some assurance that their investments will yield the expected benefit. Although investments have risen substantially, much more investments...
are needed in the coming years in order to accomplish climate targets and other goals set by various countries and regional/subregional blocs. Reliable module performance over the typical 25-30 year project life is essential for investors and system owners to realize the expected return on their investment. Considering the characteristic high fixed-to-variable cost ratio of solar PV systems, the financial metrics are particularly affected by technology failure or underperformance, as most of the required life cycle investment would have already been incurred. Questions about the reliability and durability of PV modules have engaged the attention of researchers since the earliest days of the technology’s field deployment. Government-funded R&D programs across Europe, United States, and Japan closely monitored and studied experimental PV systems, mostly on testbeds, from which important data were obtained and disseminated through conferences, journal articles, and technical reports. Similarly, PV module test protocols have continued to evolve, with key contributions from the European ESTI as well as the US Government block procurement program by the NASA Jet Propulsion Laboratory (JPL).

Accelerated lifetime testing protocols developed by these key programs constituted the seminal stages of what eventually resulted in the first draft (in 1989) of the IEC 61215 test sequence for terrestrial PV modules. The IEC 61215 has been widely credited with improved field performance of PV modules, particularly with significantly reducing infant mortality. These tests, however, do not provide validation for manufacturer warranties, which typically promise 80% of nominal power within a 25-year period. It must be mentioned that these warranties are themselves evolving—80% in more than 25 years or more than 80% in 25 years.

Meanwhile, through the 1980s and 90s, the technology was introduced to various countries in Africa and was viewed as an important technology that could have positive impact on national electrification programs and enhance the provision of basic services, such as water supply and health. As costs at the time were prohibitive, early installations were mainly owned by institutions such as state agencies and other nongovernmental agencies. For example, in Ghana, the parastatal agency in charge of cocoa marketing (the Ghana Cocoa Marketing Board) began using the technology in the 1980s to power its radio communication systems in remote and unelectrified areas.

For almost four decades, PV technology has been applied in Ghana for various purposes and in different applications. Yet, not much has been accomplished in the area of monitoring of operational performance, degradation, and failure. Photovoltaic modules, once exposed, endure environmental and operational stresses that emanate from factors such as humidity, temperature, ultra-violet radiation, high voltage, and mechanical stresses (Figure 1). These stresses have adverse impact on various components of the PV modules—packaging materials, adhesion, semiconductors, metallization, etc, which, in turn, drive performance loss. An understanding of the drivers of performance loss and availability of quantitative field-verified estimates of degradation rates holds benefits for all actors along the solar PV value chain. For instance, while R&D institutes involved in PV cell development could use such data for the development of more enduring cells, project developers and system integrators are empowered to generate more realistic performance and revenue forecasts.

Even though Ghana’s plans for the energy sector clearly envisage a major role for renewable energy in general, and solar PV in particular, the subject of empirical assessment of module performance and its degradation remained largely unexplored—with little information available in the open literature. Early work on PV module performance in Ghana was reported by Adanu on a 268 Wp module monitored at the University of Ghana in the 1990s. The paper reported module performance on some selected days. It, however, did not provide information on how the system performed on an annual basis, or how its performance was likely to evolve over time. Other authors of that era reported on technology uptake, government projects, and policy, as well as the role of PV in national electrification. More recently, authors such as Koffi et al, Quansah et al, and Mensah et al have presented findings on empirical assessment of solar PV systems in Ghana, covering topics such as temperature response of various silicon and nonsilicon PV technologies, as well as performance metrics of kW- to MW-scale grid-connected systems.

In an effort to address questions bordering on field performance of PV modules, module performance degradation, and failure in Ghana, research has recently (since 2015) been conducted to characterize field-aged PV modules across the country. The outcome of the research was communicated on an ongoing basis, as new systems from various subclimatic zones of country (and of various configurations) were studied. The findings were presented in five (5) key journal and conference papers.

This objective of this paper was to present a consolidated climate-aggregated analysis of field data obtained from electrical characterization and defect (visually observable) documentation on modules installed at twenty-nine (29) locations across Ghana and covering various subclimatic zones. It is hoped that this synthesis will provide further insight into field performance of PV modules and make more data available for system developers and other actors in the solar PV value chain.

## 2 | METHOD

### 2.1 | Characteristics of modules studied

The PV modules studied were part of installations which were owned by government agencies, educational institutions,
private homes. For systems installed in private homes, they were all systems which were part of government-sponsored PV dissemination programs. Availability of reliable module reference data informed this selection approach. Where nameplate data were insufficient, additional data were obtained from the PV module database of the design and simulation software PVSYST®. The characteristics of the modules encountered in the nationwide study are presented in Table 1. The modules were mainly from Europe, with a few coming from Asia (China). They comprised monocrystalline silicon (mc-Si) and polycrystalline silicon (pc-Si) technologies and had rated power in the range of 36 Wp for the earliest module (HS.40.1 N) to 170 Wp (Schott Poly 170) for some of the relatively recent ones (Table 1).

| Module type        | Manufacturer                | Module technology | Max. Power ($P_{nom}$) | Short-circuit current ($I_{sc}$) | Open-circuit voltage ($V_{oc}$) | $I_{mpp}$ | $V_{mpp}$ |
|--------------------|-----------------------------|-------------------|------------------------|----------------------------------|---------------------------------|----------|----------|
| ASE-50-PWX-D       | ASE GmbH, Germany           | pc-Si              | 49.5                   | 3.10                             | 21.6                            | 2.85     | 17.4     |
| HS.40.1 N          | HOLEC HH, Netherlands       | pc-Si              | 36.0                   | 2.30                             | 22.0                            | 2.1      | 17.0     |
| Isofoton I-110/12  | Isofoton, Spain             | mc-Si              | 110.0                  | 6.76                             | 21.6                            | 6.32     | 17.4     |
| Isofoton I-100     | Isofoton, Spain             | mc-Si              | 100.0                  | 6.54                             | 21.6                            | 5.74     | 17.4     |
| Isofoton I-50      | Isofoton, Spain             | mc-Si              | 50.0                   | 3.27                             | 21.6                            | 2.87     | 17.4     |
| Baodin Solar       | TT Baodin Group, China      | pc-Si              | 50.0                   | 3.20                             | 21.6                            | 2.90     | 17.2     |
| aleo 150-MSi       | Aleo Solar GmbH, Germany    | mc-Si              | 150.0                  | 4.93                             | 43.3                            | 4.35     | 34.9     |
| aleo S_03          | √Aleo Solar GmbH, Germany   | mc-Si              | 165.0                  | 5.10                             | 43.5                            | 4.64     | 35.8     |
| Schott Poly 170    | Schott Solar, Germany       | pc-Si              | 170.0                  | 5.3                              | 44.0                            | 4.78     | 35.5     |

FIGURE 1 Environmental and operational factors responsible for module degradation and failure (Source – Authors)
2.2 Locations and climate characteristics

The Köppen-Geiger classifications of climates are one of the most widely used. Ghana’s land mass falls within latitude 5°N-11°N and longitude 3°W-1°E, and by the Köppen-Geiger classification, its climate is classified as tropical climate (A) of the monsoon (Am) type and savanna with dry winter (Aw) type. This implies that the average temperature of the coolest month is above 18°C and precipitation in the driest month is less than 60 mm. However, subclassifications of climatic conditions are often necessary for various purposes (eg agrometeorology and disease prevalence). One such subclassification, provided by Beckley et al, is adopted for this study. Beckley et al classify Ghana’s climate from latitude 0-6°N as Humid (H), from latitude 6-10°N as Sub-Humid Humid, and latitude 10-12°N as Sub-Humid Dry (SHD). These climate zones encompass five agroecological zones (rain forest, semi-deciduous forest, Guinea savannah, Sudan savannah, and coastal savannah). In Figure 2, subclimatic zoning of the locations of study is shown and color-coded as green (Humid), red (Sub-Humid Humid), and yellow (Sub-Humid Dry).

Representative long-term climatic data for the study locations were obtained from climatological databases and are presented in Figure 3. They show monthly variation of solar irradiation (Figure 3A), ambient temperature, and relative humidity (Figure 3B) for Accra (Humid), Kumasi (Sub-Humid Humid), and Navrongo (Sub-Humid Dry).

For each climate category, the weighted average age \( A_w \) of modules assessed was estimated using Equation 1.

\[
A_w = \frac{1}{N} \sum_{i=1}^{N} n_i A_i
\]

where \( n_i \) is the proportion of modules in a given climate zone which were found at location \( i \); \( A_i \) is the age of modules at location \( i \); and \( N \) is the total number of locations in a given climate zone from where modules were assessed.

With reference to Table 1 and the climate categorization method shown in Figure 2, a summary of modules studied is shown in Table 2.

2.3 Module inspection—visually observable defects (VODs)

Defects visible to the eye often provide useful clues to underlying material-level degradation. For instance, the degradation of the encapsulant material results in a visually...
observable yellowing/browning, which in turn leads to losses in short-circuit current of modules. Visual inspection is therefore widely used as a relatively inexpensive method, in conjunction with other techniques for PV system performance monitoring and diagnosis. Work conducted by the IEA/OECD (IEA Photovoltaic Power Systems Programme (PVPS) Task 13) has resulted in a widely used visual inspection checklist for PV systems, which makes it possible for researchers to use consistent vocabulary to describe observed defects. Module defects encountered in the study were categorized according to the component of the module within which they were observed (Table 3). Description of the defects observed followed the vocabulary used by the IEA/OECD. Potential defects in various PV module components were envisaged as per Table 3.

### Field measurements

Current-voltage (I-V) measurements on the PV solar modules were conducted with a TRI-KA® I-V curve tracer and its accompanying TRI-SEN®, which measures irradiance, module temperature, and inclination. The current and voltage measurement range of the TRI-KA® is 0.1–15 A and 1–1000 V, respectively, and has measurement uncertainty of ±1% (for both current and voltage). The TRI-SEN® has irradiance

| Climate subcategory | Module types studied |
|---------------------|----------------------|
| Humid (H)           | Isofoton I-100, Holec HS-40.1 N, Baodin Solar, aleo 150-M5i, aleo S_03 |
| Sub-Humid Humid (SHH)| ASE-50-PWX-D, Schott Poly 170 |
| Sub-Humid Dry (SHD)  | Isofoton I-110/12, Isofoton I-100, Isofoton I-50 |

**Table 2** Module types encountered in various climate subcategories
and temperature measurement range of 100-1200 W/m² and 0-100°C, respectively, with uncertainties of ±3% and ±5%. Measurements were taken within the solar window (10 AM-2 PM), as to obtain irradiance levels as close as possible to 1000 W/m². Work by Anderson has shown that translation of measured data to standard test conditions (1000 W/m², 25°C, and air mass 1.5) is more accurate if the measurement is undertaken as close to STC as possible. Minimum irradiance was maintained at 700 W/m², and translation of measured data to STC was accomplished per expressions proposed by Kaplanis and Kaplani. Thermal images were acquired with a Fluke® TI400 Infrared Camera. This was used to a limited extent and did not show evidence of hot spot formation.

### RESULTS AND DISCUSSIONS

#### 3.1 Module age characteristics and applications

The weighted average age of the installations studied was 16.0 for SHD, 16.3 for SHH, and 17.7 for H climate subcategories and altogether comprised 1118 module-years (age distribution shown in Figure 4). The actual ages ranged between 6 and 32 years. The number of modules assessed in each subcategory is also shown (Figure 4).

The modules were deployed in grid-connected and off-grid modes. The off-grid applications comprised battery-charging and water-pumping systems (Table 4). The type of mounting consisted of rack-mounted, roof-flushed, and pole-mounted systems.

### 3.2 Module performance loss in various climate categories

Power loss ($P_{\text{max}}$) in the Humid climate subcategory (shown in Figure 5A) ranged between a low of 0.8%/y and a high of 7%/y, with a median value of 1.8%/y. The loss factors, that is, the short-circuit current ($I_{\text{sc}}$), open-circuit voltage ($V_{\text{oc}}$), and fill factor (FF), respectively, showed median degradation rates of 1.1%, 0.4%, and 0.5%/y. $I_{\text{sc}}$-related losses therefore seem to dominate the module power loss in the Humid climate subcategory.

Module power loss in the Sub-Humid Humid climate category ranged from 0.55% to 2.07%/y, with a median of 1.43%/y (Figure 5B). Losses in the explanatory variables (median values) were 0.49%, 0.18%, and 0.89%/y for $I_{\text{sc}}$, $V_{\text{oc}}$, and FF, respectively. Losses in fill factor therefore appeared dominant in the SHH climate category.

Figure 5C shows module power degradation rate for systems in the Sub-Humid-Dry climate category. It shows median power loss of 1.5%/y, with a range of 1.1%-2.4%/y. The composite degradation rate for the category was most influenced by losses in short-circuit current—median value of 0.8%/y. Losses in $V_{\text{oc}}$ and FF were 0.3% and 0.5%/y, respectively.

For each of the explanatory variables, least-square regression analysis was run to ascertain the relative
importance in the various climate categories. Figure 6A shows the correlation between $I_{sc}$ loss rate and module power loss rate in all three climate categories. A stronger correlation is seen between $I_{sc}$ losses and $P_{max}$ losses in the Humid (H) climate category with a correlation coefficient of almost 90%.

| Location no. | Climate | Module Tech. | Application | Field years | Mounting type |
|--------------|---------|--------------|-------------|-------------|---------------|
| 1            | SHH     | pc-Si        | Battery-charging | 19          | Rack-mounted  |
| 2            | √       | √            | Grid-connected | 10          | Roof-flushed  |
| 3            | H       | √            | Battery-charging | 32          | Pole-mounted  |
| 4            | √       | √            | √            | 10          | Roof-flushed  |
| 5            | √       | mc-Si        | Grid-connected | 16          | Rack-mounted  |
| 6            | √       | √            | Water-pumping | 11          | Pole-mounted  |
| 7            | √       | √            | √            | 6           | √             |
| 8            | SHD$^a$ | √            | Battery-charging | 16          | √             |
| 9            | √       | √            | √            | 16          | √             |
| 10           | √       | √            | √            | 16          | √             |

$^a$Twenty-two modules were studied in the SHD climate and have been lumped according to three major municipalities in which they are located.

**FIGURE 5** Degradation (%/y) in module performance indicators, (A) climate category H, (B) climate category SHH, and (C) climate category SHD.
Similarly, the strength of the relationship between module degradation rate ($P_{\text{max}}$) and fill factor ($P_{\text{max}} = f(FF)$), as well as $P_{\text{max}}$ and open-circuit voltage ($P_{\text{max}} = f(V_{oc})$), is tested in Figure 6B,C. FF losses show (Figure 6B) no correlation with power loss in the SHD climate category (with $R^2$ value of .06), while stronger correlations are found in the H and SHH climate categories with coefficients of 0.8 and 0.68, respectively.

The results from these studies suggest, for instance, that installations in the Humid climate category (Figure 5) with lowest degradation rate (0.8%/y) may be expected to take 25 years...
before its maximum power falls below 80% of rated output (Figure 7). However, based on median degradation rates found for the different climate subcategories (1.43%-1.8%/y), it would take a much shorter period to 11-14 years to reach this critical threshold (Figure 7). Nevertheless, crossing the warranty threshold does not imply the end of a module’s useful life.6

3.3 | Visual observable defects (VODs)

Visually observable defects (VODs) were documented in all three climate subcategories, using the classification in Table 4. Overall, front-side defects were dominant, followed by defects related to cell metallization and junction box (Figure 8). A module could exhibit more than one defect in a given category; for instance, at the front side of the module, defects such as delamination, formation of bubbles, and glass breakage could all be observed in a given module. Figure 9 shows some VODs that were documented in the study (browning, delamination, corroded metallization, snail tracks, burn marks in junction box, degraded j-box adhesive shattered, and front-glass). From Figure 8, front-of-module defects were the most prevalent in all climate categories. Additionally, modules in climate category H recorded more VODs than other climates. A further breakdown of front-of-module defects is shown in Figure 10 and shows encapsulant browning and delamination as the most dominant VODs across all three climate categories.

Although climate SHH had high incidence of bubbles on the front side (70%), these were minor in extent (of the order of 1 mm diameter) and did not appear to have had much impact on power loss based on the contribution of $I_{sc}$ and FF losses.14 No other defects were visible. Also observed was the visible impact of installation flaws (Figure 11). As shown in Figure 11(A-C), these installation defects had resulted in accumulation and hardening of debris on modules, collection of rainwater in cable ducts, and impediments to water runoff by module frame.

3.4 | General discussions

As the impact of climatic conditions significantly affect module operation and degradation, the preceding results from these studies have been aggregated and presented according to climatic subcategories (H, SHH, and SHD). For the response variable ($P_{max}$) and explanatory variables ($I_{sc}$, $V_{oc}$, and FF), the distribution of actual degradation rates in all three climate subcategories is shown (Figure 5). In Figures 5A-C5-8, the minimum, maximum, and median values are highlighted. The Humid (H) climate subcategory shows the highest median power loss—of 1.8%/y—compared with 1.43% and 1.5%/y for the Sub-Humid Humid (SHH) and Sub-Humid Dry (SHD) categories, respectively. $P_{max}$ losses in categories H and SHD are dominated by $I_{sc}$ losses (1.1% and 0.8%, respectively), while losses in SHH category are dominated by FF losses (0.89%). The range of degradation rates found in the Humid climate category is much wider than the others (eg, 0.8%-7%/y for $P_{max}$). The extreme end of the range was due to the impact of some “uncertified” modules which were also poorly installed and had degraded substantially (this is described in more detail in Ref. 17). In all climate categories, the annual linear degradation rates found in this study are substantially higher than values of 0.5%-0.8%.
reported from major meta-analytical reviews.\textsuperscript{15,33,34} A further comparison may be drawn with a similar nationwide study in India, which found degradation rates of 1.17\% and 1.43\%/y for mc-Si and pc-Si, respectively.\textsuperscript{35} For purposes of comparison, Table 5 presents a summary of similar studies conducted by other researchers from various parts of the world. It shows, that even though a range of 0.5\%-0.8\% annual degradation has been reported for median values, much higher degradation rates have also been observed (eg, Rajput et al\textsuperscript{36} and Belmont et al\textsuperscript{37}).

Installations in climate subcategories H (Accra area) and SHH (Kumasi area) appear to endure a stronger combined effect of high temperature and high humidity throughout the year, compared with systems installed in the SHD climate (Navrongo area) (Figure 3A,B). On the other hand, installations in the SHD climate are exposed to a greater effect of high temperature and UV (ultraviolet) radiation exposure. Consequently, one may expect the degradation and failure modes reproduced by the dump-heat test in the IEC

\textbf{FIGURE 9} Images of some defects observed in field-aged modules (A)—delamination and browning, (B)—snail track and browning, (C)—degraded junction box adhesive, (D)—burns in junction box due to arcing, and (E)—crack on front glass

\textbf{FIGURE 10} Details of front-of-module VODs observed in various climate categories
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61215 sequence (stage 10.13)\textsuperscript{42} to be more prevalent in field-aged installations in the southern to mid-part of the country (Humid and Sub-Humid Humid) than in the northern part (Sub-Humid Dry). By analogous reasoning, the effects of TC200 (IEC 61215 stage 10.11)\textsuperscript{42} are likely to be more prevalent in installations in the SHD climate than in H and SHH.

**TABLE 5** An overview of similar PV module degradation studies

| Authors           | Module technologies studied | Location         | Years of exposure | Losses reported                        | Major defects observed                                      |
|-------------------|-----------------------------|-------------------|-------------------|----------------------------------------|-------------------------------------------------------------|
| Makrides et al\textsuperscript{38} | mc-Si pc-Si Thin films       | Nicosia, Cyprus   | 5                 | mc-Si:0.64%/y pc-Si:0.62%/y Thin films:1.78%/y | --                                                          |
| Rajput et al\textsuperscript{36}   | mc-Si                        | Gurgaon, India    | 22                | 1.9%/y                                 | Defects in busbar, cell, and string interconnection ribbons |
| Pozza and Sample\textsuperscript{39} | mc-Si                        | Ispra, Italy      | 20                | 0.22%/y                                | Yellowing of encapsulant                                    |
| Lorenzo et al\textsuperscript{40}  | mc-Si                        | Madrid, Spain     | 17                | 0.53%/y                                | Backsheet delamination, cracks in junction box, degradation of ARC |
| Bandou et al\textsuperscript{41}   | mc-Si                        | Adrar, Algeria    | 28                | 1.22%/y                                | Yellowing and browning of encapsulant, delamination of encapsulant |
| Belmont et al\textsuperscript{37}  | mc-Si                        | Phoenix, Arizona  | 26                | 2.3%/y                                 | Intensive encapsulation browning                             |
| This study        | mc-Si                        | Ghana—SHD         | 16                | 1.5%/y                                 | Front-of-module defects—delamination, encapsulant browning, and formation of bubbles |
|                   | mc-Si/pc-Si                  | Ghana—H           | 17.7              | 1.8%/y                                 |                                                             |
|                   | mc-Si/pc-Si                  | Ghana—SHH         | 16.3              | 1.43%/y                                |                                                             |

**FIGURE 11** Some observed installation defects showing (A) extensive debris accumulation and hardening, (B) cable ducts retaining rainwater, and (C) installation frame impeding water runoff
CONCLUSION

The objective of this paper has been to present a subclimate-based aggregated analysis of recent studies in Ghana that focused on a nationwide assessment of field-aged solar PV modules.

A wide range of degradation rates was observed for the sixty-five modules studied in all three climates in this study. The annual degradation rates for individual modules ranged from 0.8%-7%/y, 0.55%-2.07%/y, and 1.1%-2.4%/y, for Humid (H), Sub-Humid Humid (SHH), and Sub-Humid Dry (SHD) subclimate categories, respectively. The corresponding median values observed were 1.8%, 1.43%, and 1.5%, respectively, for H, SHH, and SHD climate categories, respectively. Losses in short-circuit current dominated power loss in the Humid and Sub-Humid Dry climates (1.1% and 0.8%/y, respectively), while losses in fill factor drove power loss in the Sub-Humid Humid climate category (0.89%/y). The Pmax degradation rate found in this study is substantially higher than median and mean values of 0.5%-0.8%/y which have been reported from meta-analytical studies as being representative of crystalline silicon (x-Si) modules.

Although there is the need to expand the number of modules studied, the results of this research suggest that modules installed in Ghana will generally take less than 15 years to fall below 80% of initial power. This duration could be as short as 11 years (based on median degradation rate of 1.8%/y).

Visually observable defects (VODs) were most prevalent in the Humid (H) climate, with occurrences registered in all seven of the module defect categories defined. Front-of-module and cell metallization defects were dominant. The Sub-Humid Dry (SHD) climate was next in VODs and had occurrences in four out of seven defect categories. These were dominated by front-of-module and junction box–related defects (mostly, degraded adhesive). The H climate appears to impose more stresses than other climates due to the combined effect of high humidity and high temperature. This is consistent with the comparatively high incidence of module delamination and browning observed in climate H and the high contribution of Isc losses to power degradation.

Meanwhile, in the Sub-Humid Humid climate, VODs were observed in only one defect category (front-of-module); although they occurred in 70% of modules, they were minor bubbles (of the order of 1-mm diameter) and had a smaller impact on power losses as evidenced by the lower contribution of Isc losses compared with FF losses. The superior contribution of FF losses to power decline suggests increased series resistance within the module. Thermomechanical fatigue and breakage in solder bonds/interconnects are not readily visible to the unaided eye and therefore account for the lower record of VODs in the SHH climate.

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