Risk Priority Number Analysis of Photovoltaic Power Plants

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ABSTRACT

Over the course of their lifetime in the field, photovoltaic (PV) modules develop defects and undergo performance degradation. The type of defects and rate of degradation depend upon semiconductor/technology type, module construction type, installer workmanship, manufacturer quality control, and the installed environment. Some defects are purely cosmetic, while others may pose safety risks or cause degradation. Simply reporting the observed number (or percentage) of defect types in a plant is of little use to stakeholders, unless each defect is quantitatively correlated with the degradation rate corresponding to that defect. This quantitative correlation can be achieved using a risk priority number (RPN) approach to assess the risk associated with module defects, and determine the appropriate action, such as panel removal for warranty claims or safety reasons. This report presents RPN for observed performance and safety defects at seven PV plants covering three climatic conditions: hot-dry (Arizona), cold-dry (New York), and temperate (Colorado).

Keywords

Reliability
Durability
Degradation rate
Defect
Risk priority number (RPN)
Warranty claims

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1 INTRODUCTION

1.1 Project Background

Cumulative installations of photovoltaic (PV) modules in the United States have increased significantly over the last decade to levels of ~10 gigawatts (GW) installed capacity on an annual basis. Today commercially available PV modules typically have a 20-25-year warranty, but estimates show them capable of producing acceptable power for 30 years or more. Over the course of their lifetime in the field, PV modules develop defects and experience performance degradation. The defect type and rate of degradation depend upon semiconductor and technology type, module construction type, manufacturer quality control, installer workmanship, and the installed environment. Some defects are purely cosmetic, while others may pose safety risks or cause degradation. Simply reporting the observed number (or percentage) of defect types in a plant is of little or no use to stakeholders, unless each defect is quantitatively correlated with the degradation rate or safety risk corresponding to each defect. This quantitative correlation can be achieved using a risk priority number (RPN) approach to assess the risk associated with each module defect, and determine the appropriate action, such as panel removal for warranty claims or safety reasons. This report presents RPN for observed performance and safety defects at seven PV plants covering three climatic conditions: hot-dry (Arizona), cold-dry (New York), and temperate (Colorado).

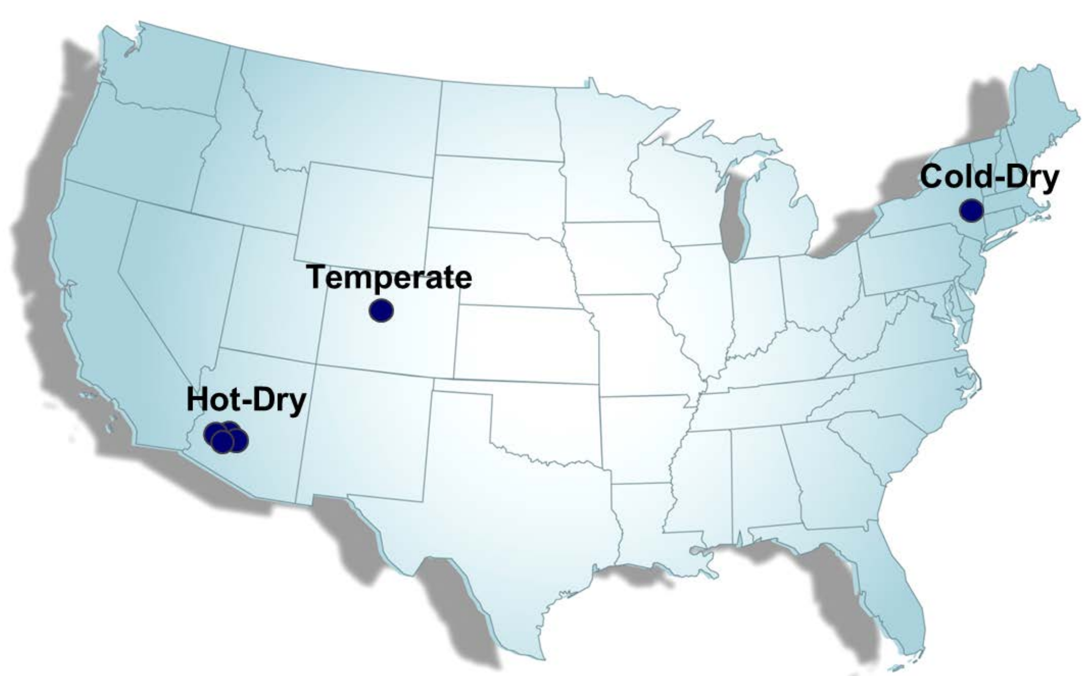

Figure 1-1
Seven site survey locations for RPN analysis

The RPN analysis of the seven plants was based on safety and performance evaluations performed as part of EPRI's PV Life Cycle Analysis project.[1] As part of the supplemental project scope, site condition surveys were conducted at over 30 PV systems across the U.S. Systems were evaluated on an engineering basis to support determination of the optimal action, i.e., system maintenance, re-powering or project decommissioning. The project also included development of an economic analysis tool that allows developers to consider the full life cycle costs of different project options, and to support owners of aging PV systems in making informed decisions regarding repair or decommissioning.

Methodologies for system decommissioning, disposal, and recycling were established. Finally, a technical manual[2] containing the methodologies and tools developed above was provided to help the broader solar industry and its stakeholders conduct site condition surveys and understand PV life cycle considerations.

End-of-life diagnoses for PV plants are predominantly due to age-related PV module material defects and degradation, which vary depending on the local weather conditions. The key indicator of the presence of material defects and degradation is a decrease in system performance. PV systems are unique in design, installation and location. As such, each system has unique aging and performance degradation characteristics. For example, a system installed near a body of salt-water may age differently relative to a system installed in an inland location.

As the number of photovoltaic systems installed continues to increase, understanding the range of degradation rates and defects and factors influencing them will be valuable to determine the likely power output and the financial risk of future projects. In this project, this was accomplished using the RPN technique developed by Kuitche et al. [1] and Shrestha et al. [2, 3]. RPN values were further classified into three categories: Safety RPN (S-RPN), Performance RPN (P-RPN) and Global RPN (G-RPN) [4], [5]. The G-RPN is the sum of the S-RPN and the P-RPN. It is intended to provide a measure of the overall health of a plant from both a safety and performance perspective. Currently, PV module manufacturers provide two kinds of warranties – material defects and workmanship warranty; and power/performance warranty. Using MATLAB software developed by Moorthy et al. at Arizona State University's Photovoltaic Reliability Laboratory (ASU-PRL) [5], RPN was statistically and automatically generated for all of the modules in the plants that were surveyed. This information can be used by PV plant owners to support decisions regarding panel removal based on S-RPN and whether to make warranty claims under "Material Defect and Workmanship Issues" based on P-RPN for each defect type. The Material Defect and Workmanship claims are typically done within 5 years of installation. In addition to the Material Defect and Workmanship warranty claims, the performance data (the measured power, for example) can also be used for the power/performance warranty claims (exceeding the agreed upon degradation rate per year, for example) anytime during the specified warranty period.

[1] Additional sites were surveyed as part of the project, but module degradation rates could not be determined for some systems due to poor weather conditions that prevented current-voltage (IV) curve measurements from being taken. Some systems that were surveyed were too early in their lifetimes (3-5 years old) with few or no visual defects present, for RPN analysis to be practical.

[2] *Solar Photovoltaic Life Cycle Analysis: A Practical Handbook for Solar Photovoltaic Power Plant Owners and Operators*. EPRI, Palo Alto, CA: 2016. 3002008832.

1.2 Objectives

Climate-specific durability and reliability of PV modules are the main factors that determine the lifetime of PV modules [6]. There is a dire need in the industry to develop climate-specific and mode/defect-specific accelerated tests for existing and new modules. Performance degradation rate and visual inspection data from seven PV plants in the continental United States were gathered, and the RPN values were automatically calculated for the overall plant and for every defect in each plant. Performance degradation rates for individual PV modules were determined by comparing measured IV curves with the module's nameplate rating (IV data obtained at the time of commissioning weren't available). In this work, two objectives were pursued using defect-level and plant-level RPN data:

1. Establish the defects affecting the Pmax degradation for different climatic conditions (hot-dry, cold-dry and temperate) by statistically analyzing multiple power plants and assigning a RPN to each of the performance defects found in these power plants so the plant owners can make warranty claims under "Material Defect and Workmanship Issues".
2. Determine dominant defects in each climatic condition and assign an RPN to quantify each defect so that manufacturers, investors, and other stakeholders can come up with climate-specific accelerated tests to mitigate the effects of dominant defects. This also creates a possibility to develop defect-specific (or mode-specific) accelerated tests for the most dominant defects, independent of the climate.

2
METHODOLOGY

2.1 Defect Inspection

To generate RPN values for a plant, two databases must be created: a defect database and a degradation rate database. For larger plants, the necessary size of the databases, specifically, the number of strings and modules, can be statistically determined, as described in [7, 8]. The sample size is typically determined based on 95% confidence level and 5% confidence interval.

The National Renewable Energy Laboratory (NREL) and ASU-PRL have developed a visual inspection checklist containing 86 different types of performance defects and safety failures [6] (see Appendix A for details). Of these, 61 defect types are categorized as performance defect types that affect PV module power output and 25 defect types are categorized as safety failures that affect safety (mechanical/electrical safety or fire hazard).

Of the 61 performance defect types, 7 defect types are known to affect glass (front/rear), 22 defect types affect the cell (hotspot defect detected using IR camera), 5 defect types affect the frame, 4 defect types affect the edge seal, 5 defect types affect the encapsulant, 8 defect types affect the junction box, 3 defect types affect the backsheet, 3 defect types are specific to thin film PV modules, 1 defect type affects bypass diode short-circuit (detected using a circuit continuity detector), and 1 defect type affects wires/cables/connectors. Also, 2 more invisible defect types—module mismatch and solder bond fatigue/failure (identified through I-V measurements)—were identified to be responsible for performance loss.

Of the 25 safety failures, 4 failures affect glass (front/rear), 5 failures affect frames, 5 failures affect junction boxes, 3 failures affect wires/cables/connectors, 5 failures affect backsheets, 2 failures affect cells (hotspots are detected using an IR camera), and 1 failure affects bypass diode open-circuit (detected using a circuit continuity detector). Defects and failures grouped by module components are listed in Appendix A. The potential effects of each defect on the electrical performance parameters, short circuit current (Isc), open circuit voltage (Voc), and fill factor (FF) and the detection method for each defect are comprehensively provided in Table 2-1 [9]. The typical accelerated tests used to induce the corresponding defects or failure modes observed in the field are shown in Table 2-2 [10].

Table 2-1
Potential effect of each defect on performance parameters and detection method for each defect [the non- visual inspection detection methods are highlighted in yellow for quick tracking of non-visual methods; VI=visual inspection, IV=current-voltage measurement, IR=infrared, LIT=lock-in thermography, UV=UV fluorescence, CC=circuit continuity] [9].

Defect #	Defect – Performance Defect	Detection Method: VI/IV/IR/CC	Parameter Affected: Isc	Parameter Affected: Voc	Parameter Affected: FF
1	Front glass lightly soiled	VI	Y		
2	Front glass heavily soiled	VI	Y		
3	Front glass crazing	VI	Y		
4	Front glass chip	VI	Y/N		
5	Front glass milky discoloration	VI	Y		
6	Rear glass crazing*	VI			Y/N
7	Rear glass chipped	VI	Y/N		
8	Edge seal delamination	VI			Y
9	Edge seal moisture penetration	VI/IV			Y
10	Edge seal discoloration	VI			Y/N
11	Edge seal squeezed / pinched out	VI			Y/N
12	Frame bent	VI	Y/N		
13	Frame discoloration	VI			Y/N
14	Frame adhesive degraded	VI			Y/N
15	Frame adhesive oozed out	VI			Y/N
16	Frame adhesive missing in areas	VI			Y/N
17	Bypass diode short circuit (Equipment needed**)	IV/IR/CC		Y	Y
18	Junction box lid loose	VI			Y/N
19	Junction box lid crack	VI			Y/N
20	Junction box warped	VI			Y/N
21	Junction box weathered	VI			Y/N
22	Junction box adhesive loose	VI/wet megger			Y/N
23	Junction box adhesive fell off	VI			Y/N

Table 2-1 (continued)

Defect #	Defect – Performance Defect	Detection Method: VI/IV/IR/CC	Parameter Affected: Isc	Parameter Affected: Voc	Parameter Affected: FF
24	Junction box wire attachments loose	VI			Y
25	Junction box wire attachments fell off	VI	Y/N	Y/N	Y/N
26	Junction box wire attachments arced	VI	Y/N	Y/N	Y/N
27	Wires corroded	VI			Y/N
28	Backsheet wavy	VI	Y/N		Y/N
29	Backsheet discoloration	VI	Y/N		
30	Backsheet bubble	VI	Y/N		Y/N
31	Gridline discoloration	VI	Y/N		Y
32	Gridline blossoming	VI	Y/N		Y
33	Busbar discoloration	VI	Y/N		Y
34	Busbar corrosion	VI	Y/N		Y
35	Busbar burn marks	VI	Y/N	Y	Y
36	Busbar misaligned	VI			Y
37	Cell interconnect ribbon discoloration	VI	Y/N		Y
38	Cell interconnect ribbon corrosion	VI	Y/N		Y
39	Cell interconnect ribbon burn mark	VI	Y/N	Y	Y
40	Cell interconnect ribbon break	VI	Y	Y	Y
41	String interconnect discoloration	VI	Y/N		Y
42	String interconnect corrosion	VI	Y/N		Y
43	String interconnect burn mark	VI	Y/N	Y	Y
44	String interconnect break	VI	Y	Y	Y
45	Cell discoloration	VI	Y/N		Y
46	Cell burn mark	VI		Y/N	Y
47	Cell chipping/crack	VI	Y/N	Y/N	
48	Cell moisture penetration	VI	Y/N	Y/N	Y

Table 2-1 (continued)

Defect #	Defect – Performance Defect	Detection Method: VI/IV/IR/CC	Parameter Affected: Isc	Parameter Affected: Voc	Parameter Affected: FF
49	Cell worm mark (snail tracks)	VI	Y	Y	Y
50	Cell foreign particle embedded	VI	Y/N		
51	Interconnect discoloration	VI	Y/N		Y
52	Solder bond fatigue / failure	IV/LIT			Y
53	Hotspot less than 20˚C	IR			Y
54	Encapsulant delamination over the cell	VI/UV	Y	Y	Y
55	Encapsulant delamination under the cell	VI			Y
56	Encapsulant delamination over the junction box	VI	Y	Y	Y
57	Encapsulent delamination near interconnect or fingers	VI	Y		Y
58	Encapsulant discoloration (yellowing/browning)	VI/UV	Y		
59	Thin film module discoloration	VI	Y/N		Y
60	Thin film module delamination - absorber/TCO layer	VI	Y	Y	Y
61	Thin film module delamination - AR coating	VI	Y		
62	Module mismatch	VI/string IV	Y		
	Defect - Safety Failures				
63	Front glass crack	VI	Y	Y	Y
64	Front glass shattered	VI	Y	Y	Y
65	Rear glass crack	VI	Y	Y	Y
66	Rear glass shattered	VI	Y	Y	Y
67	Frame grounding severe corrosion	VI			N
68	Frame grounding minor corrosion	VI			N
69	Frame major corrosion	VI			N

Table 2-1 (continued)

Defect #	Defect - Safety Failures	Detection Method: VI/IV/IR/CC	Parameter Affected: Isc	Parameter Affected: Voc	Parameter Affected: FF
70	Frame joint separation	VI			N
71	Frame cracking	VI	Y/N		N
72	Bypass diode failure	IR/CC	Y/N		Y/N
73	Junction box crack	VI	Y/N		Y
74	Junction box burn	VI	Y/N		Y
75	Junction box loose	VI	Y/N		Y
76	Junction box lid fell off	VI	Y/N		Y
77	Wires insulation cracked / disintegrated	VI			Y
78	Wires burnt	VI	Y/N		Y
79	Wires animal bites / marks	VI			Y
80	Backsheet peeling	VI	Y	Y	Y
81	Backsheet delamination	VI	Y	Y	Y
82	Backsheet burn mark	VI	Y	Y	Y
83	Backsheet crack /cut under cell	VI			Y
84	Backsheet crack /cut between cells	VI			Y
85	String interconnect arc tracks	VI	Y/N		Y
86	Hotspot over 20˚C	IR	Y	Y	Y

* Crazing is a phenomenon caused by a cluster of microcracks on the rear glass surface which could theoretically lead to glass cracks.

** Some defects, such as bypass diode failure, cannot be detected through visual inspection alone. For example, to detect a bypass diode failure, an IR camera or circuit continuity tester is needed.

Table 2-2
Selection of appropriate accelerated tests to induce specific field failure modes (Credit: Alliance for Sustainable Energy, LLC) [10]

Accelerated Stress	Failure Mode
Thermal Cycle	Broken interconnect
	Broken cell
	Solder bond failures
	Junction box adhesion
	Module connection open circuits
	Open circuits leading to arcing
Damp Heat Exposure	Corrosion
	Delamination of encapsulant
	Encapsulant loss of adhesion & elasticity
	Junction box adhesion
	Electrochemical corrosion of TCO
	Inadequate edge deletion
Humidity Freeze	Delamination of encapsulant
	Junction box adhesion
	Inadequate edge deletion
UV Test	Delamination of encapsulant
	Encapsulant loss of adhesion & elasticity
	Encapsulant discoloration
	Ground fault due to backsheet degradation
Mechanical Load	Broken interconnect
	Broken cell
	Solder bond failures
	Broken glass
	Structural failures
Dray and Wet Insulation Resistance	Delamination of encapsulant
	Ground Faults
	Electrochemical corrosion of TCO
	Inadequate edge deletion
Hot Spot Test	Hot spots
	Shunts at the scribe lines
Hail Test	Broken cells
	Broken glass
Bypass Diode Thermal Test	Bypass diode failures

2.2 Risk Priority Number

The RPN was categorically determined for each visual defect at the seven PV power plants that were surveyed. During the site visits to these power plants, thorough visual inspections were conducted to identify the defects shown in Table 1-1. RPN numbers were calculated for each defect using Equation 1.

$$\mathbf{RPN = S * O * D} \qquad \text{Equation 1}$$

Where:

S - Severity (maximum 10) which is a measure of how strongly a system or a user is effected because of the effects of the defect present.

O - Occurrence (sometimes termed as likelihood; maximum 10) which denotes how probable it is for that failure mode to occur for a predetermined time period

D - Detection (maximum 10) which is an approximation of how easily the defect or the failure mode can be identified before the failure reaches the customer.

The RPN value can reach as high as 1000. If the typical 80/20 rule[3] is applied, the defect with RPN above 200 may be considered risky, and a warranty claim may be made for this specific defect. The severity of each defect is primarily a function of the performance degradation rate (Rd) for severity rankings between 1 and 7. Severity rankings between 8 and 10 are determined based both on performance degradation and the level of safety risk ('remote' safety risk for rankings of 8 and 9, and 'catastrophic' risk for a 10 ranking). Any module having a safety severity level of 8 or higher should be replaced even if the RPN is lower than 200 due to low frequency of failure occurrence. RPN can be calculated without including "Detectability" as it is a subjective factor for some defects. Work is underway to replace the detectability factor with a "Causality" factor, which would be an objective factor that makes the RPN approach more comprehensive and robust. Causality reflects the likelihood of a detected failure mode being responsible for the power loss severity. Currently in the RPN calculation, the detection term was defined on a scale from 1-10 based on the ease of detecting the failure mode. While this term has meaning within a failure mode effect and criticality analysis (FMECA) application, where the reliability of the measurement system is being included as part of the reliability of a larger system, for the PV plant evaluation methodology, the ease of detection has less relevance. Also, similar to the RPN, a cost priority number (CPN) can also be used as an extension of RPN to determine the costs corresponding to annual O&M and energy loss associated with each defect.

Due to the large sample of data used, a MATLAB program was developed [5] to calculate the RPN for each module at the seven plants based on the severity, occurrence and detectability of the defects. The Severity (Table 2-3), Occurrence (Table 2-4) and Detection (Table 2-5) ranking tables are shown below.

[3] PV modules are typically given a warranty of 80% of original power over 20 or 25 years.

Table 2-3
Severity ranking table (Rd, degradation rate per year, %/year; remote safety failures are not of immediate safety concern but they could turn out to be safety concerns depending on the degradation rate level and bypass diode operating condition)

Severity Ranking	Severity Criteria
1	No effect, Rd < 0.3%
2	Insignificant, Rd approx. 0.3%
3	Minor cosmetic defect, Rd < 0.5%
4	Cosmetic defect, Rd < 0.6%
5	Reduced performance, Rd < 0.8%
6	Performance loss approx. to typical warranty, Rd approx. 1%
7	Significant degradation, Rd approx. 1.5%
8	Remote safety concerns, 1.5% < Rd ≤ 2% for performance defects with bypass diode open circuit failure
9	Remote safety concerns, Rd > 2% without bypass diode open circuit failure
10	Safety hazard, eighteen catastrophic safety failures (shown in Table A-2) irrespective of degradation rate.

Table 2-4
Occurrence ranking table

Failure Mode Occurrence	Frequency CNF/1000	Ranking
Remote: Failure is unlikely	≤ 0.01 modules per thousand per year	1
Low: Relatively few failures	0.1 modules per thousand per year	2
	0.5 modules per thousand per year	3
Moderate: Occasional failures	1 module per thousand per year	4
	2 modules per thousand per year	5
	5 modules per thousand per year	6
High: Repeated failures	10 modules per thousand per year	7
	20 modules per thousand per year	8
Very high: Failure is almost inevitable	50 modules per thousand per year	9
	≥ 100 modules per thousand per year	10

Table 2-5
Detection ranking table

Ranking	Criteria: Likelihood	Detection
1	Monitoring system itself will detect the failure mode with warning 100%	Almost certain
2	Very high probability (most likely) of detection through visual inspection	Very high
3	50/50 probability (less likely) of detection through visual inspection	High
4	Very high probability (most likely) of detection using conventional handheld tool e.g., IR, Megger	Moderately high
5	50/50 probability (less likely) of detection using conventional handheld tool e.g., IR, Megger	Moderate
6	Very high probability (most likely) of detection using non-conventional handheld tool e.g., diode/line checker	Low
7	50/50 probability (less likely) of detection using non-conventional handheld tool e.g., diode/line checker	Very low
8	Very high probability (most likely) of detection using performance measurement equipment e.g., IV tracer	Extremely low
9	50/50 probability (less likely) of detection using performance measurement equipment e.g., IV tracer	Remote
10	Detection impossible in the field	Absolutely uncertain

Eighteen of 25 safety failures warrant a severity rating of 10, including the following:

- Front or rear glass crack
- Front or rear glass shattered
- Frame grounding severe corrosion
- Frame joint separation
- Frame cracking
- Junction box crack
- Junction box burn
- Junction box loose
- Junction box lid fell off
- Junction box lid crack
- Wires burnt

- Wire bites/marks from animals
- Backsheet peeling
- Backsheet delamination
- Backsheet cracks.or cuts under or between cells

Bypass diodes with open circuit failures are given a severity ranking of 8, as they are not a major safety hazard.

2.3 RPN Software

The ASU-PRL RPN software program requires input from two spreadsheets, or databases, to calculate the power plants' RPN values [5]:

1. Degradation rate spreadsheet (file name "IV data"), contains IV performance data (Table 2-6)
2. Defects spreadsheet (file name "VI"), contains visual inspection data (Table 2-7)

Once these two spreadsheets are generated by the user, this program then generates RPN plots and several other reliability plots, in about three minutes, based on the input from these two spreadsheets.

Table 2-6
Sample IV data input for the degradation rate spreadsheet (Degradation rate is calculated based on age, nameplate data, and measured data.)

Module	Rated Isc	Rated Voc	Rated Imax	Rated Vmax	Rated FF	Rated Pmax	Measured Isc	Measured Voc	Measured Imax	Measured Vmax	Measured FF	Measured Pmax	Age
C2-S1-T1	3.87	42.10	3.56	33.70	73.63	120.00	3.65	41.26	3.13	33.84	70.30	105.77	17.79
C2-S1-T2	3.87	42.10	3.56	33.70	73.63	120.00	3.87	41.38	3.22	35.28	70.79	113.44	17.79
C2-S1-T3	3.87	42.10	3.56	33.70	73.63	120.00	3.71	41.33	3.31	33.51	72.48	111.04	17.79
C2-S1-T4	3.87	42.10	3.56	33.70	73.63	120.00	3.71	40.54	3.35	32.46	72.30	108.67	17.79
C2-S1-T5	3.87	42.10	3.56	33.70	73.63	120.00	3.70	41.07	3.33	33.31	73.08	111.00	17.79
C2-S1-T6	3.87	42.10	3.56	33.70	73.63	120.00	3.68	41.05	3.31	32.91	72.07	108.89	17.79
C2-S2-T1	3.87	42.10	3.56	33.70	73.63	120.00	3.75	41.05	3.36	33.07	72.12	111.16	17.79

Table 2-7
Sample IV data input for the defects spreadsheet (0=absence of defect; 1=presence of defect)

Module	Encapsulant delamination over the cell	Encapsulant delamination under the cell	Encapsulant delamination over the junction box	Encapsulant delamination near interconnect or fingers	Encapsulant discoloration (yellowing/browning)
C2-S1-T1	1	0	0	1	1
C2-S1-B1	0	0	0	0	1
C2-S1-T2	0	0	0	0	0
C2-S1-B2	0	0	0	0	1
C2-S1-T3	0	0	0	0	1
C2-S1-B3	0	0	0	0	1
C2-S1-T4	0	0	0	0	1
C2-S1-B4	0	0	0	0	1
C2-S1-T5	0	0	0	0	1

In Table 2-7, zeroes indicate no defects or module failures, and ones indicate the presence of one or more defects or failures. This is a partial table, whereas the full spreadsheet includes 86 columns for each of the defect categories.

3
RESULTS

RPN results and degradation rate (R_d) for each of the seven systems evaluated are described in this section. As described in Section 2, modules containing a specific defect with RPN value above 200 are considered risky and may be candidates for warranty replacement. Safety severity levels of 8 or higher, likewise, should be replaced, even if the RPN is lower than 200. Performance measurements were carried out for all modules at all sites to calculate degradation rates based on nameplate rating, field measurement performance data and module age. As described in [11,12], single measurements of degradation based on nameplate rating can introduce significant variation to the Rd results. Determination and requirement of nameplate ratings with tolerance limits have been standardized recently in 2016 and 2017 [13,14], and manufacturer selection of nameplate ratings in the past with undisclosed higher or lower tolerance than measured performance can inflate or deflate degradation rates.

3.1 Site AZ2: RPN and Rd

AZ2 is an 8-year old system with 57 poly-Si modules installed on a rooftop in Arizona with hot-dry climatic conditions. All of the modules in this system displayed slight discoloration of the encapsulant and backsheet, and a few modules showed bubbles in the backsheet. With less than 200 RPN for each of the three observed defects, no specific defect is considered to be risky in this relatively new plant (Figure 3-1). The Pmax degradation is primarily attributed to FF and Isc degradations, which in turn are attributed to solder bond degradation and encapsulant discoloration, respectively (Figure 3-2).

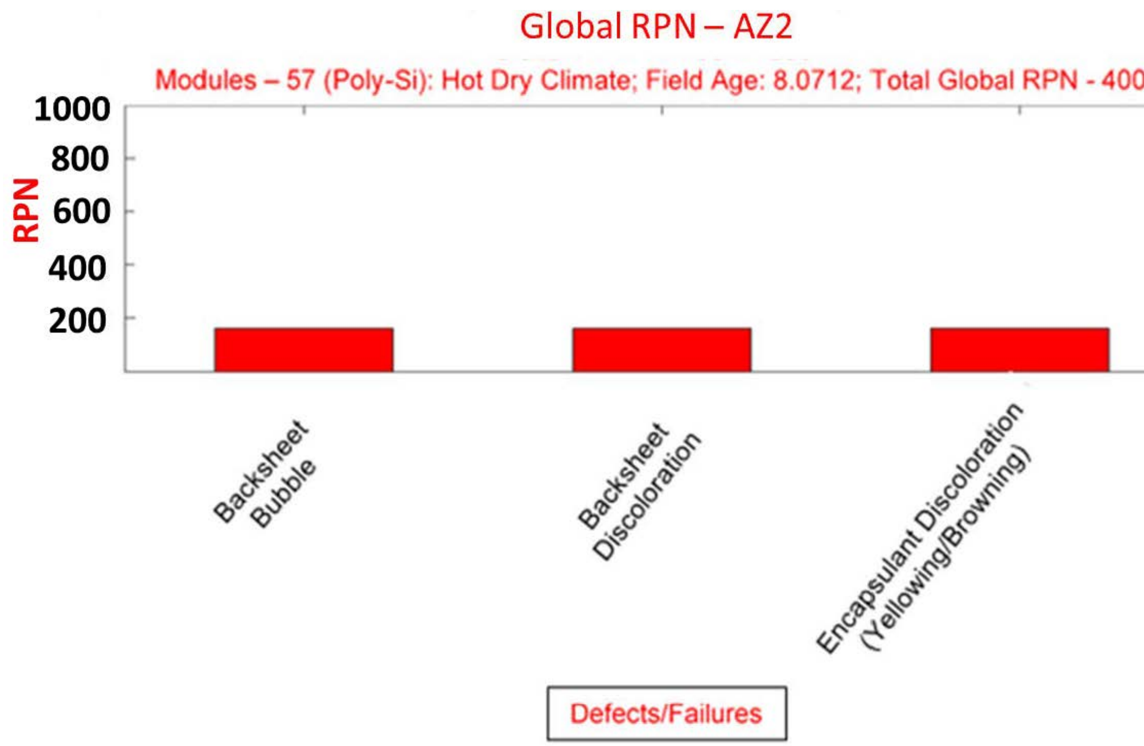

Figure 3-1
Global RPN for site AZ2 (hot-dry climate)

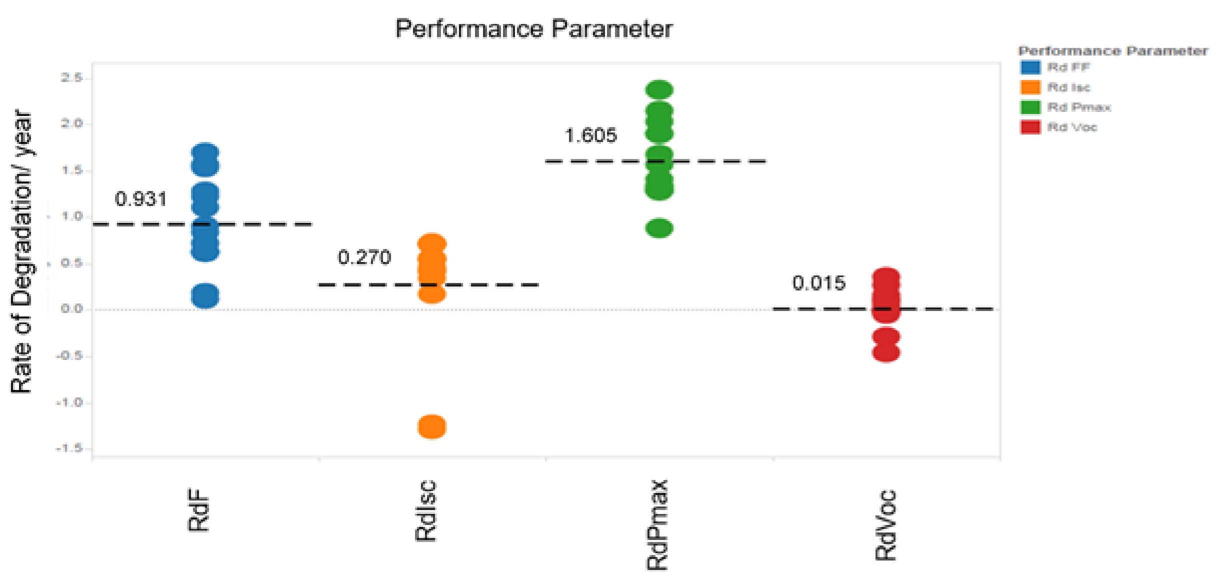

Figure 3-2
Performance parameter affecting the Pmax degradation rate of defect containing modules for site AZ2 (hot-dry climate)

3.2 Site AZ3: RPN and Rd

AZ3 is a 16-year old system with 168 mono-Si modules installed on a fixed tilt rack at 0° tilt in Arizona with hot-dry climatic conditions. All of the modules in this system displayed discoloration of the encapsulant, and a few modules experienced bypass diode failures. With less than 200 RPN for each of the two observed defects, no specific defect is considered to be risky (Figure 3-3). The Pmax degradation is primarily attributed to FF and Isc degradations which, in turn, are attributed to solder bond degradation and encapsulant discoloration, respectively (Figure 3-4).

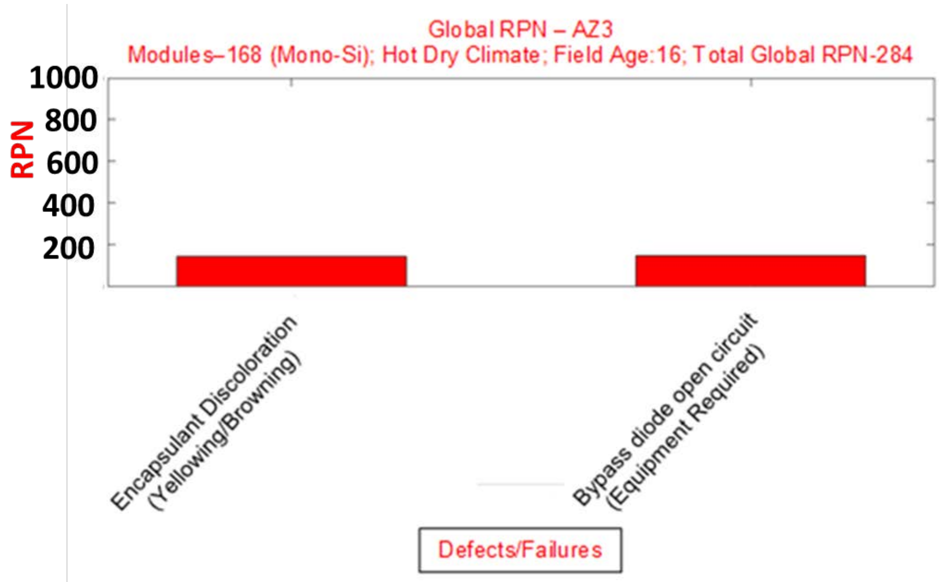

Figure 3-3
Global RPN for site AZ3 (hot-dry climate)

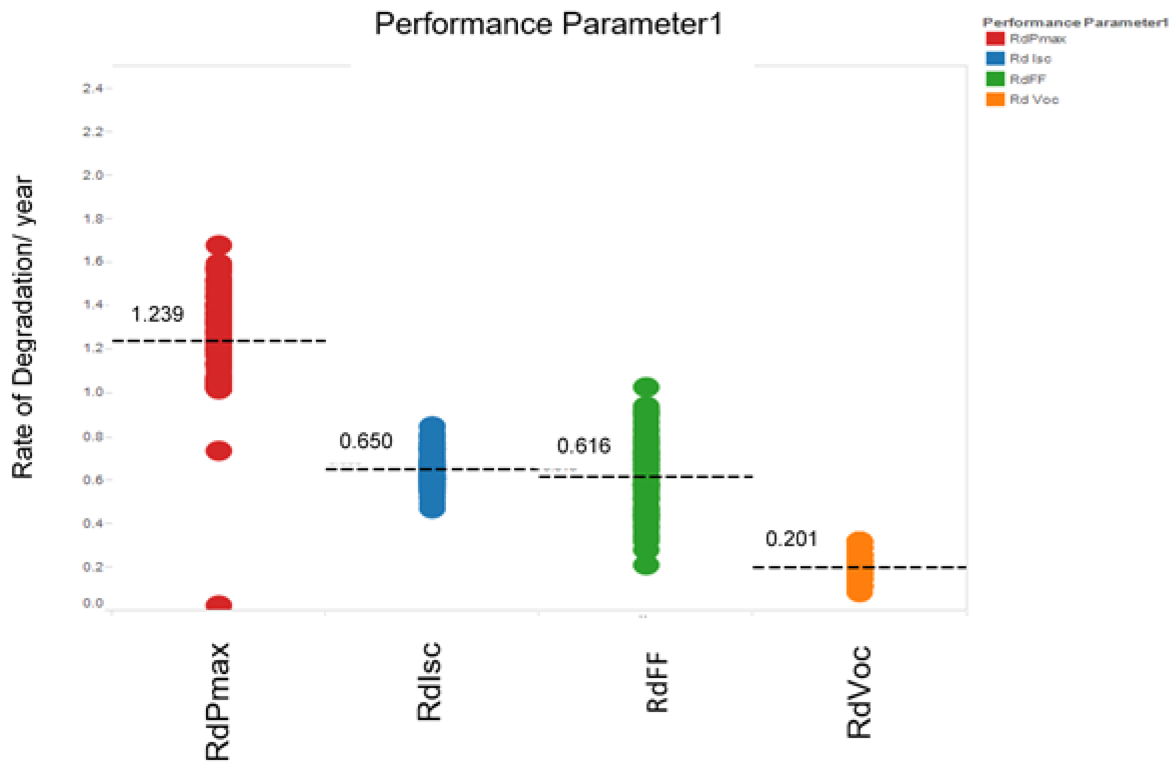

Figure 3-4
Parameters affecting the Pmax degradation rate of defect containing modules for site AZ3 (hot-dry climate)

3.3 Site AZ6: RPN and Rd

AZ6 is a 12-year old system with 65 mono-Si modules installed on a one-axis tracker in Arizona with hot-dry climatic conditions. Many modules in this system displayed solder-bond fatigue and discoloration of the encapsulant. Three of the four observed defects showed less than 200 RPN, and thus are not considered high risk (Figure 3-5). Only the solder bond degradation defect with more than 400 RPN is considered to be a risky defect. The Pmax degradation is predominantly attributed to FF and marginally attributed to Isc degradation, which may be caused by solder bond degradation and encapsulant discoloration, respectively (Figure 3-6).

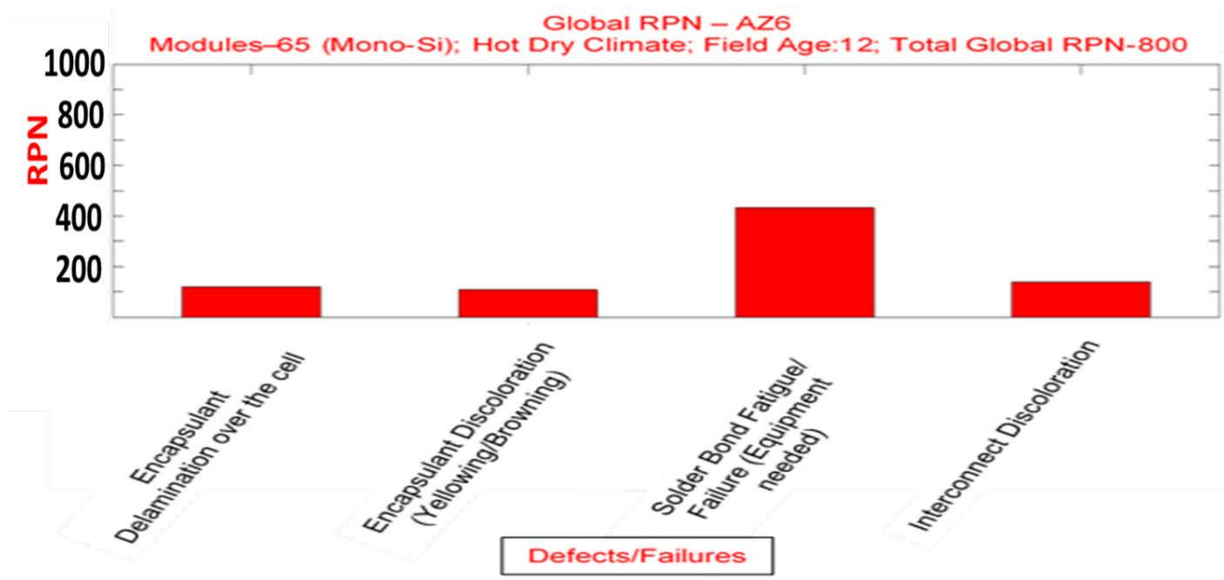

Figure 3-5
Global RPN for Site AZ6 (hot-dry climate)

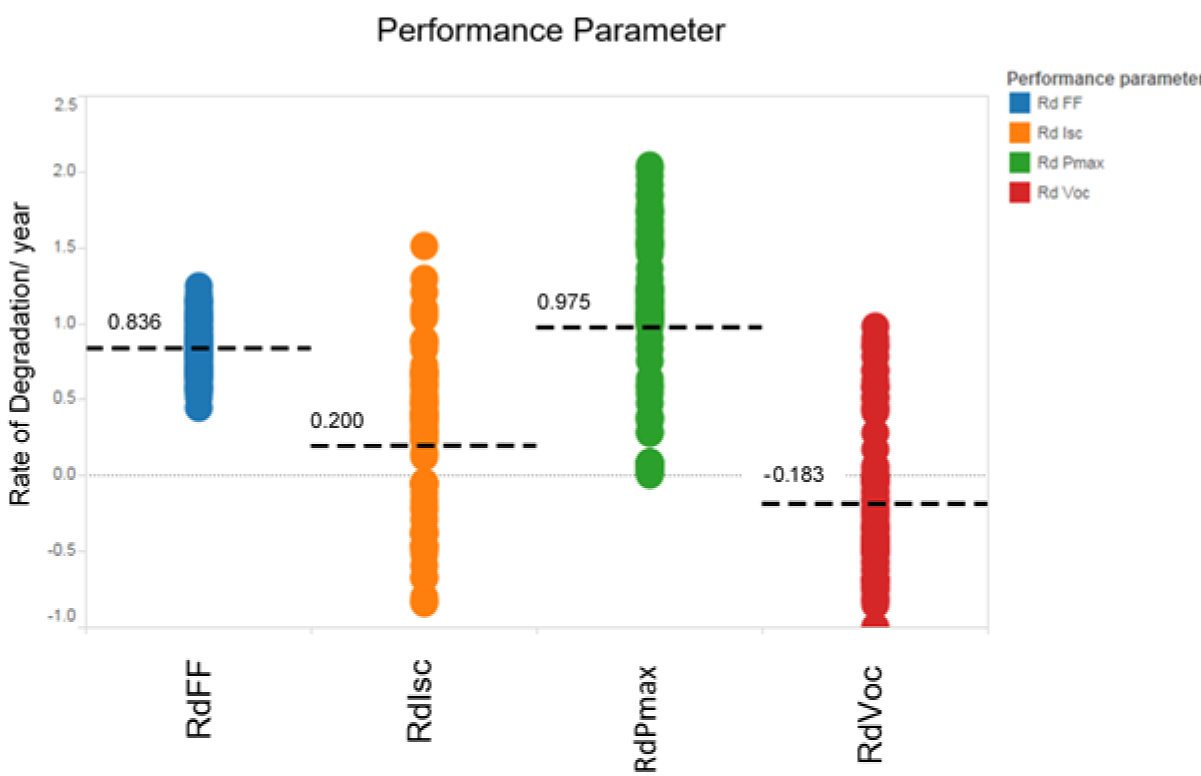

Figure 3-6
Parameters affecting the Pmax degradation rate of defect containing modules for site AZ6 (hot-dry climate)

3.4 Site AZ7: RPN and Rd

AZ7 is a 5-year old system with 84 HIT modules installed on a 10° fixed tilt rooftop rack in Arizona with hot-dry climatic conditions. All the modules in this system displayed discoloration of the encapsulant and many displayed solder-bond fatigue. Five out of six observed defects had an RPN value less than 200 (Figure 3-7). With an RPN exceeding 600, the solder bond degradation is the riskiest defect in this relatively new plant. The Pmax degradation is attributed to FF and Isc degradations caused by solder bond degradation and encapsulant discoloration, respectively (Figure 3-8).

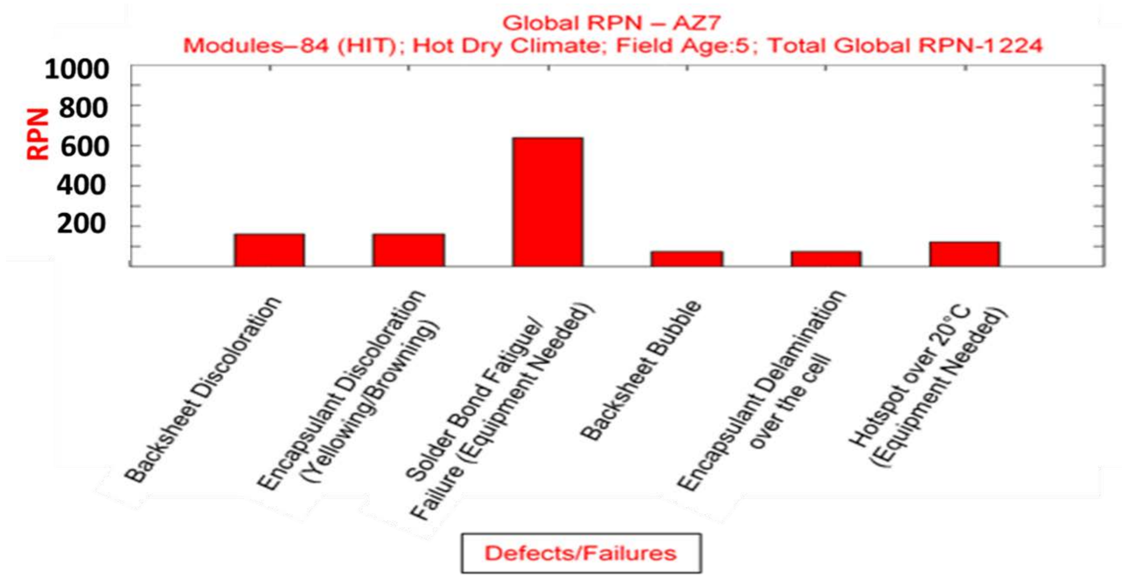

Figure 3-7
Global RPN for Site AZ7 (hot-dry climate)

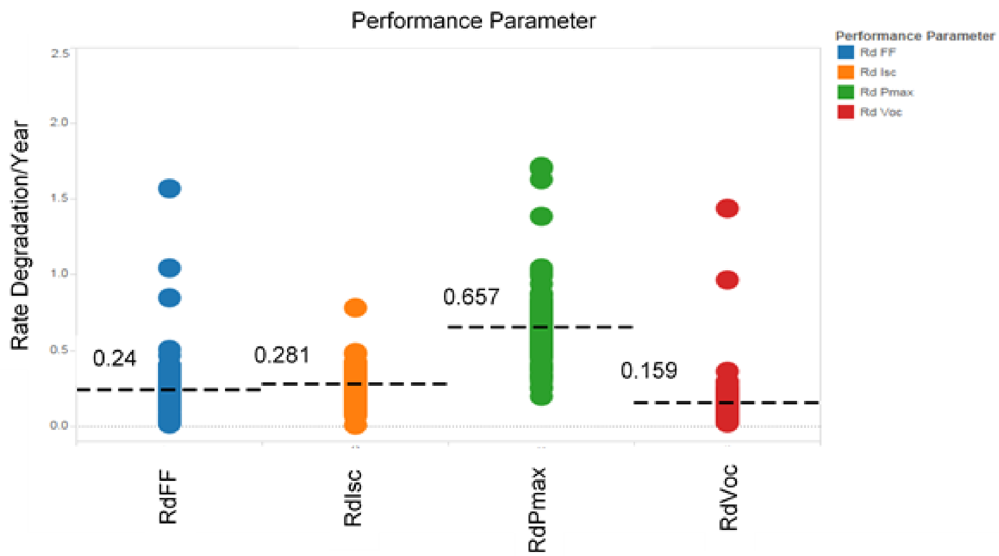

Figure 3-8
Parameters affecting the Pmax degradation rate of defect containing modules for site AZ7 (hot-dry climate)

3.5 Site AZ8: RPN and Rd

AZ8 is a 9.4-year old system with 231 poly-Si modules installed in Arizona with hot-dry climatic conditions. Many of the modules in this system displayed discoloration and delamination of the encapsulant. All five observed defects showed less than 200 RPN, and thus are not considered risky defects (Figure 3-9). The Pmax degradation is attributed to FF and Isc degradations, which are attributed to solder bond degradation and encapsulant discoloration, respectively (Figure 3-10). The negative Voc degradation rates reported here could be attributed to nameplate underrating rating by the manufacturer.

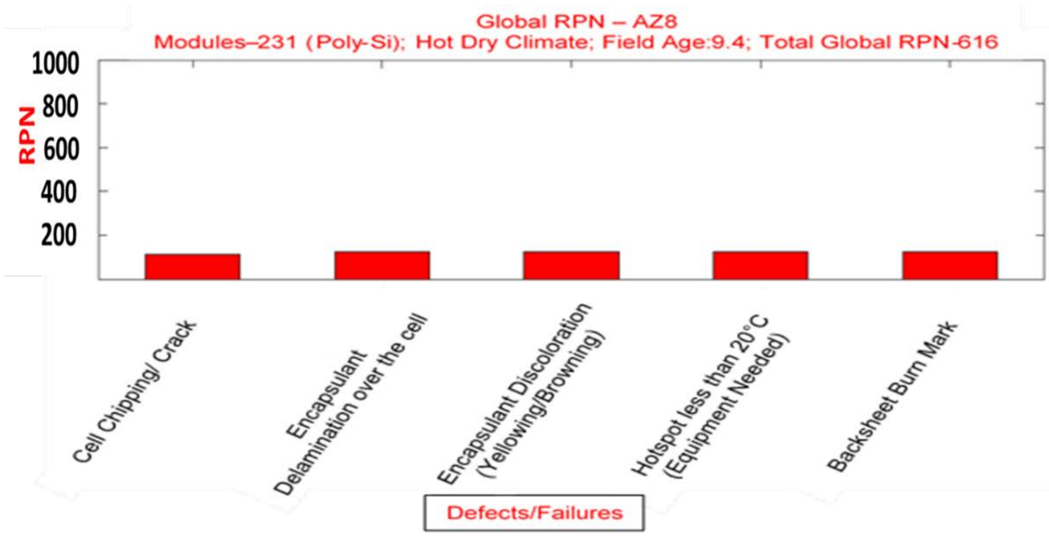

Figure 3-9
Global RPN for Site AZ8 (hot-dry climate)

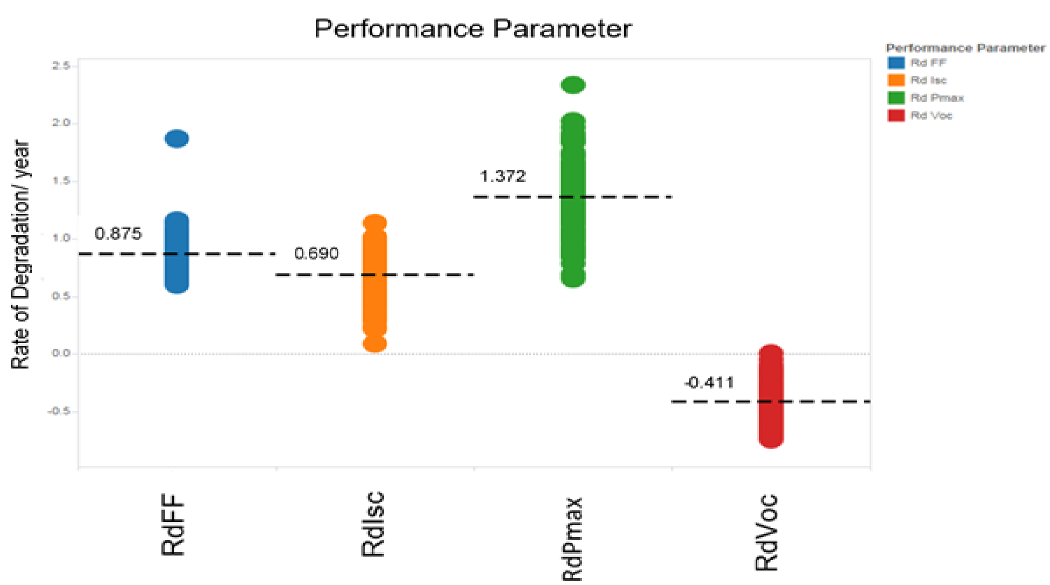

Figure 3-10
Parameters affecting the Pmax degradation rate of defect containing modules for site AZ8 (hot-dry climate)

3.6 Site NY1: RPN and Rd

NY1 is an 18-year old system with 46 poly-Si modules installed on a 41° fixed tilt rooftop rack in New York with cold-dry climatic conditions. All of the modules in this system displayed discoloration of the encapsulant and many displayed bypass diode failures. Seven out of eight observed defects showed less than 200 RPN and are not considered risky defects (Figure 3-11). The open circuit failures of the bypass diodes are the most risky defect with an RPN value exceeding 200. The Pmax degradation is primarily attributed to FF degradation due to solder bond degradation (Figure 3-12).

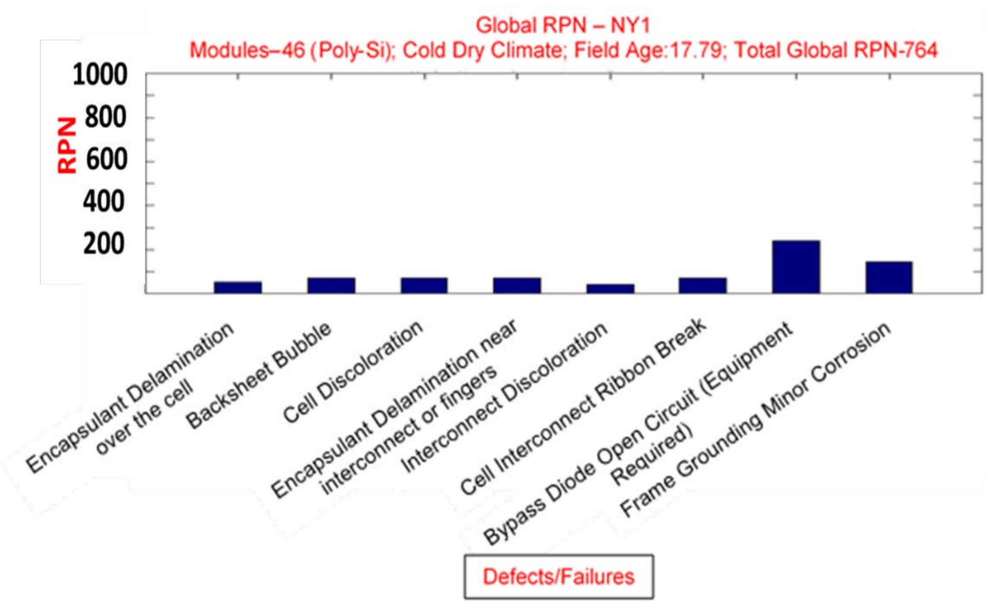

Figure 3-11
Global RPN for Site NY1 (cold-dry climate)

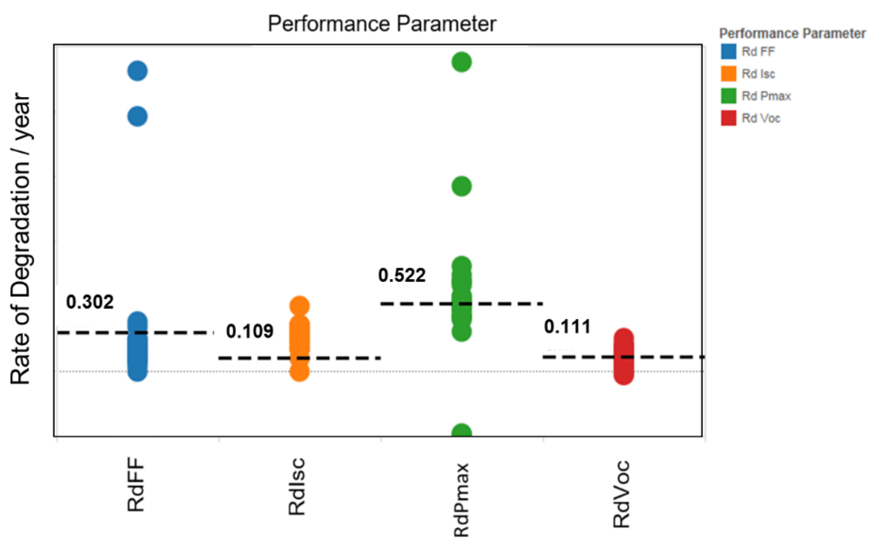

Figure 3-12
Parameters affecting the Pmax degradation rate for site NY1 (cold-dry climate)

3.7 Site CO2: RPN and Rd

CO2 is a 5-year old system with 24 mono-Si modules installed on a 39° fixed tilt rack in Colorado with temperate climatic conditions. Cell chipping and discoloration of the encapsulant were prominent defects in this relatively new system. Both observed defects showed less than 200 RPN (Figure 3-13). However, the Pmax degradation rate is unacceptably high, exceeding 2.5%/year (Figure 3-14). This Pmax overrating is most likely arising from the overrating of FF, and hence the RPN data presented in Figure 3-15 are not considered reliable.

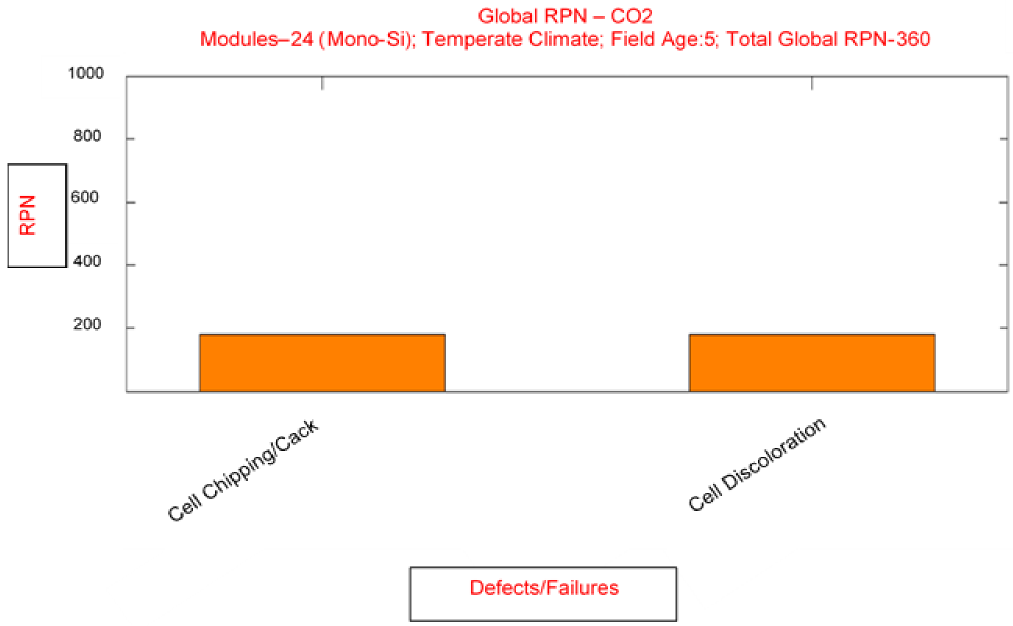

Figure 3-13
Global RPN for Site CO2 (temperate climate)

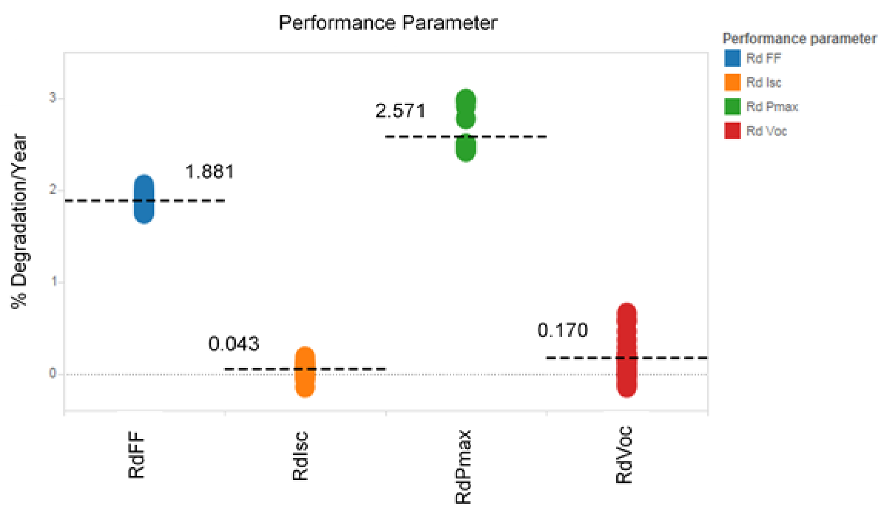

Figure 3-14
Parameters affecting the Pmax degradation rate of defect containing modules for site CO2 (temperate climate)

3.8 Annual Degradation Rates of Different Technologies

Performance measurements were carried out for all the statistically selected modules of five different technologies (c-Si, HIT, a-Si, CdTe and CIGS) at all of the twenty-six investigated sites of the project to determine the degradation rates based on the nameplate rating, field measured performance data and age of the modules. Figure 3-15 provides the degradation rates of the five PV cell technologies in Arizona (AZ), Texas (TX), Colorado (CO) and New York (NY). Since the degradation rate calculation depends on the accuracy of the nameplate rating, a few of the calculated degradation rate data presented in this figure may not be reliable and those unreliable data are shown in this figure [15]. It is to be noted that the degradation rates shown in the section may be, in some cases, different from that of the degradation rates presented in the previous RPN sections. This difference is due to the following reason: the degradation rate calculation presented in this section is based on the degradation rates of all the statistically selected modules in the plant whereas the degradation rates presented in the RPN analysis sections are based on the degradation rates of the defect containing modules only.

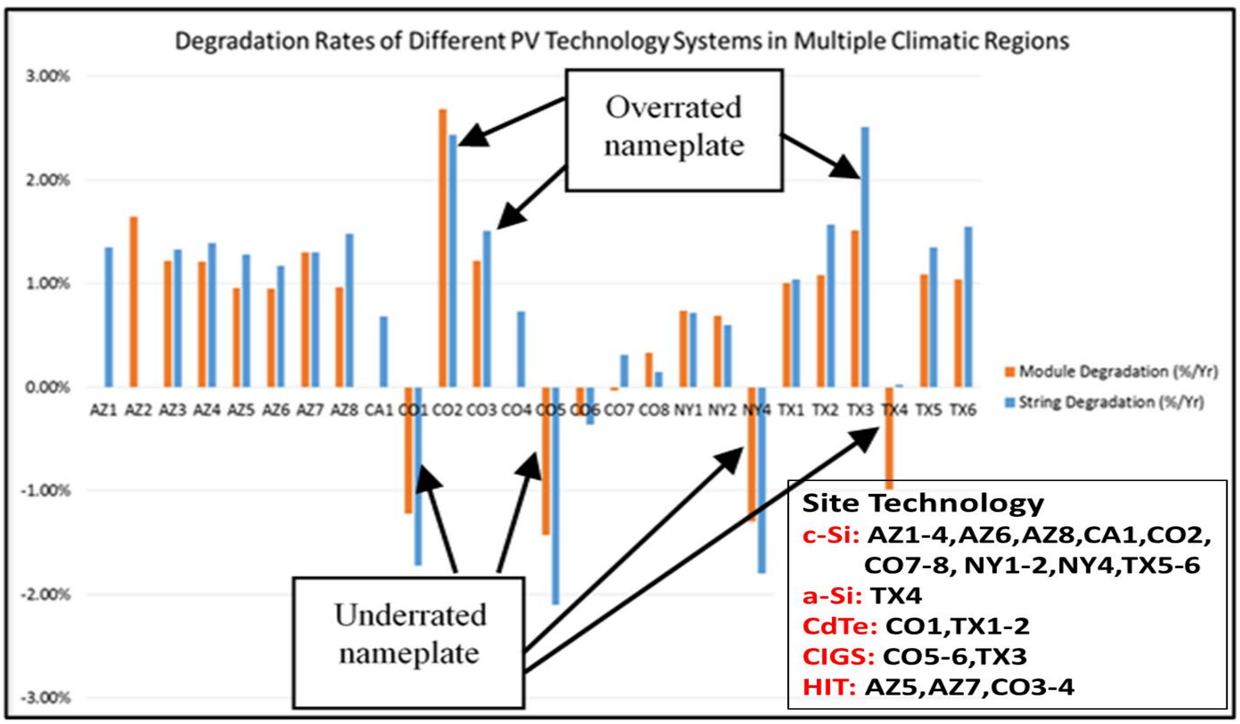

Figure 3-15
Comparison of module and string degradation rates of multiple technologies in diverse climates of hot-dry (AZ), cold-dry (NY), hot-humid (TX) and temperate (CO).

4 CONCLUSIONS

The modules evaluated in each plant were selected based on a statistical approach. For the degradation rate determination presented in Section 3.8, all of the statistically selected modules were considered. For the RPN analysis determination presented in Sections 3.1 through 3.7, the degradation rates of only defect-containing modules were considered.

Seven different PV plants spanning three different climatic regions (AZ, NY, CO) and containing crystalline silicon modules aged between 5 and 18 years were subjected to the RPN evaluation. The RPN value for each observed defect was determined based on the severity (degradation rate per year), occurrence (frequency of each observed defect) and detectability. In four of the seven plants (AZ2, AZ3, AZ8, CO2), no defect with RPN exceeding 200 was observed, and thus these plants were determined to be ineligible for defect (material or workmanship) warranty claims. In plants AZ6 and AZ7, the solder bond fatigue defect has an RPN higher than 200, and hence all modules which have solder bond fatigue may be eligible for defect warranty claims. In plant NY1, the bypass diode failure has an RPN higher than 200, and hence all modules which have diode failures may be eligible for defect warranty claims.

In the hot-dry and hot-humid climates, module and string degradation rates (excluding the overrated and underrated modules) were found to be higher than 1%/year, likely due to harsh temperature conditions. Since these degradation rates are greater than the typical performance warranted degradation rate of 1%/year, these modules installed in hot climates are considered not meeting the typical degradation rate warranty requirements and are potentially eligible for warranty replacement. In the cold-dry and temperate climates, module and string degradation rates (excluding the overrated and underrated modules) were less than 1%/year due to relatively milder temperature conditions, and hence they are considered meeting the typical degradation rate warranty requirements.

5
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A
DEFECTS AND FAILURES BY CATEGORY

Table A-1
Performance defects/failures by category (61 defects)

<table>
<tr><th>Glass</th><th>Frame</th><th>Junction box</th><th>Cell</th></tr>
<tr><td>Front glass lightly soiled
Front glass heavily soiled
Front glass crazing
Front glass chipped
Front glass milky discoloration
Rear glass crazing
Rear glass chipped</td><td>Frame bent
Frame discoloration
Frame adhesive degraded
Frame adhesive oozed out
Frame adhesive missing in areas</td><td>Junction box lib loose
Junction box warped
Junction box weathered
Junction box adhesive loose
Junction box adhesive fell off
Junction box Junction box wire attachments loose
Junction box wire attachments fell off
Junction box wire attachments arced</td><td rowspan="3">Cell discoloration
Cell burn mark
Cell crack
Cell moisture penetration
Cell foreign particle embedded
Cell interconnect discoloration
Gridline discoloration
Gridline blossoming
Busbar discoloration
Busbar corrosion
Busbar burn marks
Busbar misaligned
Cell interconnect ribbon discoloration
Cell interconnect ribbon corrosion
Cell interconnect ribbon burn mark
Cell interconnect ribbon break
String interconnect discoloration
String interconnect corrosion
String interconnect burn mark
String interconnect break
Hotspot less than 20°C</td></tr>
<tr><th>Edge Seal</th><th>Encapsulant</th><th>Backsheet</th></tr>
<tr><td>Edge seal delamination
Edge seal moisture penetration
Edge seal discoloration
Edge seal squeezed out/ pinched out</td><td>Encapsulant delamination over the cell
Encapsulant delamination under the cell
Encapsulant delamination over the junction box
Encapsulant delamination near interconnect or fingers
Encapsulant delamination (yellowing/browning)</td><td>Backsheet wavy
Backsheet discoloration
Backsheet bubble</td></tr>
<tr><th>Wires</th><th>Thin Film</th><th>Bypass Diode</th><th>Others</th></tr>
<tr><td>Wires corroded</td><td>Thin film module discoloration
Thin film module delamination-absorber coating
Thin film module delamination- AR coating</td><td>Bypass diode short circuit</td><td>Module mismatch
Solder bond fatigue/failure</td></tr>
</table>

Table A-2
Safety defects/failures by category (25 defects)

Glass	Frame	Bypass diode	Junction box
Front glass crack Front glass shattered Rear glass crack Rear glass shattered	Frame grounding severe corrosion Frame grounding minor corrosion* Frame major corrosion* Frame joint separation Frame cracking	Bypass diode open circuit*	Junction box crack Junction box burn Junction box loose Junction box lid fell off Junction box lid crack
Wires	**Backsheet**	**Cell**	
Wires insulation cracked Wires burnt Wires animal bites / marks*	Backsheet peeling Backsheet delamination Backsheet burn mark Backsheet crack / cut under cell Backsheet crack / cut between cells	String interconnect arc tracks Hotspot over 20°C*	

*Not an immediate catastrophic safety failure (the eighteen non-asterisk defects shown in this table are immediate catastrophic safety failures).

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