STABILIZATION AND PERFORMANCE CHARACTERISTICS OF COMMERCIAL AMORPHOUS-SILICON PV MODULES

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ABSTRACT

The successful commercialization of any new photovoltaic technology is difficult. Understanding the product's performance and aging characteristics is a prerequisite for the manufacturer. Amorphous-silicon thin-film modules are now in commercial production, and their market penetration is being limited to some degree by a lack of understanding of environmental influences that impact system design and operation. This paper summarizes our detailed performance characterization of multiple modules from four different manufacturers over several years of continuous outdoor exposure in Albuquerque, NM. Common stabilization characteristics have been observed for both tandem and triple-junction modules of recent vintage, and the influences of solar spectrum and seasonal (thermal) annealing have been clearly identified. Implications for system performance modeling are presented.

INTRODUCTION

Several factors influence the performance of all photovoltaic modules, including solar irradiance level, operating temperature, soiling, solar spectrum, and the angle-of incidence at which sunlight strikes the module. For a-Si modules the situation is further complicated in that the a-Si material properties also change, somewhat reversibly, with the solar irradiance and operating temperature history of the module. As a result, a great deal of research has been conducted in an attempt to explain the performance characteristics of a-Si modules and systems [1, 2, 3, 4, 5, 6]. A performance model based on degradation mechanisms with two different activation energies has been proposed to explain the rapid initial degradation and the seasonal oscillation in performance observed in the field [1]. The cumulative effect of environmental factors on performance of a-Si modules as they age is commonly referred to (somewhat euphemistically) as the "stabilization" process. Analysis of hundreds of performance measurements on modules continuously exposed outdoors enabled us to separate the effects of various factors influencing a-Si module performance, resulting in an improved understanding of the performance characteristics that can be expected in different system applications. The complexity and uncertainty associated with system design using a-Si modules will be minimized when the influences of all relevant factors on module performance have been quantified.

TEMPERATURE COEFFICIENTS

The term "temperature coefficient" is widely used, and often confused. The classic definition of the temperature coefficient for a parameter relates to the change in that parameter when only temperature is varied, other factors that might influence the parameter being held constant. Temperature coefficients for I_{sc}, I_{mp}, V_{oc}, V_{mp}, P_{mp}, FF, and Eff can all be determined for photovoltaic modules. Typically, measurements are made at conditions that mimic the ASTM Standard Reporting Condition (1000 W/m^2, AM1.5). The engineering units used to report temperature coefficients vary and might be A/°C, V/°C, W/°C, 1/°C, %/°C, or ppm/°C.

At Sandia, module temperature coefficient measurements are performed outdoors under stable environmental conditions in order to mimic actual operating conditions [7]. The module is first shaded to reach a temperature near ambient, then it is quickly uncovered and current-voltage measurements are recorded as the module warms to operating temperature. Regression analysis is used to determine temperature coefficients for I_{sc}, I_{mp}, V_{oc}, and V_{mp}; coefficients for other parameters (P_{mp}, FF) are derived from these four values.

Table 1 gives measured temperature coefficients believed to be representative for a-Si modules from the four manufacturers (A, B, C, D) included in this study. Coefficients for single-junction (1-a-Si), tandem-junction (2-a-Si), and triple-junction (3-a-Si) modules are given. The units for the four basic coefficients have been reduced to 1/°C, and the temperature coefficient for maximum-power (P_{mp}) is given in the commonly quoted units of %/°C. In summary, the P_{mp} coefficients for a-Si modules are negative but about half the magnitude of typical crystalline silicon modules, about -0.25 %/°C for a-Si and about -0.5 %/°C for c-Si.

Table 1. Typical temperature coefficients measured for "stabilized" a-Si modules, c-Si module for comparison.

Type	dI_{sc}/Dt (1/C)	dI_{mp}/dT (1/C)	dV_{oc}/dT (1/C)	dV_{mp}/dT (1/C)	dP_{mp}/dT (%/C)
A, 3-a-Si	.0008	.0015	-.0046	-.0044	-.30
B, 2-a-Si	.0006	.0011	-.0033	-.0034	-.23
C, 2-a-Si	.0009	.0015	-.0045	-.0044	-.30
D, 1-a-Si	.0008	.0012	-.0037	-.0039	-.28
c-Si	.0003	-.0005	-.0039	-.0048	-.52

SOLAR SPECTRAL INFLUENCE

Another factor that can influence the daily and seasonal performance of a-Si modules is the spectral content of sunlight that changes continuously over the day. Test results previously reported clearly illustrated the effect of changes in solar spectral irradiance on the performance of different PV modules [5]. Test procedures have been developed that relate the spectral influence to the time-of-day dependent absolute air mass (AM_a) while ignoring the more subtle and random influences of atmospheric factors such as water vapor content, aerosols, and turbidity [8]. Since AM_a can be calculated from site altitude and the sun's elevation angle this approach makes it easy to address solar spectral influence in PV system design models.

Daily Influence

Figure 1 illustrates the solar spectral influence measured for typical a-Si modules related to absolute air mass. Measurements for a typical crystalline silicon module are shown for comparison. The relative performance of the a-Si modules is highest at low air mass conditions representative of mid-day operation, while the c-Si module peaks for early morning or late afternoon conditions. The empirical relationship shown in Figure 1 was normalized to a value of one at the standard AM_a=1.5 condition. The shape of the AM_a relationship depends on the spectral response characteristics of the photovoltaic module, in particular, the spectral response at long (red) wavelengths relative to that at short (blue) wavelengths. If the blue response is low and the red high, then higher relative I_{sc} will result at large AM_a. Amorphous silicon modules show decreasing relative I_{sc} as air mass increases because their spectral response is limited to wavelengths less than about 900 nm.

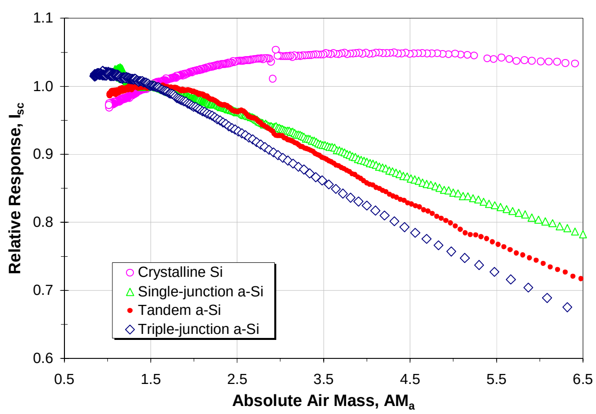

Fig. 1. Measured solar spectral influence on a-Si module I_{sc} related to air mass; c-Si module shown for comparison.

Seasonal Influence

The effect of solar spectral variation can also be quantified on a seasonal or annual basis. Using the daily influence of solar spectrum illustrated in Figure 1, the seasonal influence can be calculated using a PV system design model and hourly-average solar resource data as given in the National Solar Radiation Database [9]. The performance model developed at Sandia [10] was used to quantify the seasonal influence of solar spectrum for an a-Si module fixed at latitude-tilt in Albuquerque, NM. Figure 2 shows the ratio of average-daily energy production, with spectral influence included, divided by the energy production assuming no spectral influence (AM_a=1.5). For a-Si modules, this analysis indicated a 2% enhancement in performance in mid-summer relative to the AM_a=1.5 spectrum, and a 5% decrement in mid-winter. In Albuquerque for a module at latitude-tilt, the energy-weighted air mass is 1.1 on a mid-summer day and 2.3 on a mid-winter day. Tracking or other module orientations (horizontal, vertical) will result in different seasonal influences for solar spectrum, also shown in Figure 2. For 2-axis tracking, the energy-weighted air mass is 1.5 on a mid-summer day resulting in a relative spectral influence near 1.0.

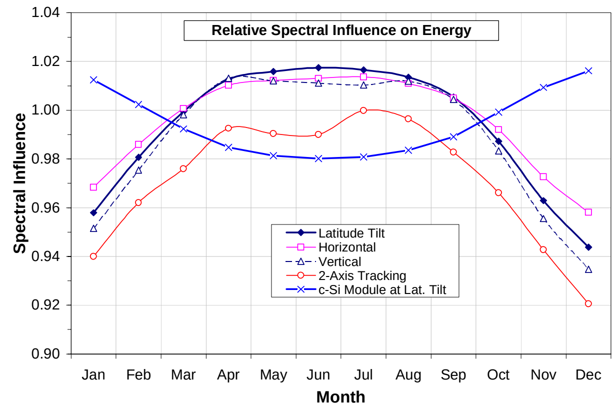

Fig. 2. Ratio of energy produced with spectral influence to energy produced without spectral influence (AM_a=1.5) for an a-Si module in Albuquerque. Different module orientations and a c-Si module are shown for comparison.

MEASURED STABILIZATION CHARACTERISTICS

A large database of performance measurements has been accumulated at Sandia and is being used to analyze the stabilization characteristics of commercial a-Si modules during continuous outdoor exposure. Figure 3 illustrates data recorded over a 5-yr period, where each point on the chart resulted from regression analysis of several hundred I-V curves measured during that day. Our analytical procedure accounted for the affects of irradiance, temperature coefficients, and solar spectrum in order to determine performance at ASTM Standard Reporting Conditions [11]. Thus, the data shown in Figure 3 do not contain the influence of seasonal variations in solar spectrum. In order to directly compare different a-Si technologies, the maximum-power (P_{mp}) values were normalized by dividing by the value obtained on the module's first day of outdoor exposure. The figure shows normalized P_{mp} for thirteen a-Si modules from four manufacturers as measured chronologically. The modules shown represent single-junction, tandem-junction and triple-junction a-Si technologies. With one exception (#1701 had resistive load), modules were "aged" outdoors in an open-circuit condition. The modules had not been previously exposed outdoors or light soaked in the laboratory.

Fortunately, many of the characteristics observed were common to all the modules evaluated. If "stabilized" is defined as the power level achieved after about 1-yr exposure and midway between seasonal oscillations, the following general observations can be made:

1. Previously unexposed a-Si modules showed an initial rapid degradation in power over the first 6 months,
2. The majority of the modules tested reached a "stabilized" power level about 20% below the initial (1^{st} day) power after about 1 year,
3. Modules initially exposed at different times of year stabilized at the same level,
4. The effect of seasonal oscillation (thermal annealing) was clearly evident in all modules tested accounting for about ±4% variation from the "stabilized" level,
5. Module operating temperatures >40 °C was needed before the thermal annealing process occurred,
6. It is not known for how many years the seasonal thermal annealing process will persist,
7. All performance parameters were affected similarly during the outdoor stabilization process, degrading as follows: I_{sc} by about 6%, I_{mp} by about 13%, V_{oc} about 5%, V_{mp} about 8%, and P_{mp} by about 20%,
8. Modules in early stages of process development stabilized at 25 to 35% below the initial power.

THERMAL ANNEALING

Thermal annealing is the term used to describe the recover of some or all of the initial performance of a-Si modules subsequent to extended periods at elevated temperature. Assuming as proposed by others that degradation in the initial performance of a-Si modules during outdoor exposure can be adequately represented by two reversible mechanisms with different activation energies, then it should be possible to relate these phenomena to site-dependent environmental parameters. Our outdoor performance measurements on commercial a-Si modules tend to support this two activation-energy model. The initial rapid degradation in a-Si module performance has been related to a high activation energy mechanism requiring high module temperatures (>80 °C) to reverse the process [1]. Although rare in the field, it is possible that module temperatures above 80 °C could occur, perhaps for some roof-mounted applications. It is worthy of note that today's module qualification test procedures use a 90 °C thermal annealing step to return a-Si modules to their initial performance following accelerated aging procedures [12]. The second degradation mechanism has a lower activation energy, and our data indicated it can be reversed at lower module temperatures (>40 °C).

Our data indicated that the maximum benefit gained by reversing this second degradation mechanism was about 7% from winter to summer. The summer improvement "saturated" at about a 7% improvement even though daily operating temperatures were well above 50 °C. Thus, the benefit to be gained by seasonal thermal annealing is likely to be site or application dependent. For applications with daily module temperatures exceeding 40 °C, the benefit of seasonal annealing should be realized. Cold climates with daily module temperatures below this level will not result in thermal annealing, and climates such as Albuquerque will produce the seasonal oscillations observed in Figure 4.

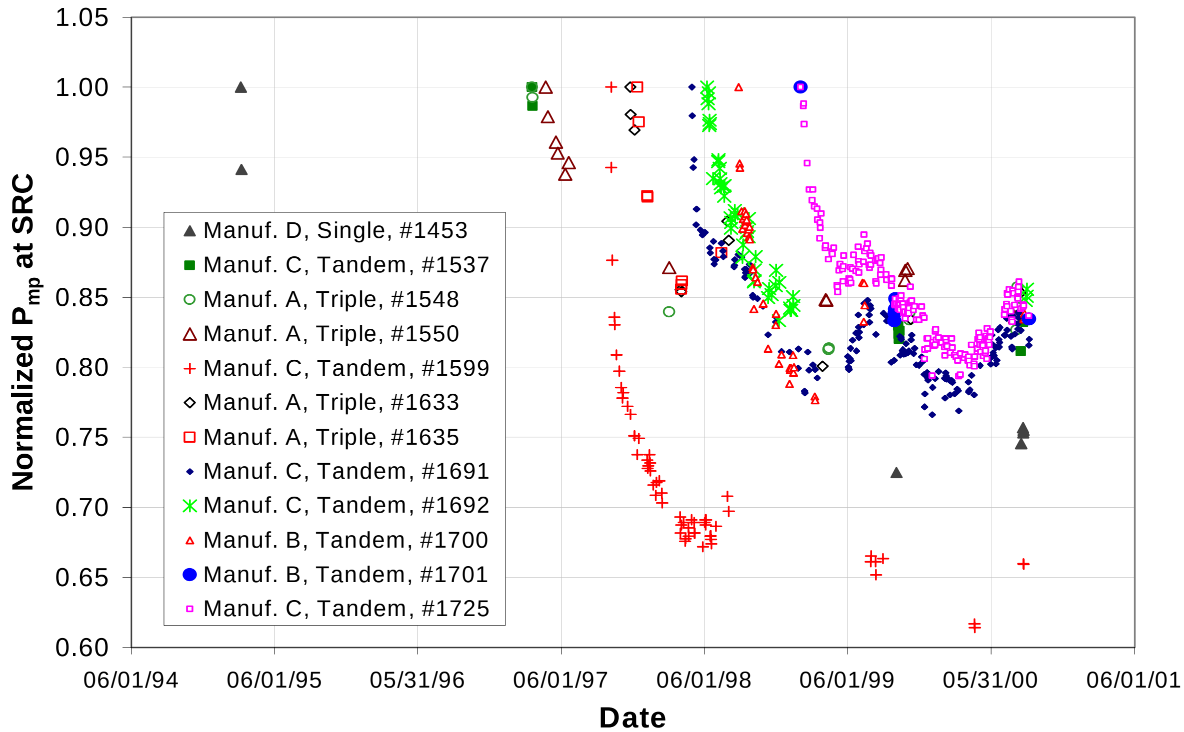

Fig. 3. Normalized performance at SRC for 13 a-Si modules from 4 manufacturers measured over a 5-yr period of continuous outdoor exposure in Albuquerque, NM. (Module #1599 was a developmental module prior to process optimization by Manufacturer C.)

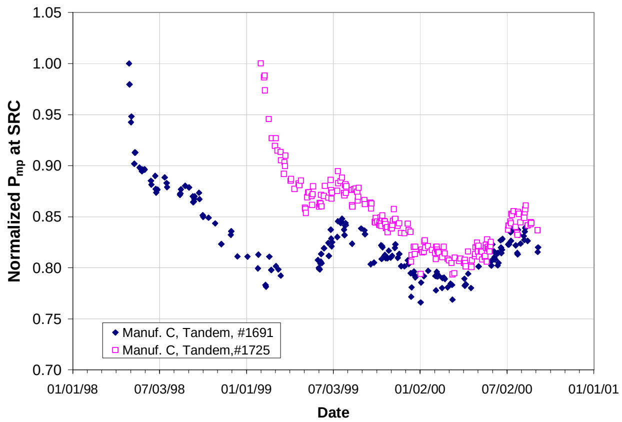

Fig. 4. Seasonal (thermal) annealing is clearly evident in two tandem-junction a-Si modules during continuous outdoor exposure in Albuquerque, NM. The additive influence of solar spectral variation is not included in the data displayed.

DISCUSSION

Significant debate has occurred in the literature over the last few years regarding the influences of thermal annealing versus solar spectrum on the performance of a-Si photovoltaic systems. Some have argued that seasonal patterns observed in system performance were due to elevated summer temperatures causing thermal annealing, and others contended that relatively higher performance in summer was due to the more favorable (blue rich) solar spectrum. Our investigation indicated that both factors play a significant role in observed system behavior. For a module at latitude-tilt in Albuquerque, seasonal thermal annealing resulted in a 7% higher performance in summer relative to winter. Superimposed on this thermal effect is the spectral influence which resulted in 2% higher energy production in summer relative to the standard AM_a=1.5 spectrum, and 5% lower energy production in winter. The net result is module efficiency that is about 13% higher in summer than winter, consistent with field experience for a-Si systems.

One objective of our effort is to develop a method for relating the stabilization characteristics observed for a-Si modules to the site-dependent and application-dependent temperature-history of the module. Solar resource and meteorological data have also been recorded over the entire duration of our module exposure. So, analyses are now in progress in an attempt to develop a model that relates the thermal annealing process to cumulative exposure at different operating temperatures and solar irradiance levels. Currently, a model with three additive components is envisioned; a component with exponential decay to account for the initial high-activation-energy degradation, a sinusoidal component related to module temperature history to account for thermal annealing, and a sinusoidal component related to air mass to account for solar spectral variation.

CONCLUSIONS

Extensive outdoor testing of a variety of commercial a-Si modules over a period of five years has provided an improved understanding of the long-term performance characteristics of these modules. Both thermal annealing and solar spectral variation have been demonstrated to play a significant role in the seasonal oscillation in performance observed in many a-Si photovoltaic systems. Long-term test results appear support the two activation-energy model for thermal annealing proposed by other researchers. A more comprehensive report documenting the results of our long-term test is currently in progress.

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