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RESEARCH ARTICLE

Photovoltaic failure and degradation modes

Dirk C. Jordan[1]*, Timothy J. Silverman[1], John H. Wohlgemuth[1], Sarah R. Kurtz[1] and Kaitlyn T. VanSant[2]

[1] National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, Colorado 80401, USA
[2] Colorado School of Mines, 1500 Illinois Street, Golden, Colorado 8040, USA

ABSTRACT

The extensive photovoltaic field reliability literature was analyzed and reviewed. Future work is prioritized based upon information assembled from recent installations, and inconsistencies in degradation mode identification are discussed to help guide future publication on this subject. Reported failure rates of photovoltaic modules fall mostly in the range of other consumer products; however, the long expected useful life of modules may not allow for direct comparison. In general, degradation percentages are reported to decrease appreciably in newer installations that are deployed after the year 2000. However, these trends may be convoluted with varying manufacturing and installation quality world-wide. Modules in hot and humid climates show considerably higher degradation modes than those in desert and moderate climates, which warrants further investigation. Delamination and diode/j-box issues are also more frequent in hot and humid climates than in other climates. The highest concerns of systems installed in the last 10 years appear to be hot spots followed by internal circuitry discoloration. Encapsulant discoloration was the most common degradation mode, particularly in older systems. In newer systems, encapsulant discoloration appears in hotter climates, but to a lesser degree. Thin-film degradation modes are dominated by glass breakage and absorber corrosion, although the breadth of information for thin-film modules is much smaller than for x-Si. Copyright © 2017 John Wiley & Sons, Ltd.

KEYWORDS

photovoltaic modules; reliability; durability; failure; failure rate; degradation modes

***Correspondence**

Dirk C. Jordan, National Renewable Energy Laboratory (NREL), 15013 Denver West Parkway, Golden, CO 80401, USA.
E-mail: dirk.jordan@nrel.gov

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1. INTRODUCTION

As prices in the photovoltaic (PV) industry have decreased considerably in recent years, reliability questions have seen a proportional increased interest. Decreasing prices often entail a new bill of materials or even an entire new supply chain in commercial products. Standard qualification tests, for example, IEC 61215, can be applied to verify the general integrity of the new materials for the infant phase of the product life cycle [1]. Yet this standard test will provide little information on how this new product will fare after decades under various field conditions. The goal in developing better accelerated tests that may be used for lifetime prediction is directly tied to understanding the physics and chemistry of the underlying degradation mechanisms. One of the pitfalls of developing new accelerated tests is issues of a hidden degradation mode, a degradation mode that is masked in the accelerated test but is revealed in field exposure [2]. Another possibility is to overaccelerate one particular degradation mode that may never be observed in the field. Therefore, it is imperative to correlate not only the power loss curve, which may be nonlinear, but also the observed degradation modes and mechanisms from the field with the accelerated tests [3]. Numerous publications have focused on degradation rates were first summarized and analyzed by some of the authors and were recently updated; however, degradation modes were not discussed [4,5]. Conversely, at least similar-sized volume of information on degradation modes exists with some excellent summaries [6–8]. Extracting the overarching trends from this wealth of information, however, has been difficult for several reasons. First and foremost, a wide variety of products with unknown manufacturing and installation quality has been deployed worldwide. [9] Second, many factors may influence degradation modes and rates such as technology, climate, mounting configuration, load, etc., and these factors have not always been clearly documented. In addition, inconsistent use of reporting and terminology can be a problem. The visual inspection sheet was developed to help guide and standardize field observations, yet misidentification of some modes can still happen [10]. In case of misidentification, the correct degradation mode was incorporated into the study. Unfortunately, the visual inspection sheet has not been adapted widely in a quantitative way, which limits the data available for more detailed analysis. Finally, a significant challenge in field observation is that modules often display a variety of degradation modes simultaneously. These modes may interact or have a similar underlying mechanism. The sometimes serial and synergistic nature of degradation modes in a module can lead to misidentification of certain degradation modes.

The purpose of this paper is to summarize degradation mode trends observed wherever possible, prioritize future work based upon information assembled from recent installations and discuss inconsistencies in degradation mode identification to help guide future publication on this subject.

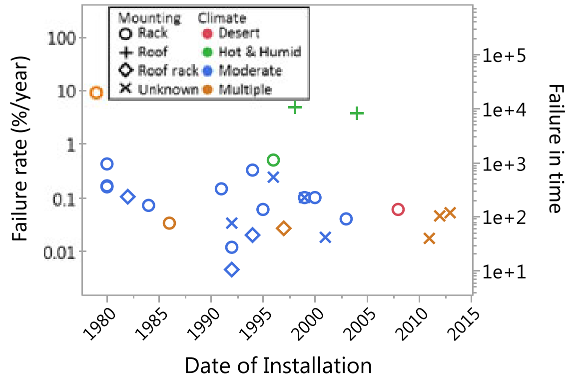

Figure 1. Failure rate in %/year (left axis) and failure in time (right axis) of PV modules and systems during the last 35 years color coded by climate and symbol coded by mounting configuration. Failure in time is a reliability metric that reports the number of failures in 1 billion module hours. Most consumer products range in the 100 to 1000 s. [Colour figure can be viewed at wileyonlinelibrary.com]

2. FAILURE VERSUS DEGRADATION

The title of this paper suggests at least a partial discourse on failure modes, yet so far, we have carefully avoided the term "failure" because of the challenge of defining it in a consistent and meaningful way. The IEC 60050-191 defines failure as "the termination of the ability of an item to perform a required function." [11] For some consumer products, that represents a fairly clear definition. For a PV module, however, this definition may not be as clear, leading to various different usages during the last decades in the PV field. For example, the Electric Power Research Institute in their extensive survey of systems installed from 1979 to 1989 used a decline in maximum power of more than 50% in a module that was not field serviceable as a definition [12]. More recently, the International Energy Agency defined a module failure as a module that irreversibly degrades in power or creates a safety problem [13]. For this treatment, data were included from publications where modules warranted replacement or where modules were said to have failed without providing a clear definition of "failed." In other instances, the provided information was not adequate to confidently determine whether failure had occurred, in which case the data could not be incorporated. While our definition of module replacement as failure may not be optimal, it allowed the compilation of a variety of data on this subject. Most commonly, failure fractions and not failure rates were reported by specifying a percentage of failed modules. The statistical failure rate is obtained from this information by dividing the failure percentage by the exposure time of the modules. Figure 1 shows the obtained failure rates as a function of year of installation in convenient units of %/year. Another reliability metric that is frequently used in other industries is failure in time, which is failure rate in units of failures per one billion operational hours. Most consumer products exhibit failures in time in the 100- to 1000-s range, a band within that most data of Figure 1 fall. The high failure rate in the early 1980s was caused by pre-Block V modules. High failure rates were more recently reported by Kato *et al.* (as evident in Figure 1 by the roof-mounted symbols), which may result from a combination of product quality, hot climate, and roof mounting, although the statistics are inadequate to draw conclusive trends from this graph [14]. Because of the varying usage of "failure," we will subsequently use the term "degradation modes" when referring to observable alterations to appearance, performance, and safety of a module.

3. CRYSTALLINE SILICON

3.1. Analysis of degradation mode trends

In addition to tracking the rate at which failed modules were replaced in the field, we studied the ways in which modules degrade over the course of their lifecycle and compared how the observed degradation modes differ in three distinct climates. We consider the effect that each degradation mode has on module performance and the prevalence of the problem, based upon frequency of observations noted in the literature. We also analyze how degradation modes have changed as the PV industry has evolved and conclude this section with a discussion about the dominant degradation modes seen in modules installed over the last 10 years. To better quantify and prioritize the multitude of published information, the number of reports for each specific degradation mode was accumulated. Only a small subset of published information specified the fraction of modules affected by that same degradation mode; each of these numbers provides valuable information about the prevalence of that mode. To further quantify the output of the analysis, a severity ranking was adopted similar to Kuitche *et al*., which is shown in Table I [15]. Severity was determined by ranking the degradation modes from 1 to 10, where 1 indicates that the observed degradation mode has no effect on performance, and 10 indicates both a major effect on power and safety. The scale is discrete and not continuous because (1) correlating specific degradation modes to certain power losses is still an active field of research, and (2) the strategy is often used to minimize potential bias and allows for better discrimination of the various degradation modes. Subsequently, the severity of each degradation mode was ranked according to Table II, some of which deserves further explanationx. Degradation related to the backsheet was divided into two categories: "backsheet insulation compromise" and "backsheet other." "Backsheet insulation compromise" includes adhesion issues, such as peeling, flaking, and cracking. The presence of this degradation can have a significant effect on power and also represents a safety hazard. "Backsheet other," however, encompasses defects such as bubbles, discoloration, and chalking, which do not affect module performance immediately. The degradation modes "glass breakage" and "diode/J-box problem" were both ranked with a severity of 5 because the performance effect spans the rating spectrum, depending upon case-specific circumstances, and thus, the average rank was assumed to be appropriate. Internal circuitry discoloration caused by corrosion and leading to series resistance increase received a medium ranking above encapsulant discoloration, as further discussed in section 3.2. Weakened solder bonds caused by internal circuitry discoloration and/or thermal cycling can ultimately fail open and lead to significant power losses and safety concerns. [3] Delamination was partitioned into major and minor categories, as minor delamination, such as shown in Figure 5(a) or (b) may not have much impact on the power production. In contrast, major delamination leads to considerable disintegration of parts or power loss from the entire module and safety becomes a major concern.

Table I. Severity rating used to rate and rank different degradation modes.

Severity	Rating
Major effect on power and safety	10
Major effect on power	8
Moderate effect on power	5
Slight deterioration of performance	3
No effect on performance	1

Table II. Summary of degradation modes with their severity rankings.

Mode	Severity
Encapsulant discoloration	3
Major delamination	5
Minor delamination	1
Backsheet insulation compromise	10
Backsheet other	1
Internal circuitry discoloration, series resistance increase	5
Internal circuitry failure, solder bond failure	8
Hot spots	10
Fractured cells	5
Diode/J-box problem	5
Glass breakage	5
Permanent soiling	2
Potential induced degradation	8
Frame deformation	3

Figure 2 shows the influence of percentage of affected modules [Figure 2(a)], then factoring in severity [Figure 2(b)] followed by inclusion of the number of reports [Figure 2(c)]. In Figure 2(a), the fraction of affected modules is plotted as a function of field exposure years partitioned by three distinct climates: moderate, hot and humid, and desert. The field exposure years are grouped into three broad categories: less than 10 years, 10 to 20 years, and finally modules exposed for more than 20 years. The median age of each field exposure category is approximately equal across climate and date of installation. The numbers above each field exposure category in Figure 2(a) refer to the number of modules that exhibited the degradation modes indicated in each column. In addition, the stacked and color-coded degradation modes are partitioned by date of installation, those that were installed before the year 2000 and those after. Degradation modes that could potentially have similar mechanisms were grouped in like colors. For instance, delamination, both major and minor, and backsheet insulation issues could be related and are therefore presented in similar red color and shading. Internal circuitry discoloration can be a precursor of failed internal circuitry. Solder bond failure can lead to hot spots; however, hot spots can also be caused by cracked cells. [3] Because most publications do not differentiate the cause for each hot spot, these potentially related degradation modes are presented in variations of green color. As modules can be affected by more than one degradation mode, the ordinate extends beyond 100%; the given numbers indicate the number of affected modules in each category, based on the number of modules reported from each data source. The same fraction of affected modules weighted by the severity ranking is displayed in Figure 2(b) and lastly the fraction of affected modules weighted by severity and number of reports in Figure 2(c). The number in Figure 2(c) indicates the number of reports in each category.

In a moderate climate and for older installations, that is, installations deployed prior to 2000, the percentage of degradation modes increase with field exposure with the exception of the first category, systems that were fielded for less than 10 years. The majority of this first category came from pre-Block V modules installed in the infancy of the terrestrial PV industry perhaps exaggerating that first category.

The largest percentage of modules exhibits encapsulant discoloration, which is aided by the fact that discoloration is also the most noticeable visual defect. Major

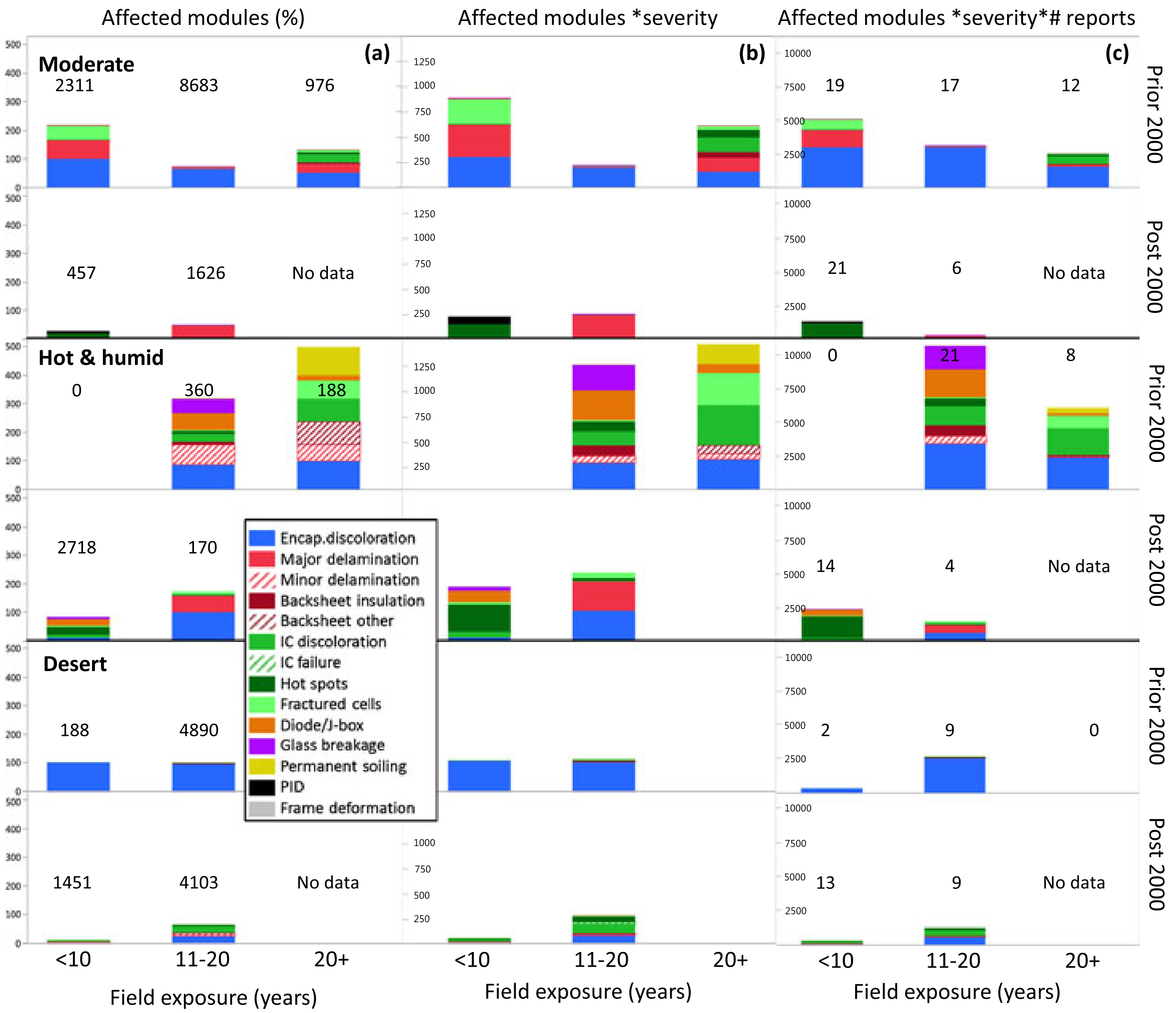

Figure 2. Fraction of affected modules stacked and color coded by degradation mode and graphed as a function of field exposure for three distinct climates (a). The number indicates the number of modules affected for each category. The degradation modes are additionally partitioned by date of installation, installations before and after 2000. In addition, the effects when the fraction of affected modules is multiplied by severity (b) and the number of reports (c) can be seen. The number in Figure 2(c) indicates the number of reports in each category. [Colour figure can be viewed at wileyonlinelibrary.com]

delamination and fractured cells are also prevalent; again, this category is dominated by pre-Block V modules. In modules fielded between 11 and 20 years, encapsulant discoloration becomes the most dominant degradation mode. As the field exposure increases further, other degradation modes begin to appear such as delamination and internal circuitry discoloration typically accompanied by series resistance increase. When the fractional percentage is weighted by the severity, encapsulant discoloration decreases owing to its lower severity ranking relative to major delamination, internal circuitry discoloration, hot spots, and backsheet insulation issues. When weighting additionally with the number of reports, the encapsulant discoloration bars expand indicating that many reports observe this degradation mode.

Still in moderate climates, the affected module percentage for encapsulant discoloration decreases notably for newer installations. These newer installations are governed by different degradation modes such as hot spots and potential induced degradation (PID) for the younger systems, and major delamination in medium-aged systems. The higher severity rankings for these degradation modes lead to an increased bar size in Figure 2(b) but decrease for all but hot spots when additionally scaled by the number of reports. Thus, potential induced degradation and major delamination are not often reported, but when it is, the effect is substantial. Hot spots that cause problems with performance or safety are frequently reported, but they only affect a small percentage of modules.

In the hot and humid climate, the fractional percentage of affected modules is in general greater than in moderate climates, although most categories in the hot and humid climate have fewer data points than the equivalent categories in the moderate climate. In older installations, encapsulant discoloration is the most common degradation mode but is accompanied here by delamination, backsheet problems, fractured cells, diode/junction box (j-box), and internal circuitry discoloration. In addition, glass breakage and permanent soiling that often can be observed along the frame edges and may eventually lead to partial shading of edge cells can be observed. In newer installations, as was observed in moderate climates, affected module percentage has decreased appreciably; however, it is still higher than the equivalent categories in the moderate climate. The younger systems show a large number of hot spots and diode/j-box–related problems. Medium-aged modules are dominated by major delamination probably because of the humidity. Perhaps somewhat surprisingly, encapsulant discoloration appears quite strongly in medium-aged modules. Older desert installations were clearly dominated by encapsulant discoloration. As in the other climates, the overall percentage of affected modules in the desert has gone down substantially in newer installations. The degradation modes evident in these modern installations are dominated by internal circuitry discoloration and hot spots. Encapsulant discoloration in post-2000 installations appears in medium-aged modules in the desert climate, but to a lesser degree than the hot and humid climate. Because some of the bar sizes are hard to distinguish, a summary of the individual categories is provided in Table A1 in the appendix.

Of particular interest are the problems that are observed in installations of the last 10 years. The Pareto chart of Figure 3 was obtained by summation of all modules affected by a specific degradation mode. The fraction with respect to the overall number of modules was subsequently determined and weighted by the severity. The data of all years is dominated by encapsulant discoloration owing to the widespread effect in the older systems. The most dominant effects in the last 10 years appear to be hot spots and internal circuitry discoloration.

Other important degradation modes in modern installations appear to be glass breakage and encapsulant discoloration but apparently only in hotter climates, as shown in

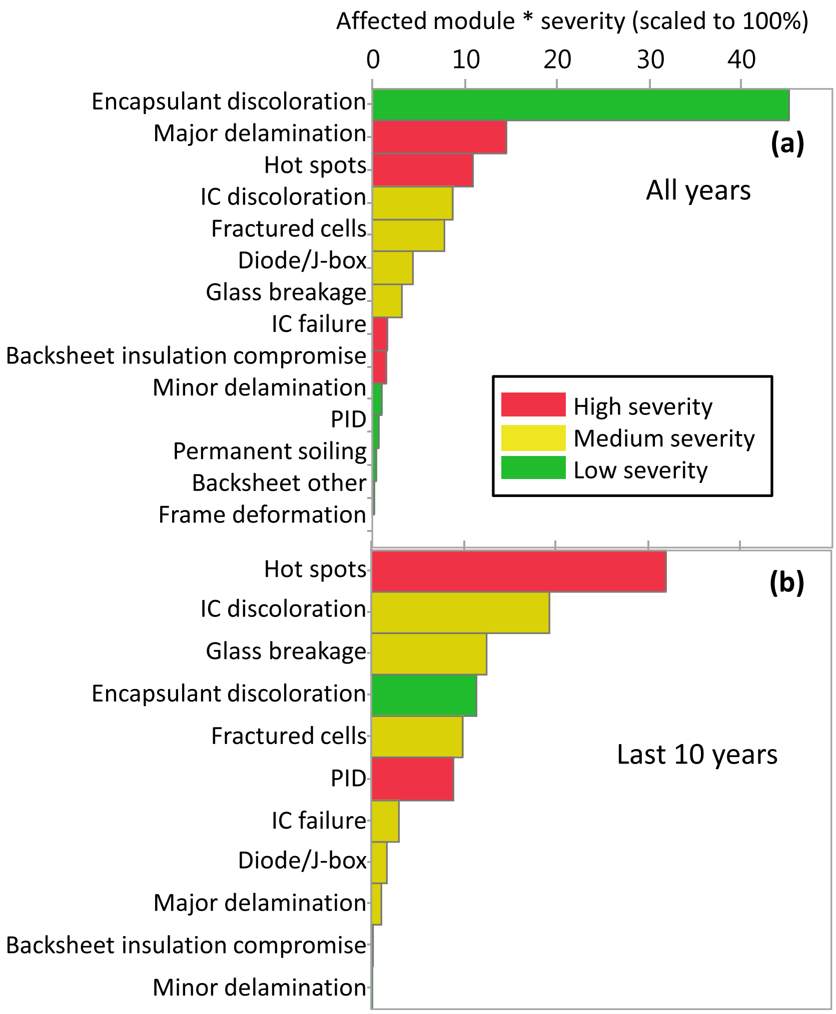

Figure 3. Pareto chart of the most significant degradation modes for all years (a) and systems installed in the last 10 years (b). The bars are color coded by severity. [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 2. In addition, fractured cells and potential induced degradation and internal circuitry failure appear to be of importance.

3.2. Synopsis of some degradation modes

As shown in Figure 3, hot spots appear to be the most important degradation modes in systems installed in the last 15 years in large part because of their high-severity ranking. Because of the considerable production variation and other factors such as climate, mounting configuration, and load, it is difficult to detail the effect of a particular degradation mode on power. The most conclusive evidence comes from studies that examine the same modules in the same configuration side by side. Figure 4 shows four studies that examined the effect of hot spots and compared them with the performance of modules of the same type that were unaffected by hot spots. The modules affected by hot spots show significantly higher power loss than modules without hot spots according to a Mann–Whitney test (p-value < 0.0001) [7,16–18]. Depending on the severity of the hot spot, they can be easily detected through infrared imagery. In the latter stages, hot spots can be visually observed from the front, as shown in Figure 4(b), where a hot spot was caused by a solder bond failure. The backside of the module (inset) can also display a burn spot.

Delamination can occur at the encapsulant-silicon interface [Figure 5(a)] or glass-encapsulant interface [Figure 5 (b)] and is often misidentified in the literature. The extra optical interface, at least in the initial phase, will lead to decrease of light that can reach the semiconductor junction. The loss is usually observed in current and may be approximately proportional to the affected surface area [19]. As the delamination progresses and/or time in that state increases, moisture may enter and corrode the internal circuitry metallization, Figure 5(c). That mechanism will lead to an increased series resistance. Delamination is often misidentified with encapsulant discoloration and/or internal circuitry discoloration. Delamination leads typically to lightening of an area whereas encapsulant and internal circuitry discoloration typically lead to a darkening.

The most common degradation mode in older systems is encapsulant discoloration. In a comparison of modules that were mounted in the same way in the same location,

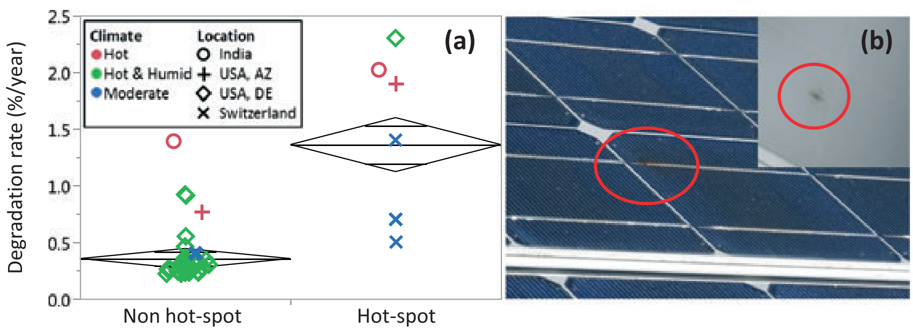

Figure 4. In side-by-side comparison, modules affected by hot spots show consistently higher degradation than modules without hot spots (a). The studies from Arizona and India used the nameplate rating, which may have influenced the absolute value. Hot spots can easily be observed by infrared imagery; however, when they are severe, they may be observed visually in the front (b) or back (inset of b). The hot spot shown was caused by a solder bond failure. [Colour figure can be viewed at wileyonlinelibrary.com]

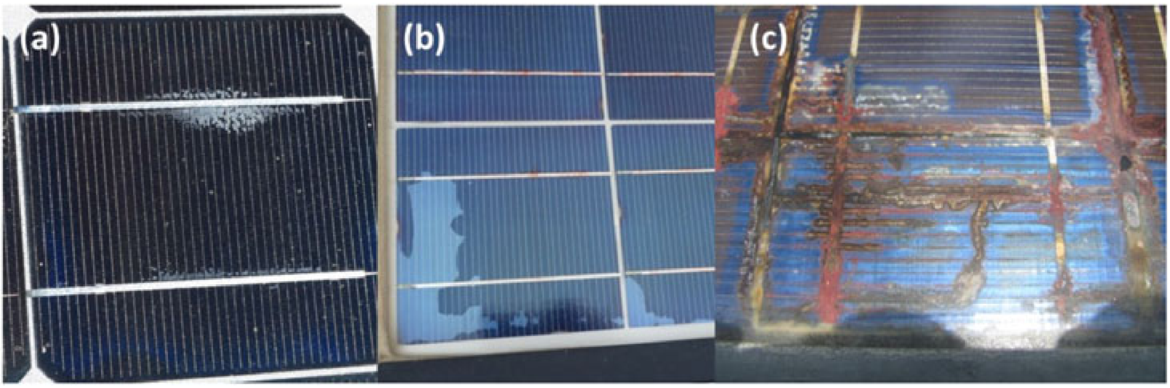

Figure 5. Encapsulant delamination can occur at the encapsulant-silicon interface and typically starts to appear along the cell busbar (a), or at the glass-encapsulant interface (b). Depending on the field exposure duration and severity, delamination can be accompanied by internal circuitry discoloration (c). [Colour figure can be viewed at wileyonlinelibrary.com]

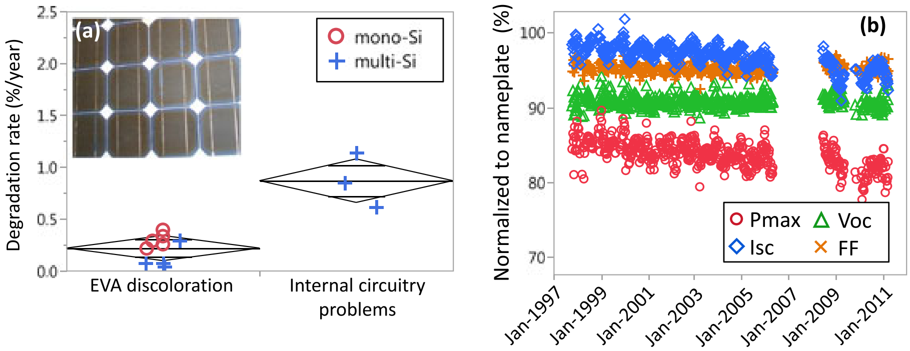

Figure 6. Encapsulant discoloration is the most noticeable degradation mode. In a side-by-side comparison, encapsulant discoloration had significantly less effect on power than modules that showed internal circuitry problems associated with series resistance increase (a). The decline is Isc dominated and appears fairly consistent during more than 10 years of field exposure (b). [Colour figure can be viewed at wileyonlinelibrary.com]

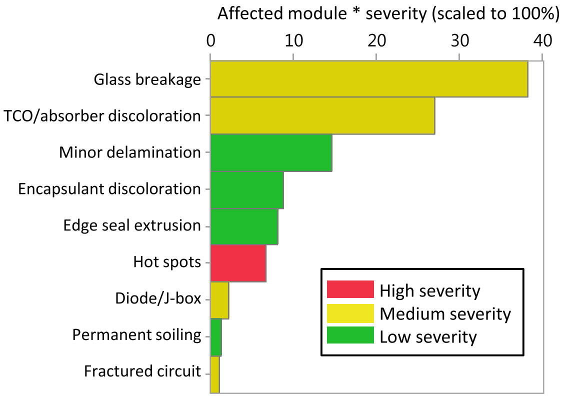

Figure 7. Pareto chart of affected modules scaled by the severity for thin-film modules. [Colour figure can be viewed at wileyonlinelibrary.com]

however, modules affected solely by encapsulant discoloration exhibited significantly lower power loss than modules affected by internal circuitry problems according to a Mann–Whitney test (p-value of 0.016), as shown in Figure 6 [20]. The decline in Figure 6(b) is short-circuit current (Isc) dominated and appears to be approximately linear over more than a decade of field exposure.

4. THIN FILM

The available information for thin-film modules is much smaller than for crystalline silicon; therefore, partitioning the data into various categories was not possible. Instead, a simple Pareto chart shows that glass breakage is the most dominant effect followed by absorber or transparent conductor oxidation. Minor delamination and encapsulant and edge seal extrusion were also reported frequently (Figure 7).

5. CONCLUSION

The reported failure rates, as defined in section 2, of PV modules fall mostly in the range of other consumer products; however, the long expected useful life of modules may not allow for direct comparison. Recent reports of higher failure rates in combined hot climate and roof mounting is a concern but must be corroborated by other observations. In general, reported degradation percentages appear to have decreased appreciably in newer installations that are deployed after the year 2000. However, these trends may be convoluted with varying manufacturing and installation quality world-wide. Modules deployed in hot and humid climates were reported with a considerably wider variety of degradation modes than those in desert and moderate climates, which warrants further investigation. Delamination and diode/j-box issues are also more prevalent in hot and humid climates than in other climates. The highest concerns of systems installed in the last 10 years appear to be hot spots followed by internal circuitry discoloration. Because hot-spots can have multiple underlying mechanisms, more detailed investigations into the causes could help alleviate the problem for future module generations. Encapsulant discoloration was the most common degradation mode, particularly in older systems. In newer systems, it appears in hotter climates, but to a lesser degree. Thin-film degradation modes are dominated by glass breakage and absorber corrosion, although the breadth of information for thin-film modules is much smaller than for x-Si.

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APPENDIX: SUMMARY TABLE

Table A1. Summary of degradation mode percentages, field exposure, climates, and date of installations.

		Climate	Moderate					Hot and humid					Desert			
		Date of installation	pre-2000			post-2000		pre-2000			post-2000		pre-2000		post-2000	
		Field exposure	0–10	11–20	20+	0–10	11–20	0–10	11–20	20+	0–10	11–20	0–10	11–20	0–10	11–20
		No. reports	19	17	12	21	6	0	21	8	14	4	2	9	13	9
Degradation mode	Severity	No. modules	2311	8683	976	457	1626	0	360	188	2718	170	188	4890	1451	4103
Encapsulant discoloration	3		99.2	67.1	50.5	0.0	0.0	0	87.4	100.0	9.9	100.0	100.0	95.1	3.3	23.2
Major delamination	5		63.9	0.0	27.1	0.0	46.7	0	0.6	0.0	0.0	57.6	0.0	1.2	0.3	2.2
Minor delamination	1		1.7	3.0	3.6	1.8	0.0	0	68.2	57.6	0.0	0.0	0.0	0.0	0.6	8.8
Backsheet insulation compromise	10		0.1	0.0	5.9	0.0	0.0	0	10.0	0.0	0.0	0.0	0.0	0.6	0.0	0.3
Backsheet other	1		0.0	0.0	0.0	0.0	0.0	0	0.0	79.7	0.0	0.0	0.0	0.8	0.0	0.2
Internal circuitry discoloration/series resistance increase	5		1.9	0.0	28.7	4.0	0.6	0	28.0	79.7	9.9	1.5	0.0	0.5	2.8	19.5
Internal circuitry failure	8		0.0	0.0	0.0	0.0	0.0	0	0.1	0.0	0.9	0.0	0.0	0.0	0.6	2.2
Hot spots	10		0.1	0.1	7.7	11.7	0.1	0	9.7	0.0	26.1	2.9	0.5	1.0	1.1	5.2
Fractured cells	5		47.5	1.2	6.5	0.5	0.1	0	3.1	63.0	5.0	10.6	0.0	1.0	1.7	1.9
Diode/J-box	5		1.9	0.0	1.2	0.0	0.0	0	58.9	18.0	21.7	0.0	0.0	0.0	0.1	0.7
Glass breakage	5		1.9	1.7	0.2	0.0	2.1	0	50.1	0.0	7.8	0.0	0.0	0.0	0.0	0.0
Permanent soiling	2		0.7	0.0	0.0	0.0	0.0	0	1.7	100.0	0.0	0.0	0.0	0.0	0.0	0.0
Potential induced degradation	8		0.0	0.0	0.0	9.7	0.0	0	0.0	0.0	1.2	0.0	0.0	0.0	0.0	0.0
Frame deformation	3		0.1	0.0	0.0	0.0	0.0	0	1.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0