NATIONAL RENEWABLE ENERGY LABORATORY

Technology and Climate Trends in PV Module Degradation

Preprint

Dirk C. Jordan, John H. Wohlgemuth,
and Sarah R. Kurtz

Presented at the 27th European Photovoltaic Solar Energy Conference and Exhibition
Frankfurt, Germany
September 24–28, 2012

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Conference Paper
NREL/CP-5200-56485
October 2012

Contract No. DE-AC36-08GO28308

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/help/ordermethods.aspx

Cover Photos: (left to right) PIX 16416, PIX 17423, PIX 16560, PIX 17613, PIX 17436, PIX 17721

Printed on paper containing at least 50% wastepaper, including 10% post consumer waste.

TECHNOLOGY AND CLIMATE TRENDS IN PV MODULE DEGRADATION

D.C. Jordan*, J.H. Wohlgemuth, S.R. Kurtz
National Renewable Energy Laboratory (NREL), 1617 Cole Blvd., Golden, CO 80401
*Tel: 1-303-384-6762; Fax: 1-303-384-6790; email: dirk.jordan@nrel.gov

ABSTRACT: To sustain the commercial success of photovoltaic (PV) technology it is vital to know how power output decreases with time. Unfortunately, it can take years to accurately measure the long-term degradation of new products, but past experience on older products can provide a basis for prediction of degradation rates of new products. An extensive search resulted in more than 2000 reported degradation rates with more than 1100 reported rates that include some or all IV parameters. In this paper we discuss how the details of the degradation data give clues about the degradation mechanisms and how they depend on technology and climate zones as well as how they affect current and voltage differently. The largest contributor to maximum power decline for crystalline Si technologies is short circuit current (or maximum current) degradation and to a lesser degree loss in fill factor. Thin-film technologies are characterized by a much higher contribution from fill factor particularly for humid climates. Crystalline Si technologies in hot & humid climates also display a higher probability to show a mixture of losses (not just short circuit current losses) compared to other climates. The distribution for the module I-V parameters (electrical mismatch) was found to change with field exposure. The distributions not only widened but also developed a tail at the lower end, skewing the distribution.
Keywords: Degradation Rates, PV Module, Performance, Photovoltaic Systems, Field Testing, Mismatch

1 INTRODUCTION

The commercial success of the photovoltaic (PV) industry has benefited from the use of accelerated stress testing to identify infant mortality problems. [1] As the industry matures, there is an increasing interest and need to go beyond qualification testing and quantify wear out mechanisms that may cause slow degradation and lead to failures[2]. Over the years, dozens of failure mechanisms have been reported. Browning or discoloration of modules can be some of the most obvious signs of degradation, but, failures of electrical connections may cause greater decrease in module output. [3] Accurate quantification of power decline over time requires an understanding of all degradation mechanisms including delamination, broken interconnects or cells, corrosion, broken glass, ground faults, and increases in shunting.[2] Some types of wear-out processes cause a steady loss of power (e.g. browning of encapsulant materials); others may show stable performance followed by a catastrophic failure (e.g. broken glass, followed by module failure because of the loss of integrity of the package); while some may show early drop in performance followed by more stable performance (e.g. light-induced degradation). [4]

At the system level, not all degradation mechanisms are equivalent (current and voltage degradation affect system performance differently), and not all modules degrade at the same rate with a single underperforming module affecting the entire string. Thus, understanding not only the degradation rates but, also, the width and shape of the distribution is important. The widths of these distributions determine the electrical mismatch and has been investigated for fielded arrays. [5] The broadening of I-V parameters after field exposure has been noted before. [6,7].

A previous study summarized more than 2000 degradation rates, concluding that the average degradation rate was < 1%/y for most products manufactured after the year 2000, with some statistical variation for some technology types, especially for products manufactured before the year 2000. [8]

This study builds on the previous study by analyzing the changes reported for the various device parameters - short-circuit current (Isc), open-circuit voltage (Voc) and fill factor (FF) - and how these vary with technology and climate zone. The possible implications of these results are discussed, especially in terms of how the module degradation may affect system performance and what degradation mechanisms may be dominating the field experience, providing a basis for prioritization of design of accelerated tests.

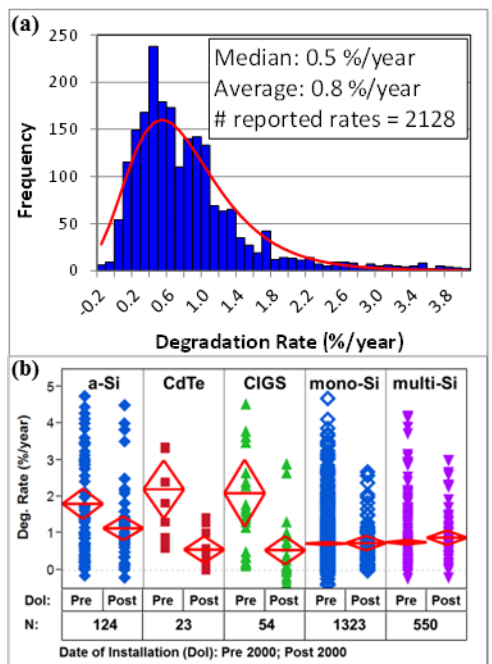

Figure 1: Histogram of published degradation rates (blue bars) with an extreme value distribution fit (red line) (a), and partitioned by technology and date of installation (b). The number in each category indicates the number of data points. The 95% confidence interval is denoted by the diamonds with the mean as the crossbar.

2 RESULTS

An extensive search resulted in more than 2000 PV degradation rates (R_d) quoted in publications and locations worldwide. The number of cited rates is large enough to allow grouping for installation before and after the year 2000, and by technology. Fig. 1 (a) provides an updated histogram with an extreme value distribution fit that will be discussed in the second subsection. Fig. 1 (b) shows the maximum power degradation partitioned by technology and date of installation. [8] The number in each category indicates the number of data points. The 95% confidence interval is denoted by the diamonds with the mean as the crossbar. Crystalline Si technologies (x-Si) appear to have remained steady at rates of approximately 0.5%/year for installations before and after the year 2000. However, thin-film technologies showed a significant move towards stability for post 2000 installations.

More than half of these compiled rates (ca.1100) contain information on at least some I-V parameters in addition to maximum power (Pmax) such as maximum-power-point current (Imax) and maximum-power-point voltage (Vmax), Isc, Voc and FF. The paper is organized in 3 subsections analyzed by technology, distribution and climate.

2.1 I-V Parameter Degradation

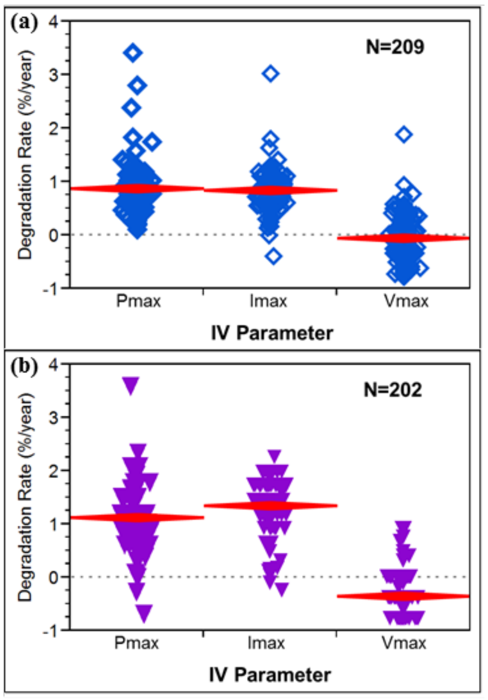

Figure 2: Degradation rates of the maximum-power-point values for power, current and voltage for mono-Si (a), multi-Si (b). As a guide for the eye, dashed lines indicate no degradation. A negative degradation implies improvement.

Figure 2 shows the annualized degradation rate for Pmax, Imax and Vmax partitioned by technology. Despite the scatter for mono- (a) and multi-Si (b), the predominant decline appears to be in current not in voltage. This is an important consideration for proper inverter sizing. Similar data for thin-film technologies are not shown because of the small number of data points.

Of further interest is how IV parameter degradation differs by technology. Fig. 3 shows Pmax, Isc, Voc and FF degradation for crystalline Si technologies (a) and (b) and thin-film (c). Due to the low number of data points the thin-film technologies amorphous silicon (a-Si), copper indium gallium (di)selenide (CIGS) and cadmium telluride (CdTe) have been overlaid on one plot. Mono-Si and multi-Si display a similar pattern in which the highest Pmax degradation is most closely correlated with Isc, followed by FF and finally Voc, which degrades little. Typical observed Isc degradation can be attributed to delamination, discoloration and cracked individual cells while a smaller percentage can be attributed to light-induced degradation and soiling. [9,10] Significantly less degradation comes from FF, typically associated with corrosion and solder-bond breakage. The pattern differs for thin-film technologies in Fig. 3 (c) despite a clustering effect by technology. All three thin-film technologies show a significantly higher FF degradation (compared with crystalline Si technologies), often associated with light-induced degradation of a-Si and an increase in series resistance in CIGS. [11]

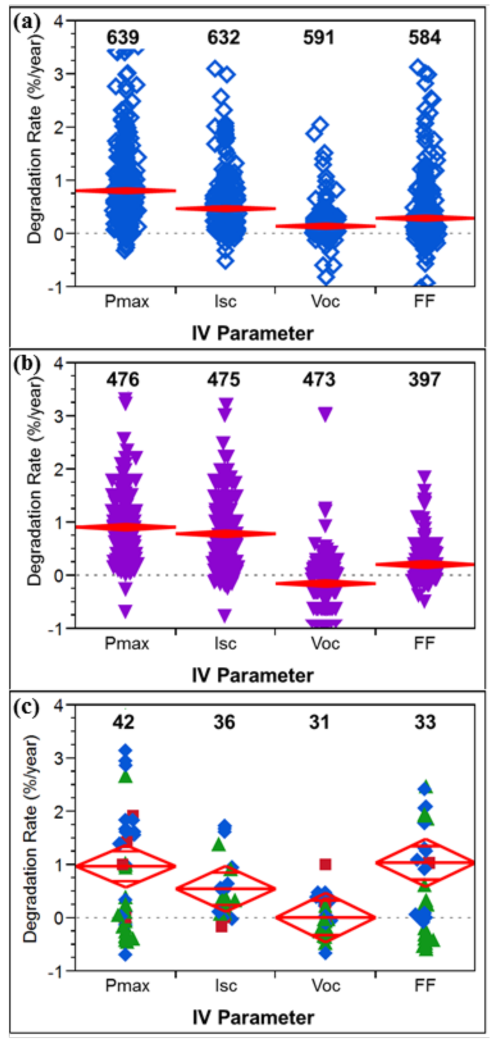

Figure 3: Pmax, Isc, FF and Voc degradation rates for mono-Si (a), multi-Si (b), and thin-film (c). The thin-film part is an overlay of a-Si (filled blue diamonds), CIGS (filled green triangles), and CdTe (filled red squares). As a guide for the eye, no degradation is indicated by a dashed line. The numbers at the top indicate the number of data points.

2.2 I-V parameter distribution

In this section we will discuss the I-V parameter distributions that determine the electrical mismatch.

Figure 4 shows how the width (a) and shape (b) of the individual I-V parameter distributions change with field exposure time for x-Si technologies. The coefficient of variation - standard deviation divided by the mean of the distribution (CoV) – is used as the metric for the width (a). The shape of the distribution is characterized by the skewness, a unitless measure of the asymmetry of a distribution (b). [12] A skewness around zero indicates a normal distribution. The I-V parameters Pmax, Isc, Voc and FF are differentiated by color and the circle size is indicative of the number of modules in a particular study. Studies with less than 8 modules are not included in this graph; the largest study included data for almost 800 modules.

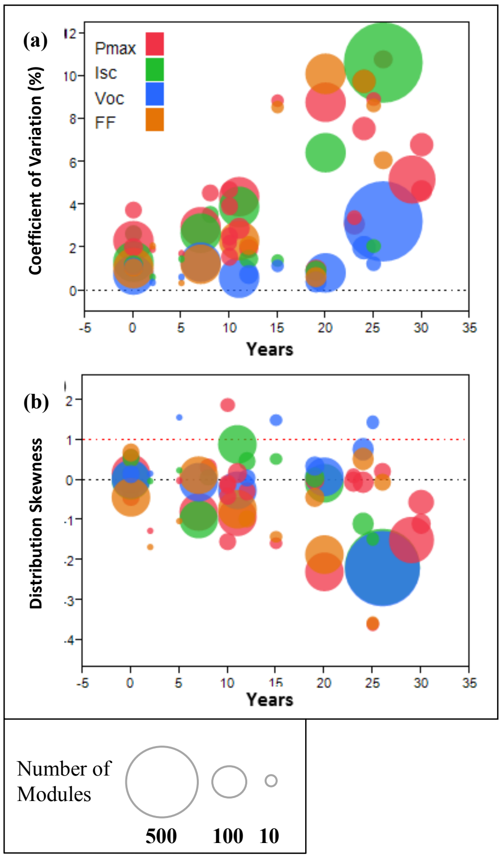

Figure 4: Bubble plot of (a) coefficient of variation (standard deviation divided by mean) and (b) the skewness of the distributions versus field exposure. I-V parameters are color-coded. The sizes of the circles indicate the number of modules in the study and the filling of the circles provides information on the shape of the distribution.

Some general trends can be distinguished from the CoV graph. 1) It appears that the CoV increases with field exposure indicating that the distribution tends to get wider. 2) The Voc CoV is the lowest of the displayed I-V parameters changing the least with field exposure. 3) Figure 4 (b) illustrates that the distributions not only tend to get wider but that they also change shape with field exposure. Most module distributions start normal but sometimes non-normality at the beginning is caused by a sharper peaked distribution. [13] Non-normality can also be caused by the binning of the manufacturer. As the field exposure increases, the negative skewness indicates that a more pronounced tail, sometimes accompanied by an outlier, at the lower end of the investigated I-V parameter is starting to develop. [14,15,16,17,18] It is important to understand that the calculated CoV could change significantly depending on whether the outlier is included in the calculation of the CoV. Furthermore, the quality of the I-V measurements could contribute to the shape of the distribution. Nevertheless, this lower tail can be understood in terms of the different failure mechanisms for a PV module listed by some of the authors. [19] In a complex system, such as a PV module, these different failure mechanisms are characterized by different distributions. The most dominant failure mechanism will cause the eventual module failure. Such a situation often can be characterized by an extreme value distribution and mirrors in shape the distribution of the overall degradation rates in Fig. 1. [20] The implications of this distribution deformation, the widening and skewing, is that it can significantly impact system performance since the lowest performing module will impact the performance of the string. For a system containing 10 modules per string and a total of 10 strings, and assuming 0.5%/year degradation over 25 years, the inclusion of a few poorly performing modules may increase the average observed system degradation rate from ~0.5%/year to ~0.7%/year, as the CoV increases from 2% to 8%. In addition, if the skewness increases from ca. zero to -2.6, the average observed system degradation is closer to 0.8%/year. [21] The 4 studies that show significant positive skewness above +1 have a small sample size indicated by the small circle.

2.3. Climate

I-V parameter degradation is likely to depend on the local conditions and climate zone. Figure 5 shows a Köppen-Geiger map overlaid with the geographical distribution of reported degradation rates (black circles). [22] The size of the circle indicates the number of reported degradation rates at a given location.

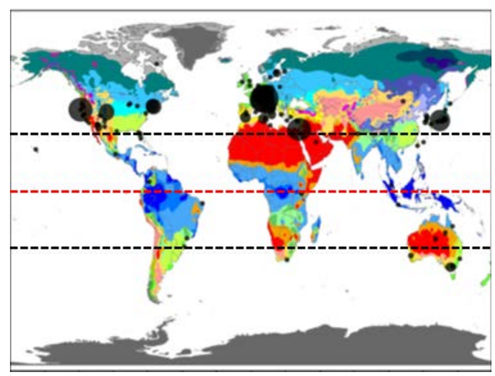

Figure 5: Geographic distribution of reported degradation rates overlaid on a Köppen-Geiger climate map with the equator and the tropic of Cancer and Capricorn. The size of the circle is indicative of the number of degradation rates at a given location.

One conclusion from the map is that no reported degradation rates exist today in many of the Köppen climate zones. Köppen was particularly interested in the interaction of climate and flora. Hence, his classification scheme is based on temperature and precipitation categories. [23] Undoubtedly, temperature and precipitation, and more specifically, humidity, are also relevant parameters for PV performance. However, additional parameters that may influence PV performance and longevity such as altitude, thermal cycling, snow load and air salinity may be just as or more important. [24]

While such a better classification scheme is being sought, the Köppen-Geiger scale provides a common basis for climate discussions. Due to the lack of information in some climate zones some sensible consolidation such as combining tropical climates (Af & Aw) with the continental hot and humid climate (Cfa) had to be made. [25]

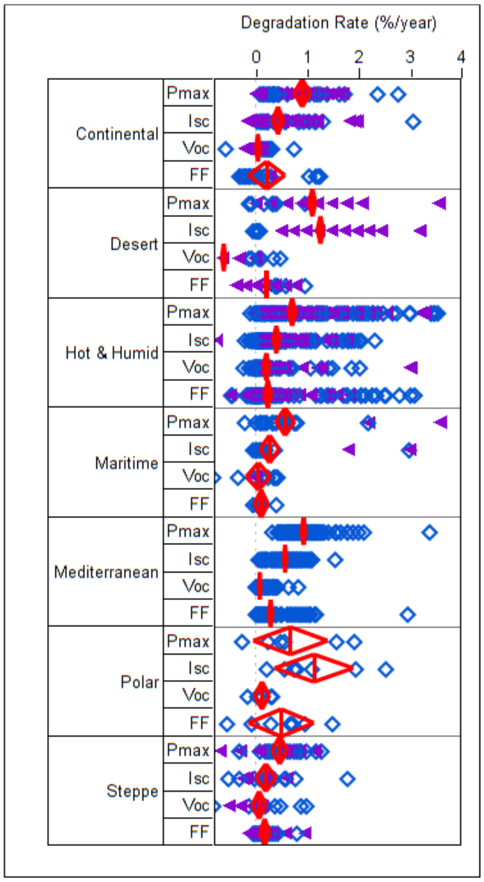

Figure 6: IV parameter degradation for mono-Si (open diamonds) and multi-Si (filled triangles) by climate zones based on Köppen-Geiger classification. The 95% confidence interval is denoted by the diamonds with the mean as the crossbar.

The IV parameter degradation distribution by climate zone for mono-Si and multi-Si is shown in Fig. 6. For most climate zones Isc degradation is the largest contributor to Pmax degradation. For the desert climate the Isc degradation exceeds the Pmax degradation while the Voc shows a small improvement. A large proportion of these data points come from a one-point study, with the risk of larger errors as discussed above. It is also possible that the high temperatures of the desert climate led to EVA browning which would manifest itself in high Isc and low FF degradation as has been recently shown for an arid steppe climate. [26] Furthermore, it is interesting to note that in the polar climate a larger FF degradation is observable than in the other climates. A possible explanation could be that snow load led to cracking of the front glass and or individual cells or that the cold temperatures particularly in the winter led to interconnect breakage due to the brittleness of EVA at lower temperatures. [27]

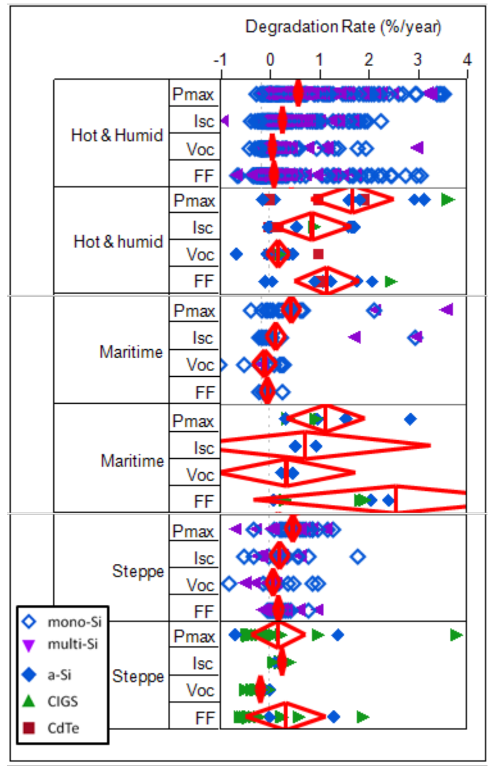

Figure 7: I-V parameter distribution partitioned by climate with Si data above and thin-film data below for each climate zone. The 95% confidence interval is denoted by the diamonds with the mean as the crossbar.

Figure 7 shows a direct comparison between crystalline and thin-film technologies by climate zones wherever both are available. Especially in the maritime and hot & humid climate the FF has a more pronounced degradation rate for thin-film most likely due to moisture ingress. Significant variation in the data can be caused by different module type, age, construction, which includes encapsulation, front- and back-sheet, electrical set-up (open-circuit, short-circuit, load resistor, grid-tied), and measurement uncertainty etc. [28]

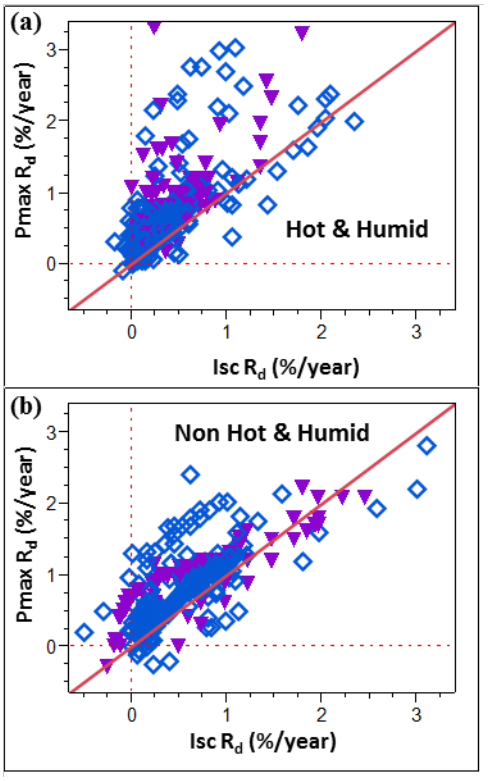

Figure 8: Correlation of Pmax with Isc degradation for hot and humid climates (a) and all other climates (b). Mono-Si is indicated by open diamonds and multi-Si by filled inverted triangles.

A final analysis was conducted to determine the correlation of Pmax degradation with the various I-V parameters (Figs 8-10). Because degradation mechanisms are different in different climates, the analysis was split between hot & humid climates (a) and all other climates (b). As guide to the eye, perfect correlation is indicated by the solid red line and no correlation is indicated by the dashed red lines. In the hot and humid climate most data are distributed between the perfect correlation and no correlation lines. In all other climates most data follow distinctly the all Isc degradation rate line with two exceptions. An additional line shifted towards higher Pmax degradation can be seen for multi-Si and for mono-Si. Each of these two lines comes from a study in which only one data point was taken because no baseline measurements were available Although it is possible that these data reflect accurate measurements, it has been shown that there is an increased probability that using data sheet values for the initial measurement resulted in misleading data [29,30]. This illustrates (a) the importance of multiple measurements and (b) in the taxing hot & humid climate some decline comes from Voc and FF, in addition Isc. Figure 9 shows some data indicating substantial Voc degradation in hot and humid climates, mostly caused by substring failure. [28] Figure 10 illustrates some modules with significant FF degradation in the hot and humid climate caused by increased series resistance. [4,10,28]

The "tail" of modules with significant FF degradation in all other climates, Fig. 10 (b) is shifted towards the higher Pmax degradation. Again, these data are from a study with one measurement only. The same study shows significant corrosion of interconnections and gridlines. [18] The location of this study is in the Mediterranean climate close to the ocean, possibly highlighting the importance of atmospheric corrosiveness.

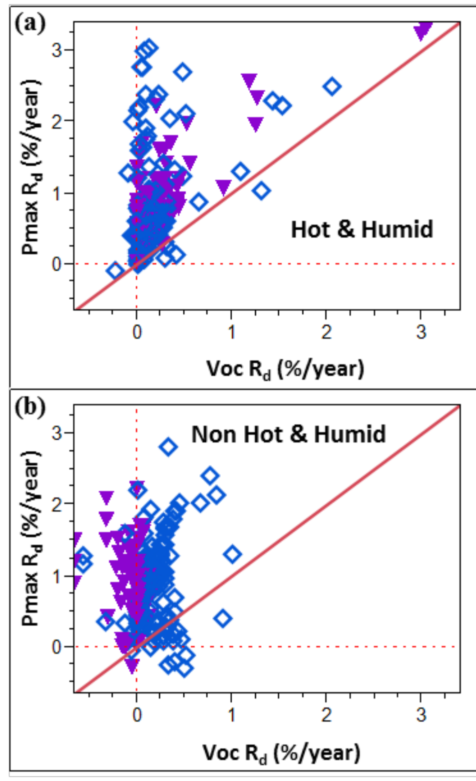

Figure 9: Correlation of Pmax with Voc degradation for hot and humid climates (a) and all other climates (b). Mono-Si is indicated by open diamonds and multi-Si by filled inverted triangles.

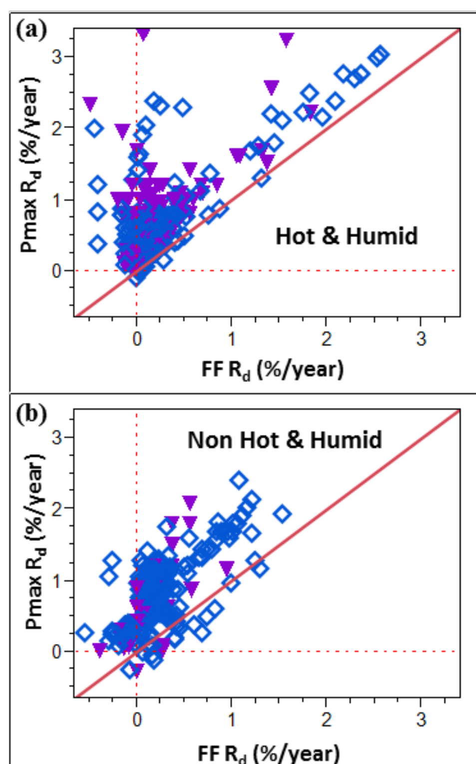

Figure 10: Correlation of Pmax with FF degradation for hot and humid climates (a) and all other climates (b). Mono-Si is indicated by open diamonds and multi-Si by filled inverted triangles.

3 DISCUSSION

The observations can help understand which degradation mechanisms may be dominating for each climate zone and for each technology type.

Specifically, the observation that the majority of crystalline silicon modules degraded most in Isc could be explained by discoloration of the encapsulant. The evidence supporting this theory includes: 1) that several of the reports specifically mentioned discoloration. [13,15,17,26,28] 2) That discoloration is known to cause a slow decrease in power production, and 3) The discoloration is known to be accelerated at higher temperatures, consistent with the observation of the highest Isc degradation in the desert. The decrease in Isc might also be explained by delamination and the associated loss of transmission of light through the encapsulant-glass interface. Some of the reports specifically noted delamination. [10,16,28] If delamination occurs, there may eventually be moisture ingress and corrosion of the internal parts of the module. Another common cause of loss of Isc can be broken cells. The effect of cell breakage may be delayed because current can continue to flow until all of the metal connections also break. At that point, there may be a more abrupt drop in the current output, but because this may only affect the photocurrent in one part of the module, we expect that loss of current from one broken cell will reduce the fill factor, not the Isc.

An understanding of the degradation mechanisms for the thin-film modules is complicated by the diversity of thin-film technology. The general observation that the fill factor decreases more than the other module parameters differentiates the situation for thin-film products from that of silicon, but does not lead to clear conclusions about the dominant wear-out mechanisms.

The relatively small changes in open-circuit voltage simplify the system design since the match between the system voltage and the desired input voltage of the inverter may not change much over the lifetime of the system. A more careful evaluation of the decreases in fill factor for the thin-film modules may lead to changes in voltage; this question may benefit from additional investigation. Similarly, as noted above, the 0.5%/yr decrease in module efficiency may correspond to significantly greater degradation rates at the system level depending on the design of the system.

4 CONCLUSION

Literature degradation rates were statistically analyzed to discern trends partitioned by technology and climate. The largest contributor to Pmax decline for crystalline Si technologies is Isc (or Imax) degradation and to a lesser degree loss in FF, especially in hot and humid climates. These observations suggest that accelerated tests quantifying discoloration of encapsulant materials, delamination, and/or loss of photocurrent from cracked cells may successfully predict wear-out rates in a majority of climates. Thin-film technologies are characterized by a much higher contribution from FF also particularly for humid climates. Development of accelerated tests to quantify wear out in thin-film modules is more challenging because of the range of mechanisms affecting the various thin-film products. Finally, studies with a significant number of identical modules show not only an increased distribution width with increasing field exposure but also development of a tail at the lower end of the distribution characterized by an extreme value distribution. The inclusion of a few poorly performing modules may increase the probability significantly of a lower system performance.

5 ACKNOWLEDGMENTS

The authors would like to thank Chris Deline from NREL and Joshua Stein from Sandia for the review of the manuscript. This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08-GO28308 with the National Renewable Energy Laboratory.

---

[1] J.H. Wohlgemuth, History of IEC Qualification Standards, Proceedings of International PV Module QA Forum, 2011, http://www.nrel.gov/ce/pvmqa_forum/proceedings.cfm#qaforum-july15.

[2] J.H. Wohlgemuth JH, et al., Using Accelerated Testing to Predict Module Reliability, 37th Photovoltaic Specialists Conference, Seattle, Washington, 2011.

[3] J.H. Wohlgemuth et al., Reliability of EVA modules, 23rd Photovoltaic Specialists Conference, Louisville, KY, 1993, 1090-1094.

[4] K. Morita et al., Degradation Factor Analysis of Crystalline-Si PV Modules through Long-term Field Exposure Test, 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan, 2003, 1948–1951.

[5] W. Damm, et al., "Power losses in PV arrays due to variations in the I-V characteristics of PVmodules." Energiemeteorologie, 1995.

[6] C.E. Chamberlin et al., Effects of Mismatch Losses in PV Arrays, Sol. Energy 54, 3, 19959, 165-171.

[7] S. MacAlpine et al., Module Mismatch Loss and Recoverable Power in Unshaded PV Installations, 38th PV Specialists Conference, Austin, TX, USA, 2012.

[8] D.C. Jordan et al., Photovoltaic Degradation Rates – an Analytical Review, Prog. Photovolt: Res. Appl., 2011.

[9] M.A. Quintana et al., Commonly observed degradation in field-aged PV modules, 29th Photovoltaic Specialists Conference, New Orleans, 2002; 1436.

[10] Sakamoto et al., Field Test Results on the Stability of c-Si PV Modules Manufactured in the 1990s, 3rd World Conference on Photovoltaic Energy Conversion, Osaka, Japan, 2003, 1888.

[11] J.A. del Cueto et al., Stability of CIGS Modules at the OTF over 2 Decades, 33rd Photovoltaic Specialists Conference, San Diego, 2008, 1.

[12] A. Sleeper, Six Sigma Distribution Modeling, McGraw-Hill, 2006.

[13] P. Sanchez-Friera, et al., Analysis of degradation mechanisms of crystalline silicon PV modules after 12 years of operation in Southern Europe, Progress in Photovoltaics: Research and Application 2011.

[14] Bing JM, Decades in the Installed Environment: Do Silicon Modules Really Last More than 20 Years?, NREL PV Module Reliability Workshop, Golden CO, USA, February 2010, http://www1.eere.energy.gov/solar/pv_module_reliability_workshop_2010.html.

[15] A.M. Reis, et al., Comparison of PV module performance before and after 11-years of field exposure, Proceedings of the 29th Photovoltaic Specialists Conference, New Orleans, LA, USA, 2002, 1432–1435.

[16] C.E. Chamberlin, et al, Comparison of PV module performance before and after 11 and 20 years of field exposure, 37th Photovoltaic Specialists Conference, Seattle, WA, USA, 2011, 101-105.

[17] D. Berman, et al., EVA Laminate Browning after 5 years in a Grid-connected, Mirror-assisted, Photovoltaic System in the Negev Desert: Effect on Module Efficiency, Solar Energy Materials and Solar Cells 1995, 36, 421–432.

[18] A. Messaoudi et al., Performance of c-Si Solar Cells after 25 years of Operation, 23rd European Photovoltaic Solar Energy Conference, Valencia, Spain, 2008, 3554–3557.
[19] J.H. Wohlgemuth et al., Reliability Testing Beyond Qualification as a Key Component in Photovoltaic's Progress Toward Grid Parity, IEEE International Reliability Physics Symposium, Monterey, CA, USA, 2011.
[20] NIST/SEMATECH e-Handbook of Statistical Methods,http://www.itl.nist.gov/div898/handbook/, date.
[21] to be published
[22] M.C. Peel, et al.,"Updated world map of the Köppen-Geiger climate classification", Hydrol. Earth Syst. Sci, 11, 2007, 1633.
[23] W. Köppen, 1918, Classification of climates according to temperature, precipitation and seasonal cycle. Petermanns Geogr. Mitt. 64, 1918, 193-203, 243-248.
[24] K. Slamova et al., Mapping atmospheric corrosion in coastal regions: methods and results, J. Photonics Energy, 2, 2012, 1-11.
[25] Hot & Humid: A, Cfa, Cwa; Steppe: BSk, BSh; Desert: BWh, BWk; Mediterranean: Csa, Csb; Maritime: Cfb, Cfc; Continental: D; Polar: E
[26] R.M. Smith et al., Outdoor PV Module Degradation of Current-Voltage Parameters, World Renewable Energy Forum, Denver, CO, USA, May 2012.
[27] N. Bogdanski et al., PV Reliability (Cluster II): Results of a German Four-Year Joint Project, 25th European Photovoltaic Solar Energy Conference, 2010, 4339.
[28] A. Skoczek, et al., The Results of Performance Measurements of Field-aged Crystalline Silicon Photovoltaic Modules, Progress in Photovoltaics, 2009, 227.
[29] Ransome S, Modeling inaccuracies of PV energy yield simulations, 33rd Photovoltaic Specialists Conference, San Diego, 2008.
[30] D.C. Jordan et al., PV Degradation Risk, World Renewable Energy Forum, Denver, CO, USA, May 2012.