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INVESTIGATING THE SEASONAL PERFORMANCE OF AMORPHOUS SILICON SINGLE- AND MULTI-JUNCTION MODULES

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ABSTRACT

The seasonal performance fluctuations observed in amorphous silicon solar cells are investigated. The dominant forces driving the increased efficiency in summer are identified, from long-term measurements, to be thermal annealing and spectral variations. A method for correcting for changes in the incident spectrum is applied in order to correct for the seasonal changes. In a second step, the fill factor is investigated in order to establish the magnitude of thermal annealing seen by these devices. The magnitude of each effect is investigated.

1 INTRODUCTION

Amorphous silicon (a-Si) modules exhibit an unusual performance variation in the course of the year in that they typically obtain maximum operating efficiency in the summer time, when average module temperatures are highest, as illustrated in Figure 1. The reasons for this behaviour are not fully understood, and this work aims to contribute to this topic by investigating the long-term performance of several amorphous silicon modules operating in two different locations.

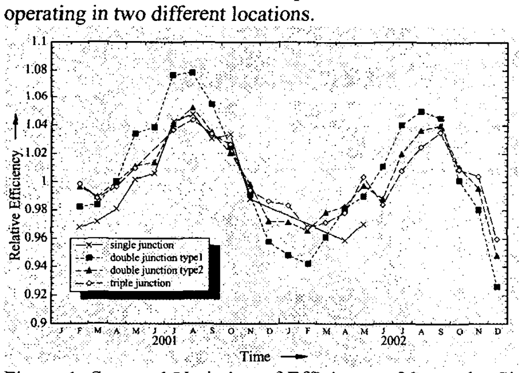

Figure 1: Seasonal Variation of Efficiency of Several a-Si Modules Deployed at NREL.

The data used in this study are taken from long term measurements conducted in Golden, Colorado and Loughborough, UK. Both systems carry out full I-V scans in regular intervals (every 15 min in Golden and every 10 min in Loughborough). Additionally, both sites measure the incident spectrum using spectroradiometers. The NREL system is an array-based system which measures the incident spectrum up to a wavelength of 1100 nm and integrates for every minute. The system operated at CREST is monochromator based and measures the incident spectrum every 10 minutes up to a wavelength of 1700 nm.

2 SEASONAL EFFECTS ON PERFORMANCE

Two reasons for the observed behaviour are likely: a shift in the incident spectrum [1] or a temperature induced annealing of Staebler-Wronski degradation [2]. It will be attempted in the following to estimate the magnitude of these effects. The two sites in this investigation have very different climates. The NREL site in Golden experiences much higher irradiances and temperature variations than CREST's test system in Loughborough. The variations of the environmental parameters to be investigated in this paper are shown in Figure 2.

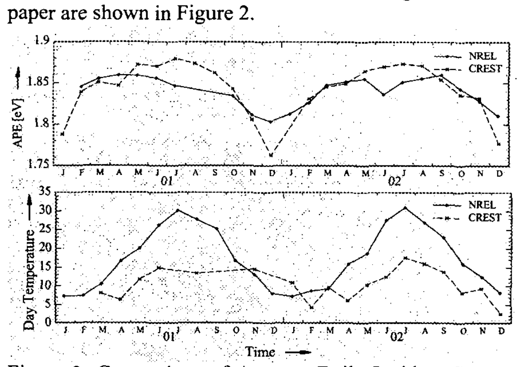

Figure 2: Comparison of Average Daily Incident Spectra and Ambient Temperatures for Each Test Site.

The parameters shown in Figure 2 are calculated for daytime only, between sunrise and sunset, and derived on a monthly basis. The average daytime ambient temperature in Golden varies significantly, spanning 25°C in the course of a year and reaching nearly 30°C, while there is only half as much variation in Loughborough data exhibiting only 15°–17°C maximum. The spectral variation may be characterised by the average photon energy (APE), which is described in more detail in [3]. A high APE indicates blue-rich irradiance, while low APE indicates a red shifted spectrum. An APE in the band 300-1100 nm (as for the NREL spectroradiometer) of 1.846 eV is equivalent to AM1.5 conditions. The values shown in Figure 2 are calculated for spectral irradiance up to 1100 nm in order to ensure consistency between the sites. The impact of the APE is not too obvious, but it is device independent. The seasonal variation shown for Loughborough corresponds to a change in the useful fraction of light for single-junction a-Si devices of ~15% with respect to the average of all measurements [4]. The higher APE in Loughborough data in Summer is likely due to elevated diffuse component over the direct which tends to be enhanced in the blue and reduced in the red

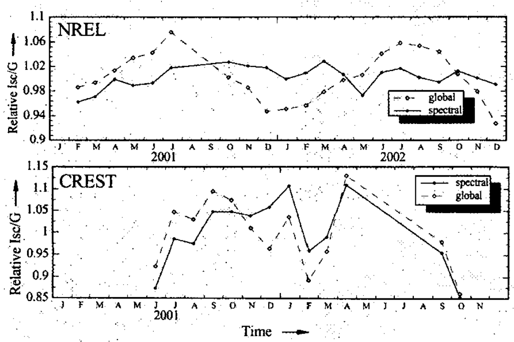

Figure 3: Seasonal Variations of the Photoresponse for Double-Junction Devices at NREL and at CREST.

portions of the spectrum when ratios of the overall irradiance are considered.

In order to investigate the magnitude of each of the effects, a simple estimation of the influence of spectrum and stabilized state is used. The efficiency η is formulated as:

$$\eta = \frac{I_{SC} V_{OC} FF}{G A_M} \tag{1}$$

where I_{SC} is the short-circuit current, V_{OC} is the open-circuit voltage, FF is the fill factor, G is the incident global irradiance measured in the same plane-of-array and A_M is the aperture area of the module. The I_{SC}, V_{OC} and FF all depend on the irradiance, incident spectrum, temperature and stabilized state. It is assumed in the following that the short-circuit current is mainly affected by the spectrum, while the predominant influence of degradation is manifest on the FF. This neglects the effect of temperature but this has been shown to be a small influence only.

3 INFLUENCE OF THE SPECTRUM

The initial question to answer is: are there seasonal changes in the short-circuit current that can be associated with changes in the spectrum? An indication is gauged by the behaviour of the photoresponse, defined as the ratio of I_{SC} over the irradiance. In Figure 3, the variations of the monthly averages of the photoresponse data are shown. The I_{SC} data are corrected in two different ways, once using the broadband irradiance, then again using the useful irradiance.

It is apparent from Figure 3 that the seasonal change is much less pronounced if the shape of the spectrum (in form of the useful irradiance) is taken into account. This is a clear indication that there is a significant effect of the spectrum on the short-circuit current. The CREST data occurs on a much shorter time scale, the module was installed in June 2001 and thus will experience its initial degradation first, resulting in a much more erratic behaviour.

The behaviour of the photoresponse in multi-junction devices is more complicated and needs a more sophisticated approach for correction. The dominant factor in determining the short-circuit current is the irradiance, which will mask typically smaller spectral effects. The behaviour of the photoresponse with varying APE of light is investigated in the following.

It has been shown that the short-circuit current of single- and multi-junction a-Si devices can be modelled using the following polynomial formula[5]:

$$I_{SC} = f(APE) \cdot G \tag{2}$$

where f(APE) is a polynomial function describing the effect of sub-cell mismatch in the stacked multi-junction and the availability of spectrally useful light. The polynomial uses the pyranometer irradiance as this is commonly available. In order to investigate sub-cell mismatch one would have to correct to the spectral content of the light first.

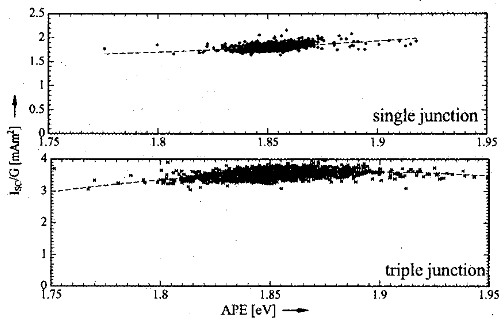

Figure 4: Influence of the Spectrum on the Short-Circuit Current of Single- and Triple-Junction Devices

The effect of the spectrum is shown in Figure 4 for a single- and a triple-junction module. Both devices are fully stabilized. In order to generate the graphs, the data was limited to daytime hours between 9:30 and 14:30, module temperatures above 25°C, and restricted variance between the pyranometer measurements and integrated spectroradiometer data to less than 5% off from the linear correlation between the two. A second order polynomial was fitted through the scatter plots as a guide for the eye and for the following analysis. The single-junction module shows a nearly linear behaviour, as expected. With increasing blue spectral fraction of the light, the useful spectral content increases and consequently so does the efficiency. The triple junction on the other hand is much less linear. This module has a wider spectral response because the bottom junction contains germanium, which widens the spectral response of the cells out to wavelengths around 990 nm. For APE values deviating from STC conditions, there can be larger decreases in the I_{SC} for stacked triple-junction cells than for single-junction cells.

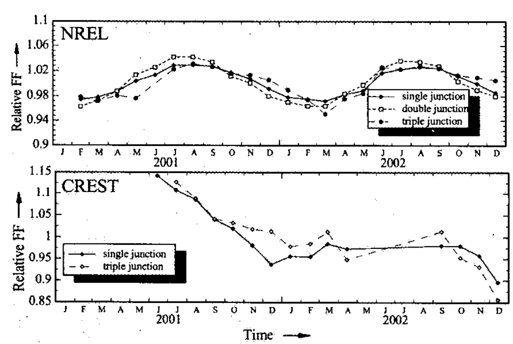

Figure 5: Seasonal Variation of the FF at NREL and CREST.

4 INFLUENCE OF DEGRADATION

It has been shown that the fill factor is a likely indicator of the stabilized state of a-Si modules [2]. Evidence that it exhibits seasonal variations is presented in Figure 5, which depicts average FF data plotted by month for times between sunrise and sunset for all three device configurations. The devices at CREST are exhibiting significant degradation in the first months of operation before a slight recovery in summer and further reduction in winter. The devices operated at NREL are fully stabilized and exhibit higher values in summer months and lower values in winter. It is unlikely that temperature could be the sole cause for this, as illustrated later in Figure 6. A second possibility that is also ruled out is that the increases in FF are caused by increases in irradiance, as often seen with crystalline silicon devices. This is not the case for a-Si, as the FF decreases with increasing irradiance, as shown in Figure 6 for a triple-junction module deployed at NREL.

Figure 6 is a composite graph portraying FF data corrected to reference temperature (25°C), read from the left-hand abscissa, and average module temperatures, read along the right-hand axis, plotted against irradiance and segregated into seasonal quarters, for a triple-junction module that has been deployed at NREL since 1997. The data is split into four quarters Q1-Q4, which coincide with Spring, Summer, Autumn and Winter seasons. These data were analysed by sorting into corresponding irradiance bins (±50 W/m^2 wide) and corrected to common temperature for FF data using linear least squares regression, or just averaged in the case of temperature data. It is clear the FF data decrease with increasing irradiance in all four quarters, which can be ascribed to be due largely to the effects of series resistance. Hence, an increase in irradiance in summer will cause a reduction in the fill factor and not the increase observed in Figure 5. Similarly, it is clear that an increase in operating temperature is not responsible for the increase in the fill factor, since all the FF data are corrected to 25°C. Indeed if average FF data obtained are plotted instead, all the data are shifted to higher values for irradiance above 500 W/m^2, because the temperature dependence is somewhat positive, and the gap between summer and winter months widens. Hence, there is a significant seasonal effect due to annealing on triple-junction performance, at least for the NREL site. The overall effect at CREST is not that apparent, as the devices are not yet fully degraded.

5 ANNEALING AND SPECTRAL EFFECTS

The influence of the spectrum on the annual performance is calculated first. This is done by calculating the power that would be generated had the spectrum been AM1.5 rather than the given spectrum using a polynomial fit as shown in Figure 4. The investigation was limited to Golden because of the longer term data. The ratio of the real power production over this corrected power production is shown in Figure 7. This data is presented as a first approximation of the magnitude of the spectral effect. It should be mentioned, though, that the polynomial used for the spectral correction was derived using the same filtering conditions as used for Figure 4, i.e. no temperature and reflection were considered, the effect of these on the results will be investigated in the future. The values are only used for the quantification of the spectral effect, they do not represent any valuation of the quality of the devices.

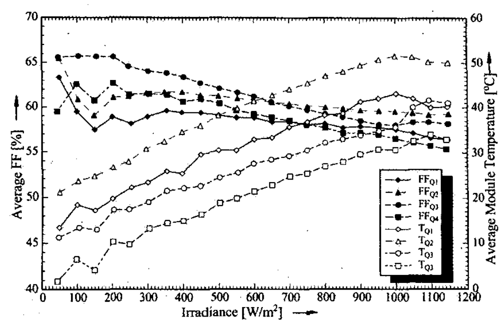

Figure 6: Seasonally Separated Irradiance Dependence of the Fill Factor Corrected to 25°C and Average Operating Module Temperatures for a Triple-Junction.

The fully degraded devices show a clear seasonal pattern for Golden. There were some issues with the spectroradiometer measurements there, notably: instrumental problems in August to September 2001, explaining the lack of data in these regions; and in June 2002, the skies were uncommonly hazy due to smoke from several massive fires burning in nearby forests in Colorado. In the summer months, the performance of the single- and the double-junction devices is very similar and an (albeit small) gain in power production is observed. The triple junction device is very close to its AM1.5 performance in summer but does not quite achieve it. The reasons for this are that a significant part of the available irradiance is bluer or redder than STC. This apparent drawback of multi-junctions of an increased susceptibility to spectral changes does not matter too much in the case of a-Si devices, as it is offset by a reduced degradation from the initial performance due to the thinner material layers.

In the winter months, a significant reduction in the power is seen for all devices. This could be expected, as the average AM is significantly higher than 1.5 and thus light is redder. There is no significant difference in the performance of the double and triple junction, while the single junction is somewhat less affected. The overall spectral effect causes a reduction in energy production for the investigated period of 5.5% for the single junction and 7.8% for the triple junction.

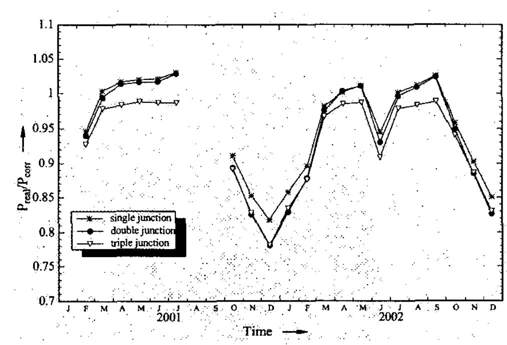

Figure 7: Seasonal Variation of the Produced Power Divided by Corrected Monthly Power for Single, Double and Triple Junction Devices at NREL.

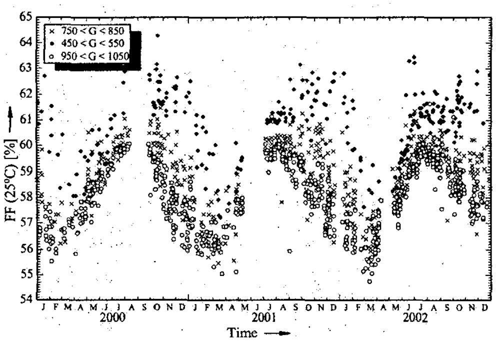

Figure 8: Seasonal Oscillations of FF Data Corrected to 25°C Module Temperature Sampled in 3 Irradiance Windows (500, 800 and 1000 W/m^2) ±50 W/m^2 wide, for a Triple Junction deployed at NREL.

Figure 8 is a graph of FF data corrected to 25°C temperature using the temperature coefficients derived and analysed by both irradiance bin and season, for the triple-junction module deployed at NREL. The data presented are sampled from three different irradiance windows, each ±50 W/m^2 wide, centred at 500, 800 and 1000 W/m^2 and filtered for predominantly clear-sky conditions. For clarity, only one-fourth of the data points, randomly marked in each set of the 3 irradiance bands, are depicted. The corrected FF values evidently oscillate with time, attaining their zenith about the beginning of autumn and sustaining a nadir at the end of winter, beginning of spring. Because cell FF at high irradiance is not very sensitive to spectral content, these data offer clear indication of the effects of thermal annealing and its magnitude for the NREL site. Disregarding the scatter, the amplitude of the FF oscillations are ±4.8%, ±3% and ±2.5% of average, respectively, in going from the low to high irradiance values.

Using the temperature coefficients obtained for I_{SC} data for the same module and performing temperature corrections to 25°C, one obtains similar corresponding oscillations in I_{SC} data against time. The temperature-corrected and normalized I_{SC} data display oscillations whose amplitudes are ±8%, ± 5% and ± 4% of average, respectively, going from low to high irradiance. Hence, these amplitudes appear marginally larger than those of the FF of the same triple-junction. I_{SC} is mainly a function of irradiance and spectrum, and not particularly sensitive to the Staebler-Wronski effect. Hence, it is expected that the sizes of the amplitude oscillations in I_{SC} represent primarily the effects of spectral variations. Further analysis of the data for the other multi-junction modules must be investigated and quantified before more definitive statements can be asserted. But for now, it appears that for the site with the greatest seasonal ambient temperature variations, both thermal annealing and spectral effects appear likely to ordain fluctuations in performance of comparable amplitude in triple-junction a-Si modules.

6 CONCLUSIONS

It is demonstrated that the seasonal performance variations observed in a-Si modules can be ascribed to a combination of both thermal annealing and spectral effects. Thermal annealing is manifest largely in fill factor variations, while spectral changes are more readily expressed via the short-circuit current. Furthermore, the data presented shows there can be substantial differences in seasonal air temperature variations and spectral variations between the two sites, whereby one or other factor can be more predominant at one locale while the other factor is more acute at the other site. Because both factors appear capable of driving performance variations of similar magnitude, the amount of fluctuation ascribed to each is rather sensitive to the environmental factors at each locale plus is also likely to be dependent on the technology (e.g., triple versus double junction, top-cell vs. bottom-cell limited).

This technology difference is apparent when investigating the spectral effect in Golden. All technologies exhibit a significant effect caused by changes in incident spectra that vary seasonally. It is shown that in winter, nearly 20% of the power can be lost due to spectral mismatch, while in summer a small increase is apparent. Annually the spectral effect causes a reduction of power production of 5-8%.

For one of the triple-junction modules deployed at NREL, temperature corrections were applied to FF and I_{SC} data, to correct these values to reference temperature (25°C), and analysed in three irradiance bands: 500, 800 and 1000 W/m^2. The resultant corrected FF and I_{SC} values exhibit seasonal fluctuations of approximately comparable amplitudes for each of these parameters: ranging from ±2.5% to ±5% for the FF, and from ±4% to ±8% for Isc, both respectively, as the irradiance ranges from 1000 W/m^2 to 500 W/m^2.

7 ACKNOWLEDGEMENTS

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