The Challenge to Move from "One Size Fits All" to PV Modules the Customer Needs

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THE CHALLENGE TO MOVE FROM "ONE SIZE FITS ALL" TO PV MODULES THE CUSTOMER NEEDS

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ABSTRACT: Historically, PV companies requested a single qualification test for a single product. As the market has grown, there have been increasing opportunities for companies to differentiate their products while still maintaining high manufacturing volumes of each product. At the same time, as PV is deployed in an increasingly broad range of conditions, modules need to be able to withstand a wide range of stresses. In some cases, targeting a specific deployment condition may allow reduction of product cost. Realizing this opportunity will require the ability to confidently predict long-term performance based on accelerated tests and known weather conditions. By working together, the community can most quickly develop tests that identify which products perform well under which conditions. This paper discusses some of the challenges of predicting long-term PV performance, including the wide range of stresses that may be encountered, the variability of the stresses from moment to moment, the complexity of some degradation mechanisms, and the dependence of accelerated testing on module geometry. The paper also describes two international projects that deal with location-specific durability evaluation and long-term module peformance.

Keywords: PV modules, reliability, durability

1 INTRODUCTION

As PV module production grows, companies have begun to explore ways to differentiate their products. For years, companies have offered products with a range of powers and physical sizes, but more recently, they have begun to market their products according to other features as well. Customers usually choose PV products based on price and efficiency, but many customers are now also choosing products based on confidence in their long-term performance or a range of other features. The confidence in performance has increased in importance as investors try to limit risk in increasingly large investments in PV.

This paper begins by exploring how some companies currently differentiate their PV products for different markets. We then discuss the challenge of confidently differentiating products according to their long-term performance because of the highly variable stresses that may be encountered and the complexities of testing for these in a timely way. Finally, we describe how current international efforts can lay the groundwork for enabling long-term predictions.

2 DIFFERENTIATION OF PV PRODUCTS

2.1 Strategies used by today's companies

Historically, PV companies have attempted to limit product cost by manufacturing a minimum number of module designs. More recently, large production volumes have enabled product diversification, and increasing competition among companies has led to a desire for product differentiation. Still, only a handful of companies are actively diversifying their product lines. For example, some companies [1] actively market products with improved aesthetics for rooftop applications and products with improved confidence in performance for utility-scale applications.

A survey of products offered by a set of 25 companies was completed by downloading datasheets directly from each company's website. The datasheets were compared to identify each company's efforts to market products with unique features to different customers. Product differentiation was ignored if it appeared to be related to updating of the product line and/or was not clearly highlighted on the datasheet. The survey showed that newer products tend to have more detailed guarantees, more complete certifications, and clearer documentation of all features.

Other than differentiation according to aesthetic considerations, only a few companies were found that are actively marketing differentiated products. Figure 1 provides statistics on the fraction of companies that offered two or more versions of their product according to five criteria. For residential applications, it is common to offer a module with a black backsheet to enable a uniform black appearance for silicon modules.

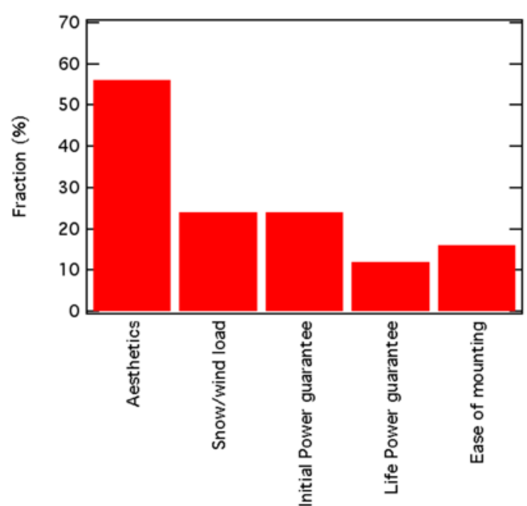

Figure 1: Fraction of companies surveyed that differentiate their products according to the indicated categories. The fraction reported in each category reflected advertisement of two or more versions of the product; some companies differentiated products in multiple categories.

Some customers choose this aesthetic all-black design over a module that uses a white backsheet. The all-black module is more attractive, but operates at a slightly higher temperature, decreasing the power output. The differentiation according to aesthetics was the most popular of those tabulated (all of the companies offer products with a range of power outputs, often by designing for a different number of cells or using cells of different efficiencies).

The second most common difference in products was related to the strength of the modules relative to snow and wind loading. The cost of a PV module is increased if thicker glass is used or if a (stronger) frame is added to a module, as Q-cells does for its CIGS module Q.SMART 75-95, which has a 5400 Pascal rating relative to the Q.SMART UF 75-95, which has a 2400 Pascal rating without the frame.

Companies appear to be moving toward tighter tolerances on initial power. Suntech has created a trademark as a marketing tool for its initial power guarantee and also offers an annual step down in its long-term guarantee for utilities [1]. Four of the companies offer linear power-output guarantees, because investors usually calculate the expected return on investment based on the stated guarantee, penalizing products that only state the guarantee after 10 or 25 y (*e.g.*, investors may assume that the modules will generate electricity at 90% of rated power for the first 10 y and 80% of rated power for the next 15 y) (Fig. 2). Others are strengthening their warranty by specifying slower degradation rates.

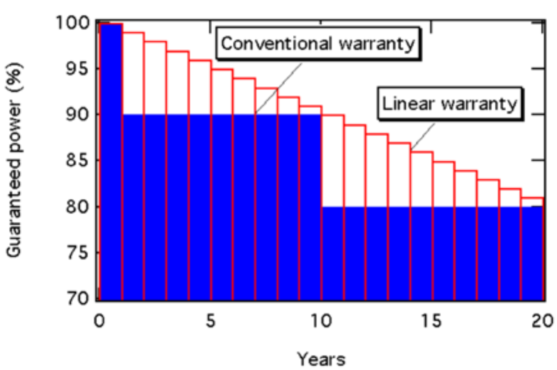

Figure 2: Example comparison of a conventional two-step warranty (90% after 10 y and 80% after 20 or 25 y) with a linear warranty with 1% reduction per year. The linear warranty guarantees more kWh generation over the lifetime of the system, since most investors assume the worst-case performance within the warranty.

A few companies also advertised special mounting systems that can reduce installation costs, or features that can improve safety. For example, an increased number of busbars can reduce the chance of arcing and were featured by two companies.

One key reason for the small amount of differentiation by durability is that manufacturers have not yet found many ways to save on cost while creating useful products. Table I summarizes some opportunities for cost reduction that might be considered today. The survey showed evidence of differentiation by only the first of these. A second key reason for the small amount of differentiation by durability is that we cannot accurately explain to customers the value of such differentiation. This will be discussed more below.

2.2 Likely trends for differentiation of products

As the PV industry grows, we may expect further differentiation of products. Based on current trends, we expect an increased emphasis on accurate predictions of the initial and long-term performance. Such predictions require an understanding of both the PV module durability and the use conditions that the module will encounter. The scientific challenge of quantifying these and using them together to make confident predictions will take many years to master. The rest of this paper is devoted to better understanding that scientific challenge and the progress that is being made.

Table I: Opportunities for cost reduction

Situation	Module modification
Low snow/wind load	Thinner glass, frameless, or less expensive frame
Low-voltage system (e.g., AC module)	Thinner backsheet
Covered back (no UV exposure to back)	Cheaper backsheet
Short-lifetime application	Flexible package
Protected from rocks or other mechanical damage	Frameless
Dry environments	Cell or packaging designs that are low-cost, but too sensitive to moisture for humid applications

3 CHALLENGES OF QUANTIFYING AGING

Predictions of the lifetime of a PV module based on accelerated testing currently come with high uncertainties. In this section, we discuss and give examples of four of the many reasons why PV module lifetime is difficult to predict and how recent studies have made progress at elucidating these.

3.1 Stresses vary greatly with location and application

Although everyone would like to see a label on a PV module indicating the expected life of the module, such a label could not be scientifically meaningful unless the location and mounting conditions of the module are also specified. The stresses experienced by a module can vary by a factor of 100 or even more. As an example, here we discuss the effects of temperature.

Most degradation mechanisms are accelerated at higher temperatures. The temperatures experienced by PV modules are dependent on the local temperature, the brightness of the sunshine, the mounting configuration, wind speed/direction, and a number of other factors. Using typical weather data and typical module temperature models, the temperature distributions can be predicted [2] as shown in Fig. 3. The tails on the high temperature side of Fig. 3 are a result of heating by sunlight. This heating is less severe when air can move on both sides of the module as can be seen by comparing the Fig. 3 distributions labeled "Open rack" and "Insulated back." Backside insulation can cause >20°C temperature increase when the sun is shining brightly, regardless of location; operation in Riyadh compared with Munich increases most of the temperature distribution curve by ~20°C.

The effect of the increased temperatures shown in Fig. 3 on the aging rate is highly dependent on the degradation mechanism. Chemists often model temperature dependence of chemical reactions using the Arrhenius equation with an activation energy that is specific for that reaction pathway. Unfortunately, activation energies are unknown for the vast majority of PV module degradation mechanisms, but estimation of the effects of temperature can be predicted by comparing results for a range of activation energies. Figure 4 summarizes the predicted lifetime for a thermal aging mechanism for typical weather in Munich or Riyadh for two mounting configurations and assuming Arrhenius behavior for a range of activation energies.

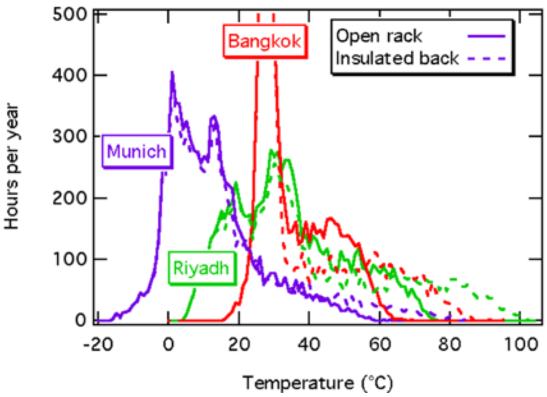

Figure 3: Typical temperature distributions expected for PV modules mounted on open racks or roof mounted with insulated backs in three locations [2].

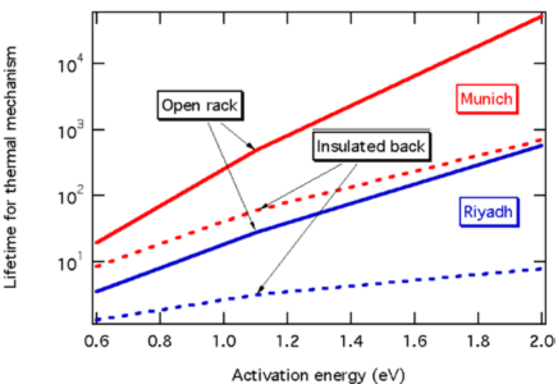

Figure 4: Predicted lifetime associated with thermal aging for 1000 h in an oven at 100°C assuming typical weather in Munich and Riyadh, the indicated mounting configuration, and based on Arrhenius temperature dependence with the indicated activation energy [2].

For an aging process that has an activation energy of ~ 1.1 eV, the lifetime associated with passing a 1000 h test in a 100°C oven increases by more than a factor of 10 for a module deployed in Munich compared with the same module deployed in Riyadh. Similarly, the style of mounting of the module can affect the aging rate dramatically. However, not all degradation mechanisms are affected equally by temperature, and these differences could be substantially less or substantially greater as shown by the left and right sides in Fig. 4, respectively. Particularly problematic, for example, would be a material that goes through a phase transition and softens at a high temperature, causing loss of structural integrity and a safety issue [3]. In practice, most degradation mechanisms involve moisture, exposure to ultra-violet light, or any of many other stresses coupled with the thermal exposure, complicating the predictions.

As PV prices are reduced and PV becomes cost competitive with more conventional electricity sources, PV markets may move toward sunny areas with high electricity prices. To the extent that these sunnier locations are hotter than Germany (the largest market for PV in recent years), the degradation rates of PV modules may increase. If this increase is as large as Fig. 4 implies, manufacturers could find significant increases in warranty claims and customers will be dissatisfied, slowing market growth.

Other stresses that can vary dramatically with location include mechanical loads from snow and wind, hail, salt spray, and ammonia. Wind and hail can be difficult to predict, because the most severe occurrences are often highly localized. While it is difficult to predict the storms that will be encountered, testing for hail and snow load is somewhat more straightforward than testing for more complicated failure mechanisms.

3.2 Quantifying weather transitions

Whereas it can be challenging to identify modules' responses to the extremes encountered in different parts of the world, it can be just as challenging to understand the importance of moment-by-moment changes in weather conditions. Failures of solder bonds and metal interconnects have sometimes been reported to cause a large loss in the power output of modules [4]. These failures are usually attributed to the cumulative damage done by thermal cycling.

Much is known about thermal fatigue, but the PV application brings new subtleties. An obvious easy assumption is that the modules experience a thermal cycle with each day. However, additional temperature cycling occurs with changes in solar irradiance during the day. The diurnal thermal cycle in many locations may be ~10°C, whereas the thermal cycle caused by a cloud may be > 25°C. Thus, the thermal transients caused by clouds may be both greater in magnitude and more frequent than the diurnal variations.

However, short thermal transients may do little damage if the original temperature is restored before plastic deformation has occurred. Factors influencing the accumulation of damage include the frequency (time scale) of the thermal fluctuations, the magnitude of the fluctuation, the average temperature, and the geometry of the sample.

Whereas it is easy to predict that deployment of PV modules in the Middle East will result in faster thermal aging, it is more difficult to predict the locations that will hasten aging caused by thermal fluctuations. Our preliminary studies imply that intermediate climates may show more thermal fatigue than both desert climates (with mostly sunny conditions and few clouds) and wet climates (with many overcast days). For example, Fig. 5 compares the temperature profiles and accumulated strain energies for two days in Golden, Colorado, with the two days causing differing amounts of damage. These calculations are described in detail elsewhere [5, 6].

3.3 Complexity of degradation mechanisms

Many failure mechanisms depend on the sequential application of multiple stresses. Past studies have described such situations [7]. For example, application of mechanical load can initiate cracks in silicon cells with little damage until additional thermal cycling extends these cracks, thus resulting in a significant drop in electrical output [7]. Similarly, cracked glass may not itself cause loss of electrical output, but subsequent moisture ingress and mechanical stresses may eventually result in complete failure of the module. Also, partial shading causes activation of bypass diodes and current flows that cause hot spots. If the bypass diodes fail, localized heating can be quite severe, leading to localized damage.

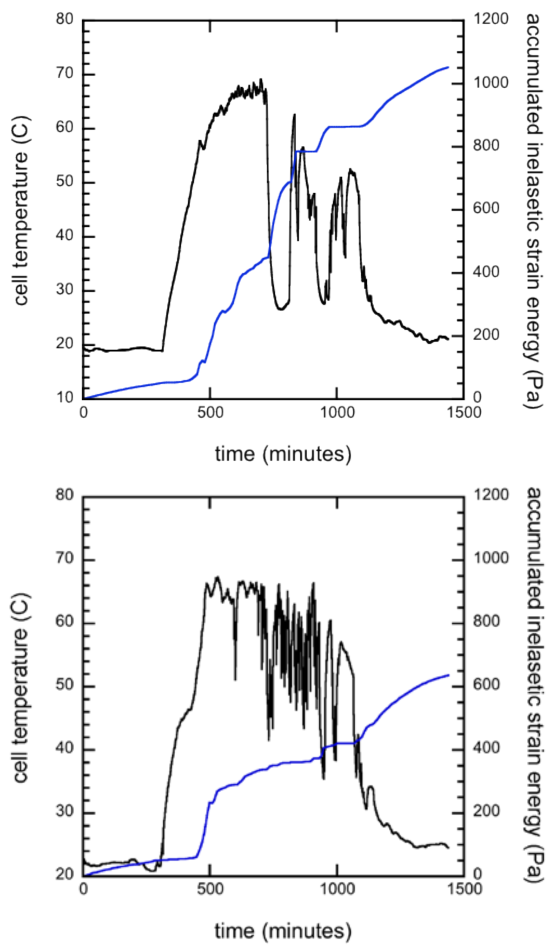

Figure 5: Comparison of temperature profiles (black) and accumulated strain energy (blue) for two days, showing how the day with ~1-h storms shows substantially more accumulated strain energy [5, 6].

Here, we describe relatively new data elucidating the complexity of potential-induced degradation. The use of high voltages (~1000 V) has recently been observed to cause very fast degradation of modules. The current qualification tests [8, 9] do not adequately identify modules that are susceptible to this, motivating the search for deeper understanding of the mechanism and leading to the development of a reliable test.

Potential-induced degradation has been shown to be most dramatic for the modules located at the (usually negative) high-voltage end of a string and is associated with the flow of leakage current. In an experiment designed to study this by deploying individual modules biased at a range of voltages [10], the leakage current is observed to be proportional to the applied voltage and to vary dramatically during the day, with the highest currents flowing in the morning on most days. Dew often collects at night (facilitating flow of leakage current in the early morning), then the module dries during the day as sunlight heats it to temperatures well above the ambient, reducing the leakage current (Fig. 6).

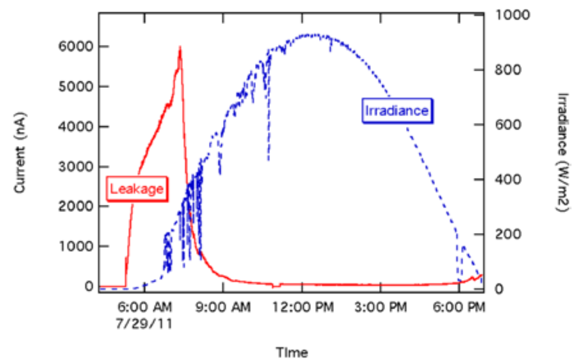

Figure 6: Leakage current for a module biased at –600 V when sunlight is shining. The leakage current is greatest in the morning before the dew has dried from the module.

Understanding the potential-induced degradation is also challenging because indoor testing shows that the degradation is reversible [10]. If the effect of the short flow of current each morning is largely reversed by annealing at higher temperature during the day, the correlation between accelerated testing and the real-world stress may be difficult to establish.

3.4 Tests may not be equal for all modules

Moisture is known to cause corrosion of PV modules and can also cause delamination and a number of other problems. Although humidity varies dramatically with climate, an additional challenge for quantifying its importance is the wide range of geometries used in PV modules.

The meaning of the standard damp-heat test applied as part of PV module qualification [8, 9, 11] is complicated, because the high humidity exposure causes much higher absolute moisture levels within the module than will be experienced in the field. Even when a module is mounted such that it will be at 85°C, the relative humidity within the encapsulant, if in equilibrium with its environment, is expected to be only between 1% and 5%. Thus degradation modes requiring both humidity and temperature may be unrealistically accelerated.

At the same time, during the relatively short time (1000 h) of the damp-heat test, not all portions of the PV module become saturated by moisture, as shown in Fig. 7. Testing of a glass-glass module construction (solid line labeled “40-cm square” in Fig. 7) is expected to give a very different effective acceleration factor compared to the same test on a glass/polymeric-backsheet module (similar to the 15-cm square curve in Fig. 7), which are both different from a real outdoor exposure. Yet, the standard qualification tests apply the same damp-heat test to all module constructions. It may be decades before we can confidently understand the relevance of the 1000-h test to predicting long-term performance in the field in a variety of locations for different module types.

4 INTERNATIONAL EFFORTS

The sharing of data internationally can help the community to better understand the importance of climate on the lifetime of PV modules. Sections 4.1 and 4.2 describe two efforts that have just been initiated and will become better defined in the next year or two.

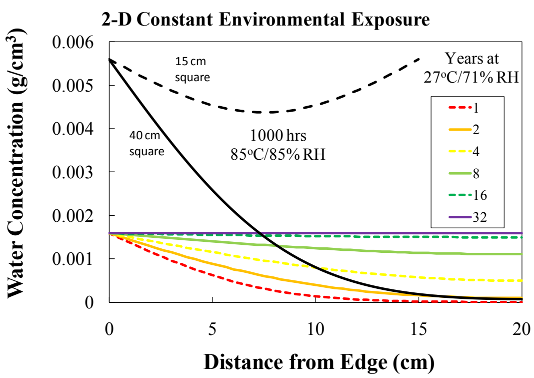

Figure 7: Comparison of moisture ingress profile modeled for exposure in damp-heat test chamber compared with simulated field exposure [12].

4.1 Quality Assurance Task Force

As described elsewhere in these proceedings [13], an international effort has been initiated to develop accelerated tests that can help to quantify wear-out mechanisms in PV modules related to various types of stresses. This effort is designed to differentiate modules according to their durability and to clearly communicate that information to PV customers.

One important aspect of the proposed rating system is documentation of the test results on each module. Twenty to thirty years from now, researchers will be able to correlate the observed longevity in the field with the initial testing, giving a basis for future predictions for that location.

4.2 Collective documentation of module outcomes

A separate international effort has been initiated under the IEA Task 13 to standardize the collection of information about modules in the field. An inspection checklist has been created to identify the types of module changes that are observed. By aggregating this information in a standard format, researchers will be able to quickly evaluate the statistics, allowing identification of trends by location or technology type.

5 SUMMARY

Some PV module manufacturers are beginning to differentiate their products according to aesthetics, mechanical strength, and the confidence with which the initial and long-term performance can be predicted. There is also interest in differentiating products according to their long-term reliability. As PV markets expand into locations with diverse climatic stresses, the challenge of being able to accurately predict long-term performance will increase. This challenge is exacerbated by the wide variation of stresses that may be encountered, by the complexity of many degradation mechanisms, and by the diversity of module designs that must be tested. International efforts to tackle these challenges are laying the foundation for improved understanding in the years to come.

6 ACKNOWLEDGMENTS

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