PERFORMANCE OF BP SOLAR TANDEM JUNCTION AMORPHOUS SILICON MODULES

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ABSTRACT

BP Solar is continually analysing performance data on various PV technologies in a long term test program. Recent data obtained from one of these sites indicate that the seasonal variations observed in amorphous silicon modules and arrays may not be due to thermal annealing and solar spectrum shifts as previously reported in the literature. A Millennia array in Germantown, MD, USA with a high tilt angle exhibits two seasonal variations a year with peaks in the spring and fall coinciding with peaks in the plane of array (POA) irradiance, not with variations in temperature or solar spectrum. Additional data will be presented in support of the hypothesis that the seasonal behavior of some of today's amorphous silicon modules is not due to thermal annealing during high temperature operations.

INTRODUCTION

There have been a number of reports of amorphous silicon modules and systems showing a seasonal variation in performance [1][2][3][4] with a maximum output in the summer and a minimum in the winter. One particular example from the Sandia work [4] is shown in Figure 1. This figure shows the instantaneous dc Performance Ratio translated to standard test conditions (1000 watts/m^2, 25 C and AM1.5 spectrum) versus time for one BP Solar tandem junction amorphous silicon module.

The variations in efficiency of a-Si modules as a function of the time of the year have been attributed to:

- Spectral effects, because a-Si has a much narrower spectral response than crystalline silicon and therefore does not perform as well in red rich light; and
- Thermal annealing, because it has been reported that at high temperatures some of the light induced degradation in a-Si can be annealed out

In this paper we will provide data that shows that neither of these explanations are sufficient to describe the observed field behaviour for BP Solar tandem junction a-Si modules.

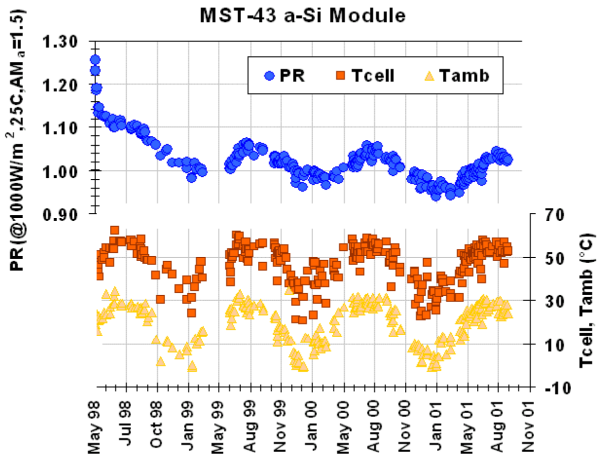

Fig. 1. Performance Ratio (PR) for a tandem junction amorphous silicon module against time and temperature.

DATA COLLECTION AND ANALYSIS

BP Solar has been conducting a PV module field performance study for a number of years. The approach to data collection and analysis performed were described in detail by the authors in two previous papers [5][6]. The data are all taken from grid tied arrays or modules with either Maximum Power Point Trackers (MPPTs) or swept IV curves to determine the energy output at the maximum power point. Data are typically plotted as Final Yield YF and Performance Ratio PR to allow for comparison of arrays and modules of different sizes.

The following definitions are used throughout this paper:

Final Yield **YF** = ΣWh / Pmax / time
Performance Ratio **PR** = ΣWh/ Pmax / ΣInsolation

An improved model for Final Yield was previously published by the authors [5].

$$\mathbf{YFycalcx} = \Sigma Irr*(A_x+B_x*\Sigma Irr+C_x*avgTamb+D_x*avgWS)-E_x \quad (1)$$

$$YFerr_x = (\Sigma Ymeasured_x^2-\Sigma Ycalc_x^2)^{0.5} \quad (2)$$

Where ΣIrr = irradiance, avgTamb = average ambient temperature, avgWS = average Wind Speed. Subscript x denotes measurement frequency, h=hourly, d=daily etc.

Equation (1) can be used to analyse measurements over different frequencies from instantaneous through hourly, daily or monthly sums and averages. A multivariate regression analysis optimises the five empirical parameters (A_x-E_x) to the module performance to minimise $YFerr_x$ in equation (2).

A typical plot of daily Performance Ratio versus time for two modules, one a single junction amorphous silicon module and the other a multi-crystalline silicon module are shown in Figure 2 along with the irradiance and ambient temperature. Note that, as reported previously by others, the amorphous silicon module has peaks of higher performance during the summer, and valleys of lower performance during the winter. The multi-crystalline module, like all crystalline silicon modules being monitored at this site, has exactly the reverse performance with the best performance ratio during the winter and the worst during the summer. The peaks in performance of the a-Si module coincide with the peaks in ambient temperature leading to the conjecture that temperature is a factor in this seasonal behaviour. However, note that the performance ratio also tracks with peaks in irradiance. The seasonal variations in performance ratio for the crystalline silicon modules is attributed to its larger negative temperature coefficient of peak power.

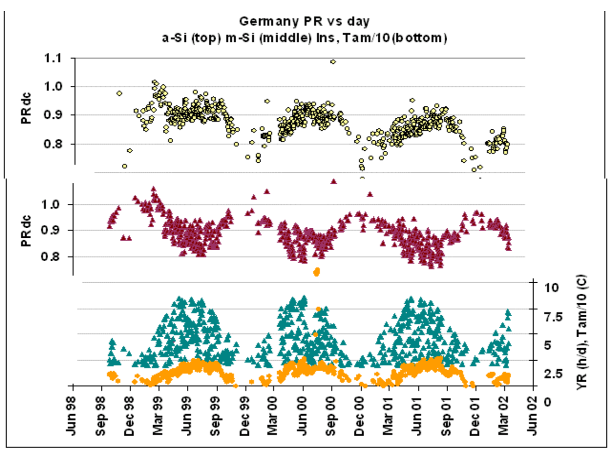

Figure 2: Daily Performance Ratio of a single junction a-Si module and a multi-crystalline silicon module for three years in Germany.

MONTGOMERY COLLEGE

SEPA (formerly UPVG) has been monitoring 3.25kWp of a 26kWp Millennia array at Montgomery College in Germantown, MD, USA since its commissioning in 1998. The PV array was mounted on an old solar thermal structure (tilted at 55° to the south to maximize hot water production in the winter whereas a tilt of 35° would have been better for PV). The inverter is an Omnion 3.4 kilowatt series 2400 with MPPT.

This was one of the earliest large arrays in which the tandem junction a-Si Millennia modules were installed, so it has been carefully monitored by BP Solar to evaluate the performance of this product. Figure 3 shows the performance ratio of the Montgomery College array plotted as a function of time.

The PR varies around 80% on high insolation days and has been stable for almost 4 years. A sinusoid has been added to indicate how the PR on sunny days varies throughout the year. Note the peaks and troughs coincide with the high and low peaks of POA insolation in spring and autumn with a twice yearly frequency. The temperature however, has a sinusoidal behaviour with a one year period. Minima in array performance occur at the lowest and highest ambient temperatures.

The spring and autumn peaks in performance ratio at Montgomery College cannot be explained by thermal annealing. The modules will be no hotter and probably cooler in spring and autumn than they will be in the middle of the summer, where it has a minimum in performance ratio.

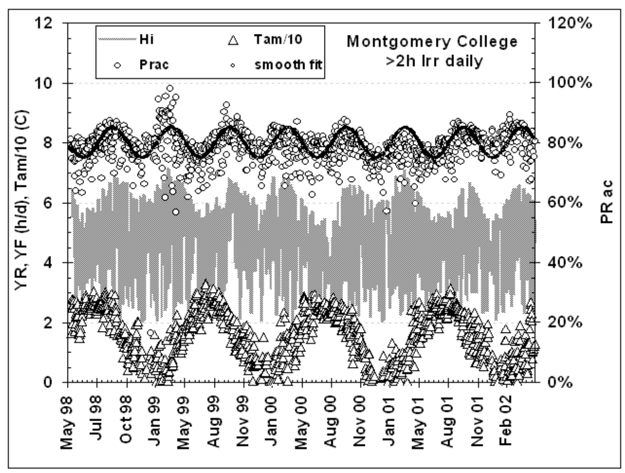

Figure 3: Daily average PRac at MD, USA Millennia site 1998-2002.

If there were a long term annealing effect the performance in the autumn should be better than in the spring. To evaluate this the Final Yield and Performance Ratio (for each season Spring, Summer, Autumn and Winter) has been plotted versus daily insolation in Figure 4. Most of the variation in Performance ratio is due to the daily POA insolation and instantaneous temperature, not to a seasonal effect. The Final Yield points have been fitted to one curve without any seasonal dependence. Most of the variation in Final Yield is due to insolation with little dependence on ambient temperature.

The other standard explanation for seasonal variation is the change in spectrum. However, spectral analysis is used to show why a-Si has lower performance in the winter when the sunlight tends to be red rich [4][7] or on very cloudy days when the spectrum appears to be blue rich. Indeed the difference in performance expected from differences in spectrum between spring and summer or summer and autumn are small. In addition, the oscillations in performance ratio is caused by the days with the largest amount of sunlight in each season not the low light level days, when we might expect spectral effects to be most severe. If the data for all days with less than 2 or even 4 sun hours is removed from the data base there is no effect at all on the periodicity or magnitude of the oscillations in PR. None of the spectral effects appear to be able to explain why the Montgomery College array would have a minimum every summer with peaks in spring and autumn.

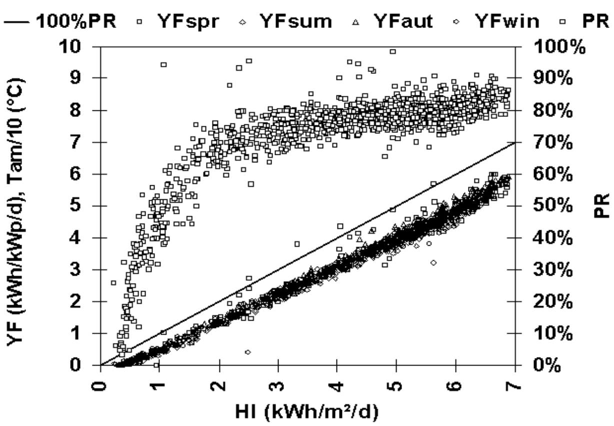

Figure 4: Daily average PR and YF versus Insolation H_I, MD, USA Millennia site.

The Empirical equations defined in references [5] and [6] gave a good fit (mostly <±4%) to the performance (PR and YF) of many types of module technologies including a-Si. In an attempt to understand the small periodicity of the Montgomery College array measurements the fitting procedure was applied to each of the 12 months individually, averaged over the years 1998 to 2002.

Figure 5 shows how the parameters vary when fitted month by month. The A parameter follows the average Irradiance quite well, indicating a super-linear dependence. While part of this super-linearity may be because bright days tend to have bluer spectra than dull days, this effect is not large enough to explain the differences between spring, summer and fall at Montgomery College. It appears that for these tandem junction a-Si modules the peak power increases super-linearly with irradiance (with no change in spectrum) over the typical span of irradiances seen on sunny days.

We have several hypotheses as to why the peak power of tandem junction a-Si modules could depend super-linearly on irradiance:

- Since a-Si is photoconductive the bulk resistance may be much higher at lower irradiances.
- Shunting and high diode factor lead to lower fill factors at lower irradiances.
- Junction matching (top to bottom) may depend on irradiance level as well as on spectrum.
- Inverter/BOS efficiency may be higher at higher light levels.

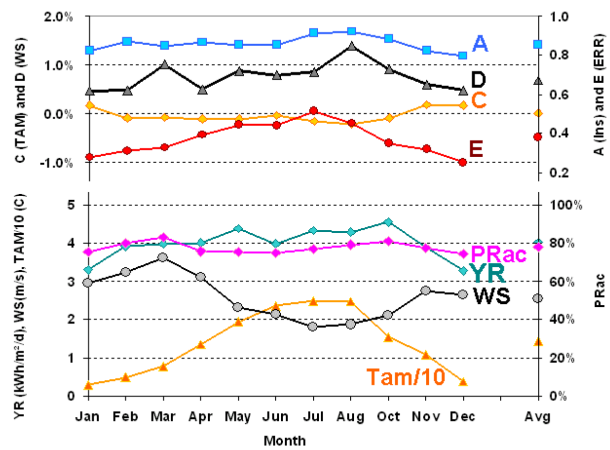

Figure 5 Reanalysing the Empirical coefficients each month (top) and the average Measurements and Meteorological data (bottom) for Montgomery College.

The E parameter (the constant loss term) follows a saw tooth shape over the year with a maximum in July and a minimum in December. The constant loss is proportional to the number of sun hours, because the inverter has a larger constant loss when on than when off.

Looking at a finer resolution than previously, we can see that some of the parameters are interrelated, for example the Wind Speed factor will have a larger effect when the difference between module and ambient temperature is the greatest. This will happen when the irradiance is higher.

THERMAL EFFECTS

There have been several reports of positive temperature coefficients for amorphous silicon arrays [2][7]. Indeed if we analyzed the Montgomery College data by month we would find that during the winter months the temperature coefficient of power is positive, while the rest of the year it is negative. However, when you directly measure the temperature coefficient of power for an amorphous silicon module the result is a negative value usually between –0.2 and –0.3%/C [4], about one half the value normally observed for crystalline silicon modules.

Measurements have been performed on several pairs of modules of different technologies in different climates tilted at 90° where one of the pair was thermally insulated with 150 mm of building insulation material (to mimic building cladding) while the other had a ventilated back. In all cases the performance of the insulated module fell with respect to the ventilated one as the temperature rose. So insulating an a-Si module to run hotter leads to a lower power than an open backed module. However, the insulated a-Si module will lose a smaller fraction of its power than a crystalline silicon module would under the same conditions.

So why does the data from some a-Si arrays yield a positive temperature coefficient? There are three possible reasons for this:

1. Power conditioning [8]: Often the peak conditioning system cannot track the peak power of the PV array to the extremes of array performance. So in either the cold winter or hot summer the measured output voltage in locked in by the peak power tracking and is therefore independent of temperature. In this case the result will likely be a small positive temperature coefficient for power.
2. Spectral effects [7]: The bluer spectrum found at higher irradiances and temperatures, results in higher quantum efficiency for a-Si modules. So on sunny warm days during the winter the spectrum is better matched to the a-Si band gap than on the cool cloudy days and the modules are more efficient. So when analyzed the data yields a positive temperature coefficient of power.
3. Peak power dependence on irradiance: Independent of the spectral changes, it appears that in some a-Si modules the power increase super-linearly with irradiance, the same process discussed to explain the spring and autumn peaking in performance ratio at Montgomery College. So on the sunny warm days the modules are more efficient and when analysed the data yields a positive temperature coefficient of power.

CONCLUSIONS

This paper has shown that seasonal dependencies of amorphous Si arrays can be explained without recourse to thermal annealing and may be just a function of instantaneous irradiance and temperatures.

The empirical equations from reference [5] can be used to study measurements at monthly intervals. The results of this analysis were the determination that:

- The output power has a super-linear dependence on irradiance.
- The constant loss term is proportional to the day length or number of sun hours as the system electronics has a larger constant loss when producing electricity than when in the standby mode.
- There is an interrelation between the effect of wind speed and the ambient temperature.

Finally, amorphous Si modules always have a negative temperature coefficient of power. Field results that indicate a positive temperature coefficient of power for certain time periods are the result of BOS, spectral shifts and non-linear irradiance behaviour resulting in larger changes than the temperature coefficient of the modules.

ACKNOWLEDGEMENTS

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