CHAPTER 5

OUTDOOR SPECTRAL EVALUATION OF CRYSTALLINE – Si MODULES

5.1 INTRODUCTION

It is becoming certain that the impact of PV modules on our daily energy needs is increasing tremendously. Their place of application has also broadened, thereby calling for the need to understand their performance in such places. Outdoor monitoring procedure of PV modules should definitely continue since the operational conditions are different to the conditions on which rated parameters are based. Understanding the performance of different PV devices under various environmental conditions assists in obtaining useful information that would help system designers in predicting energy output, making them more reliable and effective. One such parameter which is not clearly understood and affects output electrical parameters is the continuous change of outdoor spectrum.

5.2 EXPERIMENTAL PROCEDURE

PV modules used in this study are placed on a fixed rack on the roof top of our Research Centre, clear of any obstruction that might cause shading. The tilt angle of $32^{o}47'$ facing north is used since this is the latitude of Alice, in South Africa. Spectral measurements were taken using the EPP2000 (portable) fiber optic spectrometer. This instrument is capable of making various types of spectral measurements in the UV-VS-NIR (350 - 1200 nm) ranges. The EPP2000 provides 2048 wavelengths for each scan over the pre-configured range. Range and coarse resolution are determined by installed spectrometer grating groove density. EPP2000 is interfaced to a computer via digital parallel port using a 25 pin flat ribbon cable. Outdoor measurements for the current-voltage data were facilitated by a current-voltage tester employing a power supply unit as load. Figure 5.1 illustrates the module layout and the apparatus for measuring environmental conditions.

Figure 5.1: *PV module layout installed at the Institute of Technology, South Africa at tilt angle of 32°47′ facing north.*

Table 5.1: *Listed are the different types of modules used in this study including their corresponding rated power, I_{sc}, V_{oc}, Fill Factor and aperture area efficiency.*

Module type	Rated Power (W)	I_{sc} (A)	V_{oc} (V)	FF	η (%)
a-Si:H	6.5	0.49	23.87	0.56	4.60
mc-Si	36.3	2.45	21.05	0.70	11.26
c-Si	40.0	2.60	21.6	0.71	13.60
p-Si	50.0	3.40	21.30	0.69	12.30
CIS	40.0	2.68	23.30	0.64	10.44
HIT	62.5	3.75	22.50	0.74	17.70

The concept of Useful Fraction (UF) as used according to [Gottschalg, et al., 2003] is a useful parameter for quantifying the spectral influence on PV devices. One major advantage in comparison with other concepts is its ability to give direct feedback of a particular device performance since it is device dependent. One major assumption made in this concept is that the Spectral Response (SR) within the device wavelength range is

100%. In fact each device's wavelength within its spectral range has a different percentage SR. To compensate for this, the percentage Weighted Useful Fraction (WUF) as introduced in chapter 3 has been developed. Figure 5.2 shows the outdoor spectrum at different times of the day together with spectral response (SR) of c-Si module.

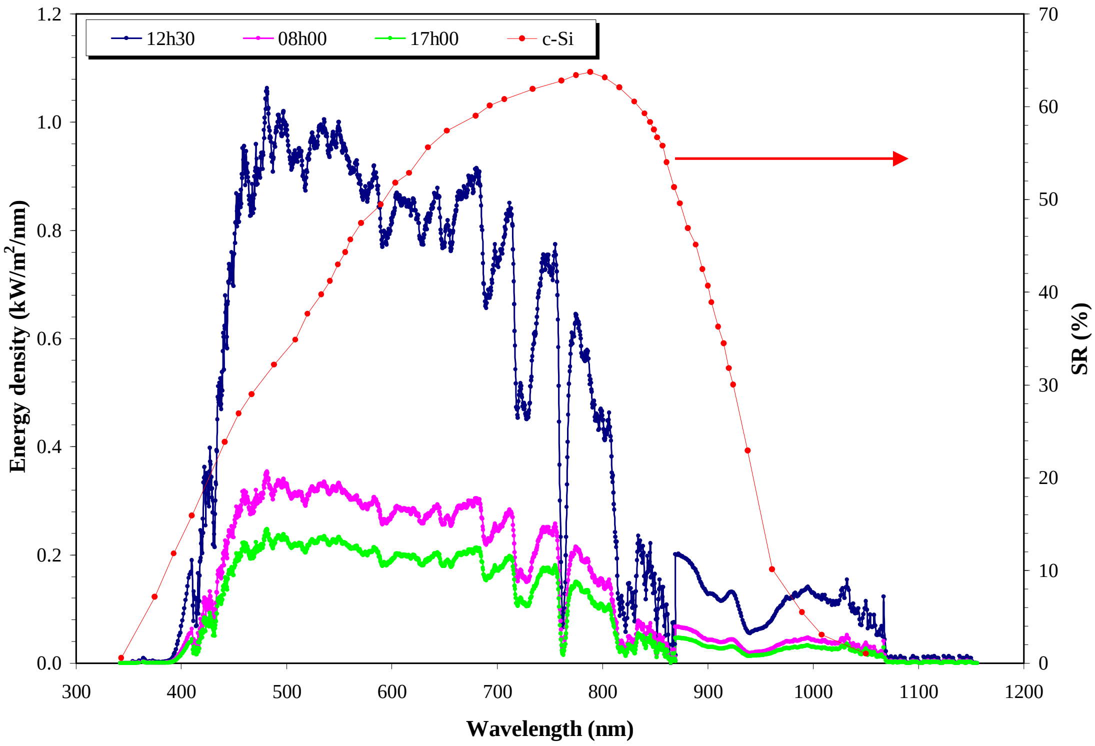

Figure 5.2: *Illustration of the change in outdoor spectrum at different times of the day. Also shown is the c-Si spectral response curve as a % at each wavelength [Kenny, et al., 2006].*

From figure 5.2 it is observed that the % of the useful energy converted to output energy at each wavelength differs. This results in the total integrated energy density within the device spectral range to be lower than when the % SR at each wavelength is not considered. The effective spectrum perceived by the module is calculated with % SR multiplied by the actual spectrum at that wavelength. Figure 5.3 shows the effective spectrum perceived by the c-Si module compared to the actual spectrum.

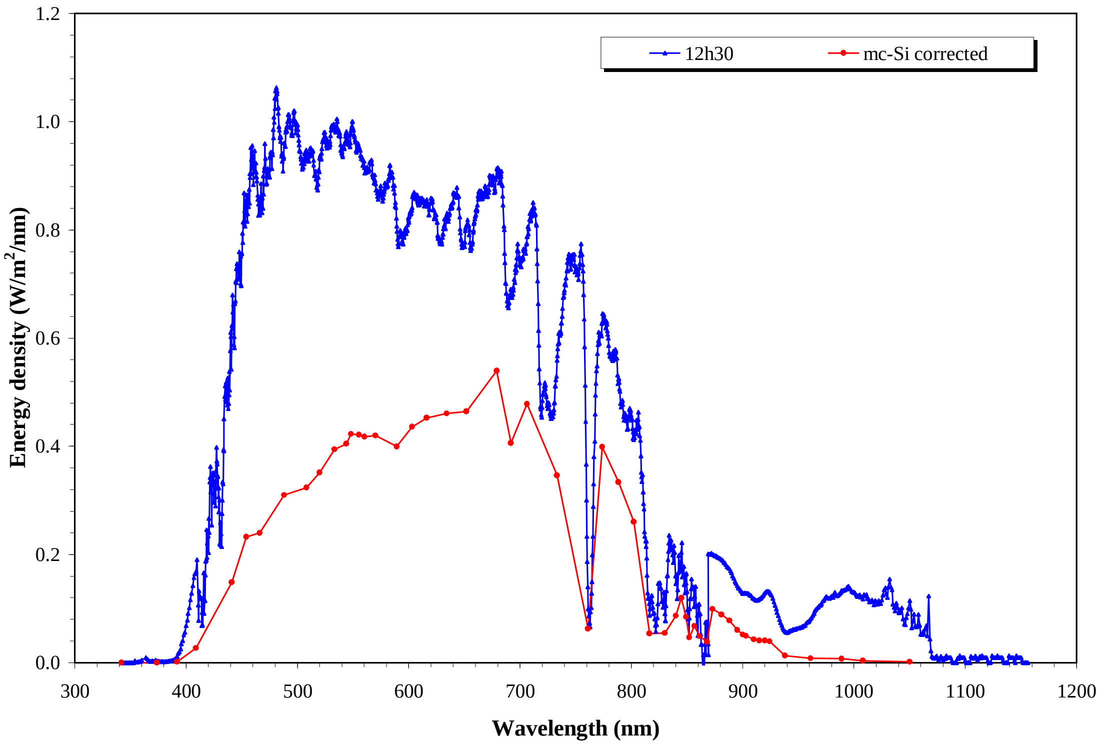

Figure 5.3: *Illustration of the effective spectrum perceived (corrected) by the mc-Si module compared to the actual (uncorrected) spectrum.*

The uncorrected SR assumes that the module responds to 100 % of incident spectrum at each wavelength. UF data indicates that corrected SR is 45.6% less in the device spectral range, resulting in the need to calculate WUF as described in chapter 3. Results presented in this chapter are for crystalline based devices namely mc-Si, mono-Si and poly-Si modules.

5.3 RESULTS AND DISCUSSION

The variation of incident spectrum has an impact on modules short circuit (I_{sc}) current. The influence of back of module temperature (T_{module}) and the change in irradiance also affect greatly the I_{sc} of the module. Determining the effect of spectrum requires the elimination of these factors by plotting each one of them with the modules I_{sc}.

Normalization of I_{sc} was achieved by dividing the module's I_{sc} with the total irradiance within the device spectral range ($G_{spectral\ range}$).

5.3.1 Spectral influence on mc - Si module's performance

The commonly adopted correlation existing between the module's I_{sc} and back-of-module temperature is of the form $I_{sc} = \left(C_0 + C_1 T_{device}\right) \times G_{SpectralRange}$ [Christian, 2002]. Firstly the relationship between $I_{sc} / G_{SpectralRange}$ = $\phi_{SpectralRange}$ (Irradiance corrected I_{sc}) is plotted against back-of-module temperature. The empirical coefficients C_0 and C_1 are obtained. This correlation does not clearly show the device spectral variations. This can be overcome by fitting the data to equation of the form: $\phi_{SpectralRange} = (C_o + C_1 T_{device}) \times f(WUF)$. This procedure allows the spectral variations to be clearly analyzed. Figure 5.4 illustrates the dependence of irradiance corrected I_{sc} with temperature.

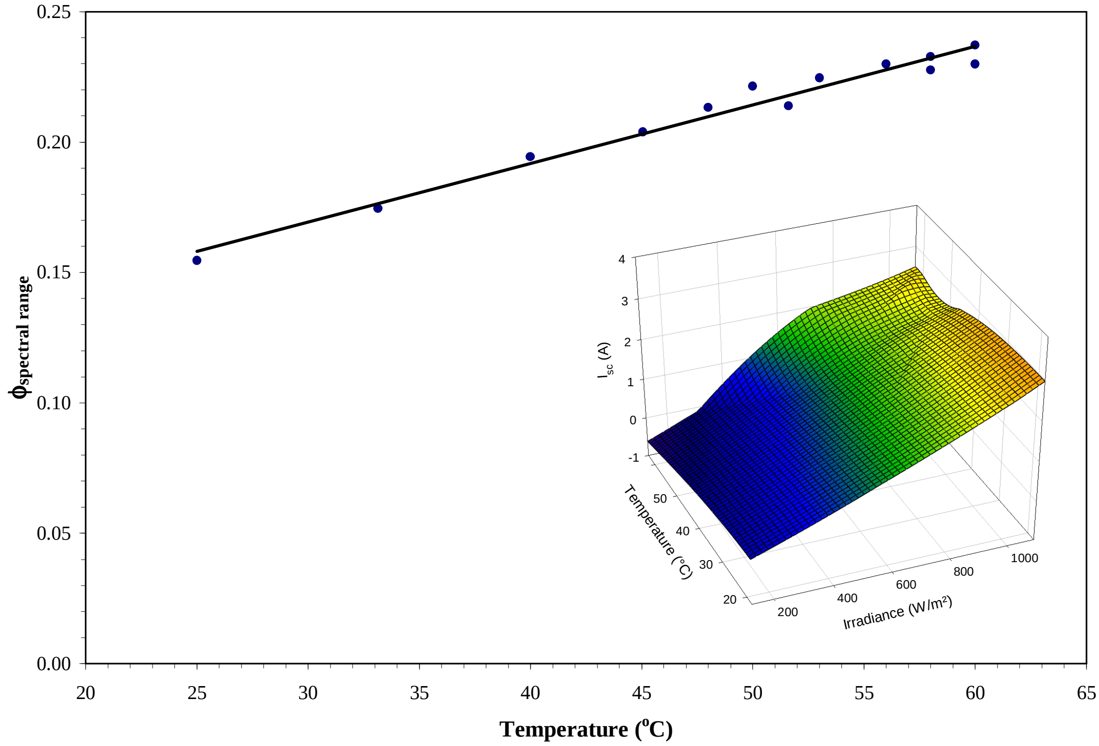

Figure 5.4: *Correlation between irradiance corrected I_{sc} and T_{device}. Inset is a 3-D graph of variations of the 3 parameters.*

The variation of $\phi_{SpectralRange}$ with temperature is linear as confirmed in figure 5.4. From the inset figure, a linear correlation between I_{sc}, temperature and irradiance is vivid. Since $\phi_{SpectralRange}$ is the ratio of I_{sc} to $G_{spectral\ range}$ and that both I_{sc} and $G_{spectral\ range}$ increases with temperature, therefore the ratio ($I_{sc}/G_{spectral\ range}$) should exhibit a linear dependence with temperature. To further understand the behaviour of $\phi_{SpectralRange}$ with outdoor spectrum, a plot of $\phi_{SpectralRange}$ versus WUF is illustrated in figure 5.5.

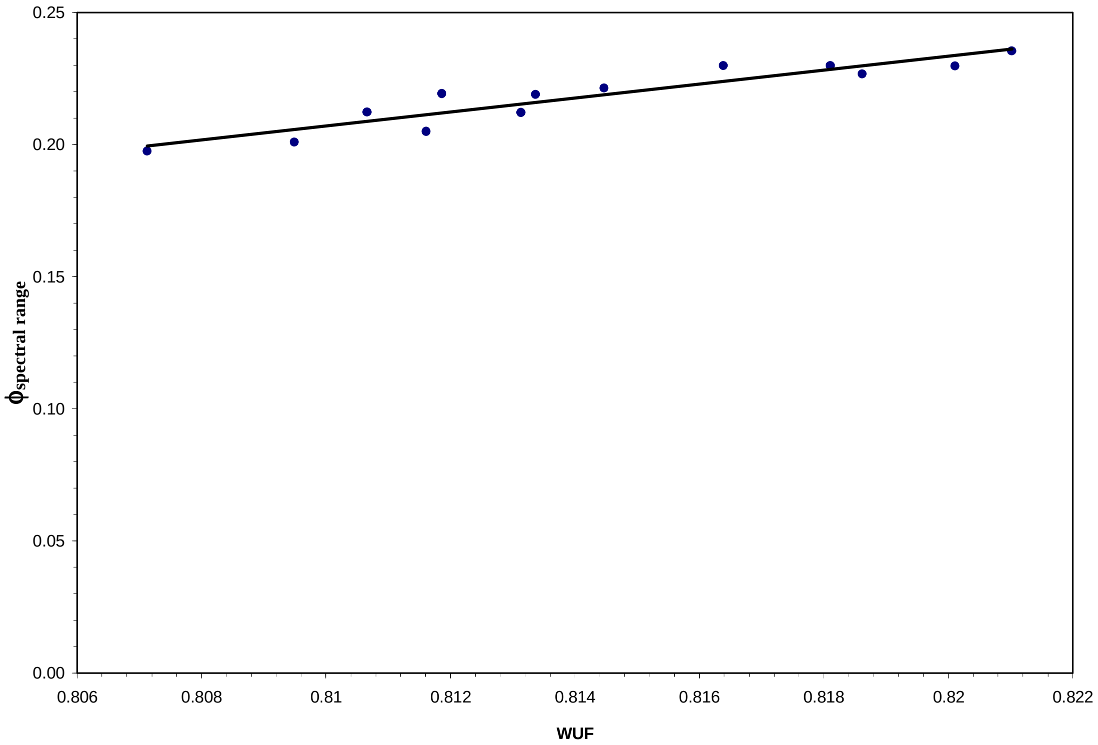

Figure 5.5: *Variation of $\phi_{SpectralRange}$ against the module's WUF.*

An increase in $\phi_{SpectralRange}$ as WUF increases is due to the fact that each WUF value corresponds to a particular irradiance value. An increase in irradiance within device spectral range results in I_{sc} increase which consequently results in an increase in $\phi_{SpectralRange}$ as WUF increases.

Analyzing how both temperature and irradiance affects $\phi_{SpectralRange}$ is of paramount importance for further understanding the effect of spectral variation. Figure 5.6 illustrates the variation of $\phi_{SpectralRange}$ with both irradiance and temperature. It should be noted that the $\phi_{SpectralRange}$ values represented in figure 5.6 have been increased by a factor of 200.

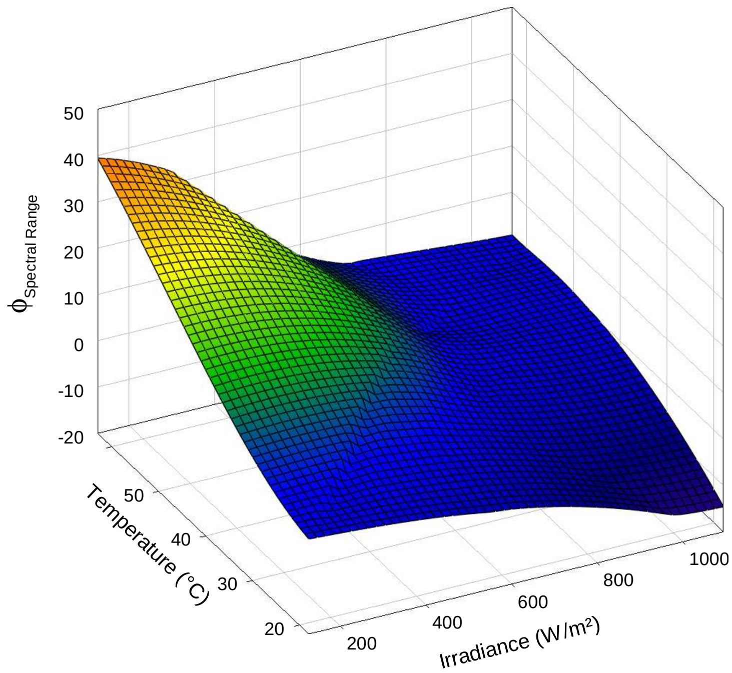

Figure 5.6: *The effects of temperature and irradiance a function of* $\phi_{SpectralRange}$.

Notably from figure 5.6 is the increase in $\phi_{SpectralRange}$ as irradiance is reduced. This behaviour contradicts what is expected if the irradiance used in $\phi_{SpectralRange}$ had been global. A linear increase relationship with G_{global} would have been expected since the irradiance effect would compensate for each other. The reason for this behaviour in figure 5.6 is due to the fact that the $G_{spectral\ range}$ used in $\phi_{SpectralRange}$ is very sensitive to outdoor changes as opposed to G_{global}. Therefore the behaviour of these two parameters is not the same which results in $\phi_{SpectralRange}$ to be high at low irradiance. This is also attributed to the dominant spectral at these conditions.

The change in I_{sc} as outdoor irradiance varies is well understood. High values of irradiance result in high values of I_{sc}. This relationship which is illustrated in figure 5.7 illustrates less scatter as the two parameters changes.

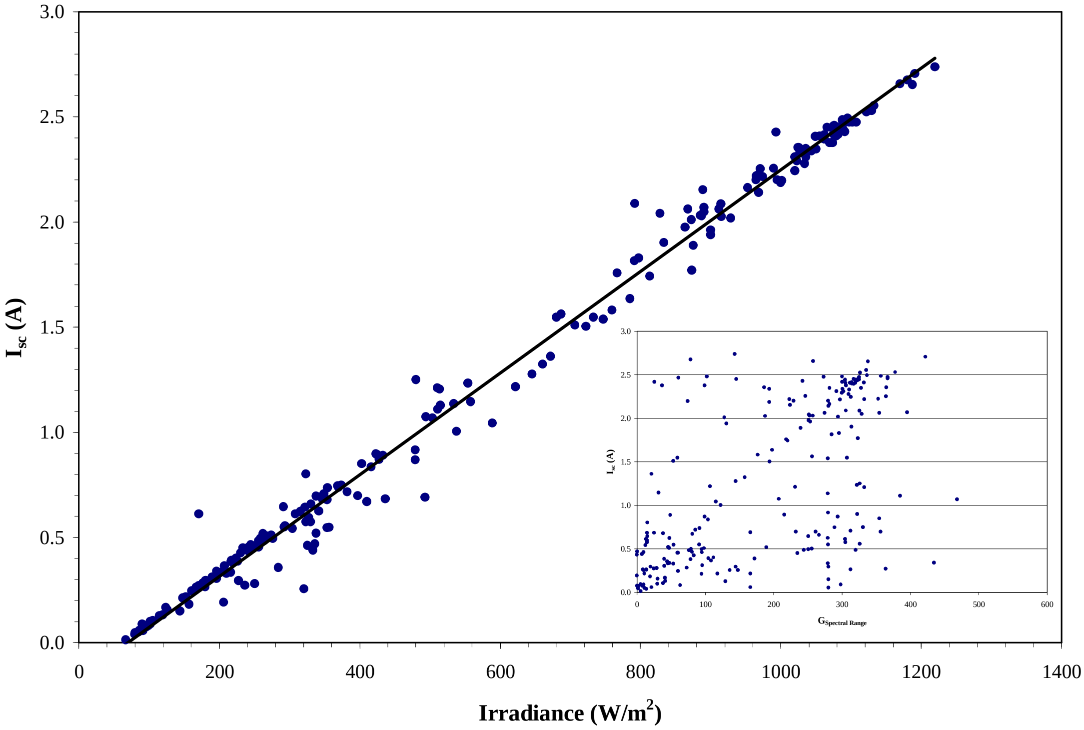

Figure 5.7: *Illustrates the effects of G_{global} (measured with pyranometer) and $G_{spectral\ range}$ (measured with spectroradiometer) on device I_{sc}.*

Analyzing an insert figure 5.7, the variation of I_{sc} as function of irradiance within the device spectral range ($G_{spectral\ range}$) is not a clear linear relationship as in the case of I_{sc} vs G_{global}. A large scatter observed as the I_{sc} varies with $G_{spectral\ range}$ of a device illustrates how sensitive the device is to the sudden changes of the outdoor environment. This shows that PV module's I_{sc} respond greatly to the outdoor spectral changes.

Outdoor spectral effects on crystalline-Si has not been as greatly documented and studied as amorphous Si devices. This has been partly due to the 'perceived' larger spectral response range of c-Si which theoretically translates to a relatively stable outdoor performance. But analyzing the outdoor spectral data and correlating this to the device performance data, a different conclusion is reached. Figure 5.8 illustrates the dependence of $\phi_{SpectralRange}$ on irradiance (G_{global}).

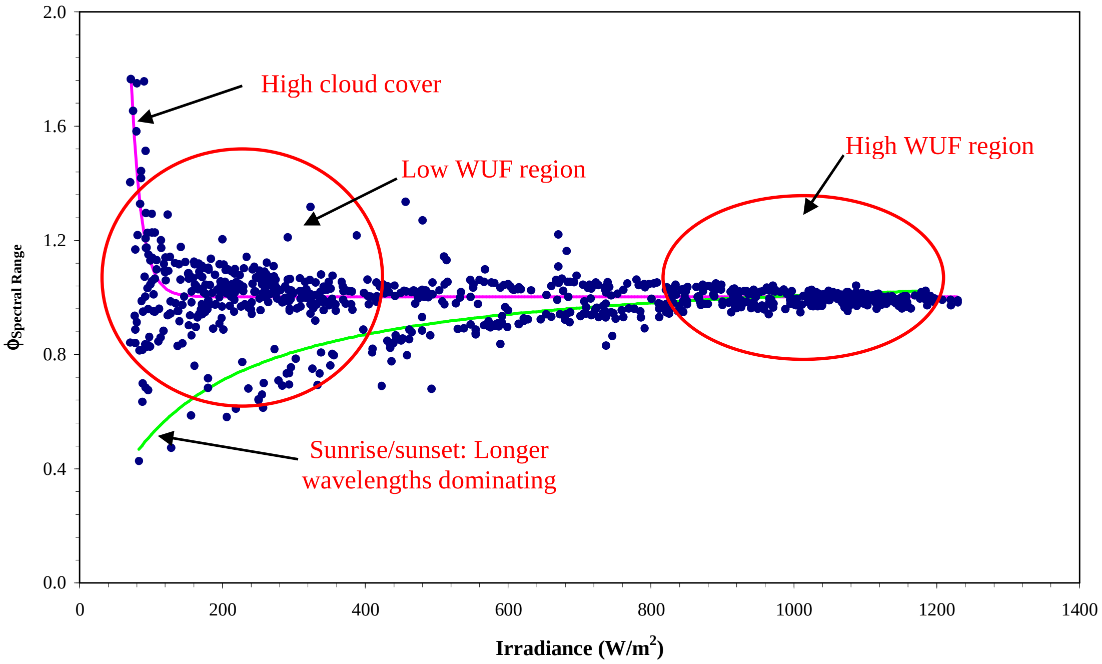

Figure 5.8: *Illustration of the dependence of $\phi_{SpectralRange}$ on the total irradiance as measured by the Pyranometer.*

The spectrally corrected $\phi_{SpectralRange}$ versus Irradiance (G_{global}) reveals the effect of outdoor conditions on device's $\phi_{SpectralRange}$. For irradiances greater than 800 W/m^2, the data points are more defined and less scattered and linear relationships exists. Below G_{global} of 800 W/m^2 and close to 300 W/m^2 the linear trend relationship that has been exhibited at G_{global} > 800 W/m^2 disappears. The scatter is more pronounced with no clear trend. This figure also reiterates the fact that PV device performance is greatly affected by the changes in outdoor conditions. For G_{global} > 800 W/m^2 it indicates 'clear sky' condition typical found under full spectrum and G_{global} < 300 W/m^2 also indicate spectrum characterized by low WUF, a typical spectrum dominated by longer wavelength (sunrise/sunset) resulting in poor performance of the device, as indicated in figure 5.8 (green curve). This can also be found under high cloud cover with mostly shorter wavelength being scattered back into the sky, letting only longer wavelength to pass through. Also the high cloud cover acts as a filter for the Infrared (IR) light and will shift the spectrum to full spectrum region (as defined in previous section) resulting in an increase in device performance indicated by the upper curve (purple). These two phenomena lead to both high values of I_{sc} and low values for I_{sc}, as is evident in figure 5.8. The change in outdoor spectrum is influenced by a number of factors. Air mass contributes greatly to the outdoor spectral variations and consequently device spectral changes as characterized by WUF. Ideally an increase in air mass (AM) results in a decrease in device WUF. The correlation between WUF and AM for mc-Si is presented in figure 5.9. Note that the AM values were calculated following the methodology used in chapter 2, section 2.6.3. This was done so that the actual time frame when WUF measurements were taken would be the same as the calculated AM values.

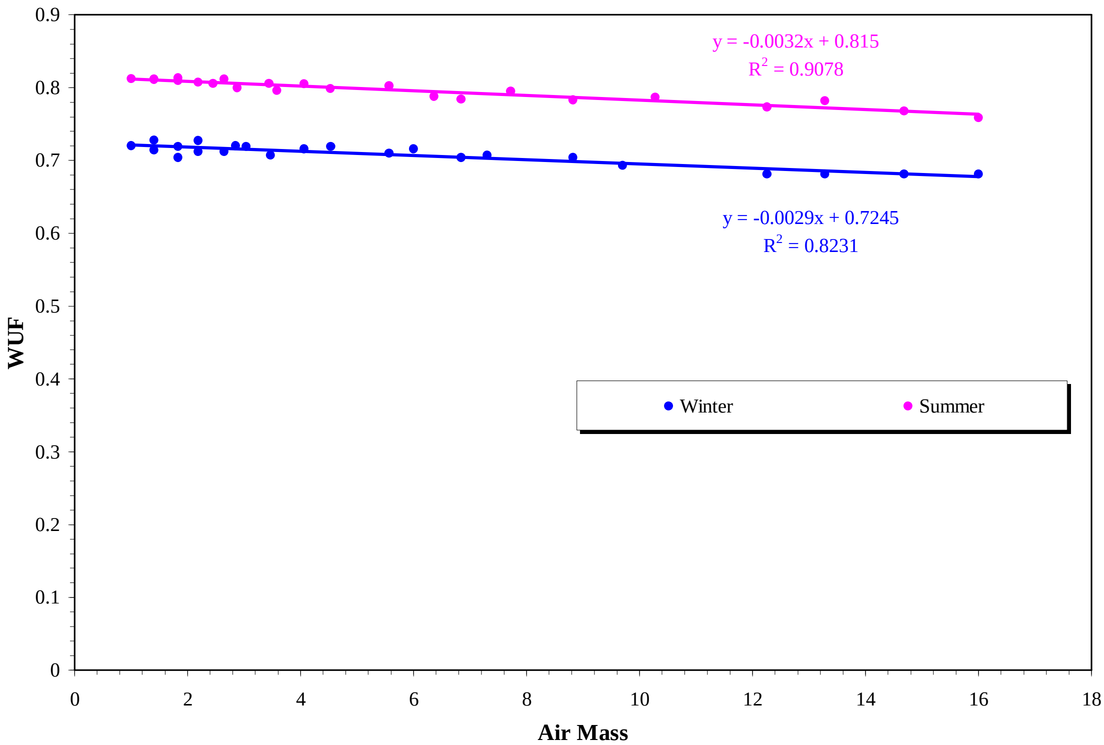

Figure 5.9: *Influence of the air mass on device spectral variations as characterized by WUF for mc-Si module for both summer and winter seasons.*

Evident from the figure 5.9 is a functional relationship between Air Mass and WUF. Large AM values correspond to larger wavelength mainly found under low irradiance levels. At these conditions, the WUF of the device will be lower than its value at AM 1.5. The variation of WUF with AM for mc-Si module for both summer and winter has the same trend as is indicated by the gradients of the two curves. Although the WUF winter values are not the same, the functional relationship between the two parameters in both cases is the same. This shows that the WUF versus AM relationship is device dependant. Depending on the type of PV module, the gradient of the WUF versus AM curve will differ. The difference is largely due to the device spectral WUF range ($\sigma_{spectral\ range}$) as described in chapter 3.

Figure 5.10 shows a typical daily WUF and AM on clear days for both summer and winter seasons.

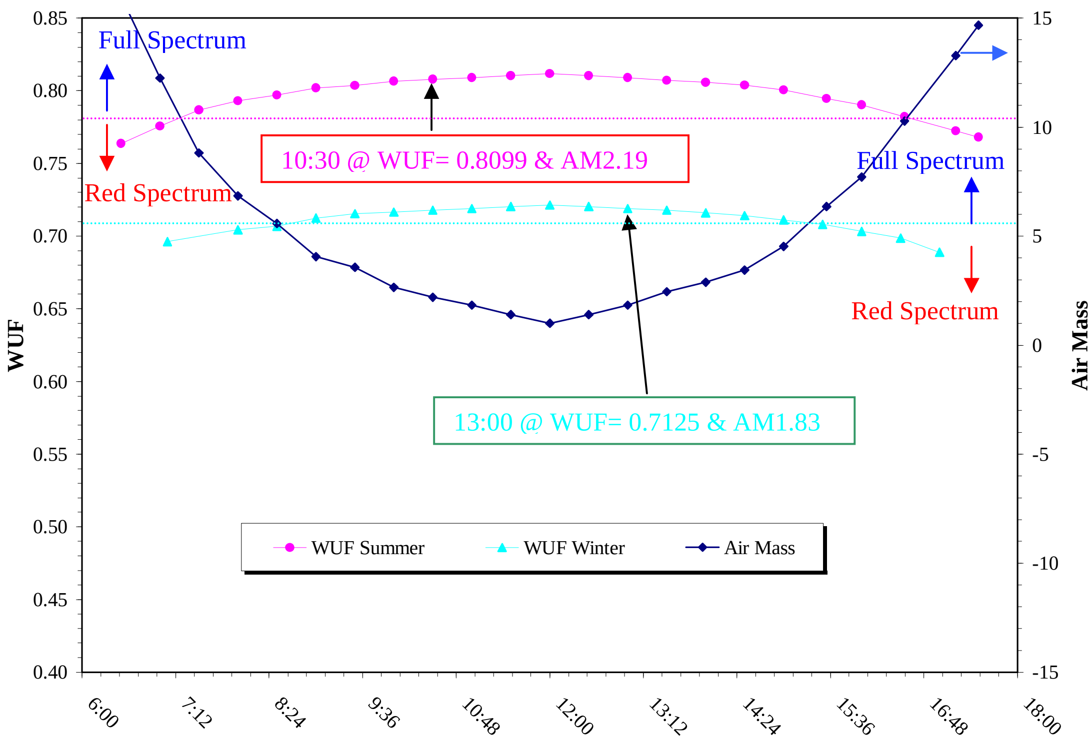

Figure 5.10: *Illustrates the seasonal WUF profile against time together with the change in AM values.*

During early morning (before 07h30) and late afternoon (after 16h00) the low solar altitude is characterized by high AM values (>8). The spectrum during these times is associated with longer wavelengths dominating due to Raleigh scattering. From the figure it is then deduced that WUF < 0.78 for summer season is indicative of a “red” spectrum while WUF > 0.78 indicates a full spectrum. The WUF in summer peaks at 10h30 at a value of 0.8099 corresponding to an AM = 2.19, which is different from AM1.5 expected at solar noon, 12h30. Furthermore, repeating the exercise for clear winter days, it was deduced also that WUF < 0.71 is indicative of “red” spectrum and WUF > 0.71 indicates a full spectrum. This procedure was adopted because the summer and winter spectra are different. The WUF was found to peak at 13h00 at a value of 0.7125, corresponding to AM1.83 during winter seasons.

Standard deviation (σ) as is defined in statistical terms is a measure of the dispersion of a collection of numbers or data set. It is also used as a measure of uncertainty. In this analysis, σ is used to determine the range of a PV device spectral response. To isolate the effect of seasonal spectral changes, the influence of WUF on FF was characterized in summer and winter. Figure 5.11 illustrates the entire spectral response range (σ_2) for mc-Si during summer and winter. Also illustrated is the half-width of the Gaussian peaks, σ_1.

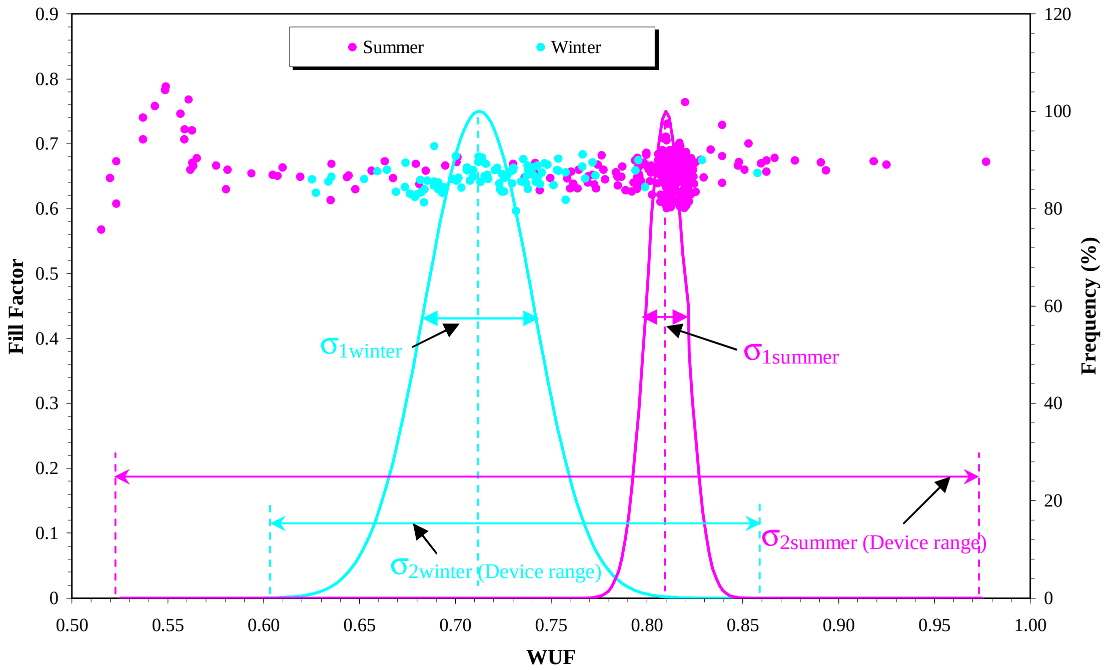

Figure 5.11: *Effect of season on device junction properties as illustrated by Fill Factor.*

Noteworthy from the figure is the low frequency (or time spent) under the red spectrum in summer. This implies that the device "prefers" a full spectrum to operate optimally. Conversely the wider $\sigma_{1winter}$ implies that the device operates optimally over a wider spectral band. More than half of $\sigma_{1winter}$ corresponds to red-shifted spectrum implying that the device prefers the red-dominated spectrum in winter.

The performance of the device FF was also compared for both clear and cloudy days. These conditions were chosen using the following criteria.

- Clear sky, between 12h30 and 13h30, with G_{global} > 900 W/m^2,
- Cloudy sky between 12h30 (noon) and 13h30, with G_{global} < 400 W/m^2 were used for this analysis.

The comparative results obtained are presented in table 5.2.

Table 5.2: *Influence of cloud cover on device junction properties as illustrated by WUF and FF.*

	$\sigma_{spectral\ range}$	WUF_{mean}	$FF_{Average}$
Cloudy days	0.562-0.893	0.8109	0.662
Clear days	0.527-0.975	0.8146	0.637
% difference	26.1	0.5	3.8

As observed from table 5.2, cloud cover has an effect of reducing the device spectral range ($\sigma_{spectral\ range}$) as compared to clear days with a wider $\sigma_{spectral\ range}$. The smaller % difference for WUF_{mean} and the average FF for cloudy and clear days shows that cloud cover has minimal effect on device spectral response.

5.3.2 Performance of mono-Si

Crystalline silicon modules used in this study (mc-Si, mono-Si, and poly-Si) should ideally behave in the same way under outdoor conditions. The effect of the three major outdoor factors that affect their performance should affect them in the same manner regardless of their ratings. Figure 5.12 illustrates the influence of air mass on WUF for c-Si module for winter and summer season.

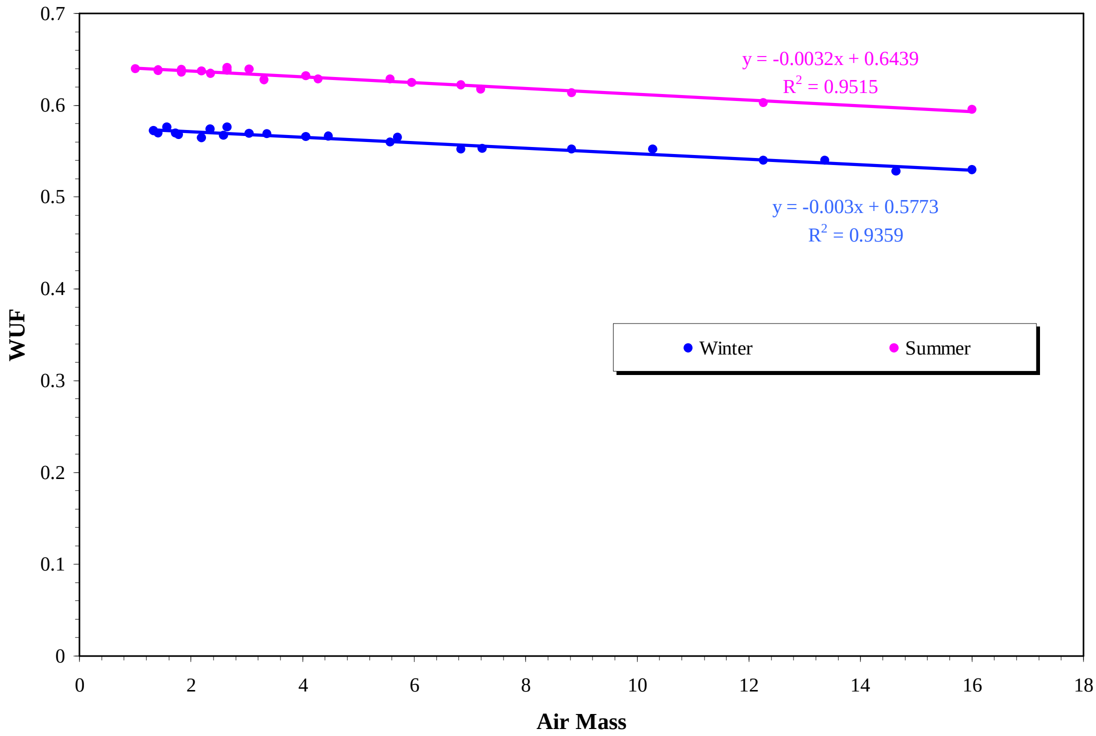

Figure 5.12: *Influence of air mass on device spectral variations as characterized by WUF for c-Si module.*

Closer analysis of figure 5.12 reveals that the gradient of the two curves for both summer and winter seasons is the same for the c-Si module. The gradient exhibited in figure 5.12 is the same with that of mc-Si in figure 5.9. This indicates that the two devices have the same AM dependence although their WUFs are different.

Figure 5.13 illustrates the variation in WUF due to seasonal changes in the spectrum. Also illustrated is the AM variation with day time.

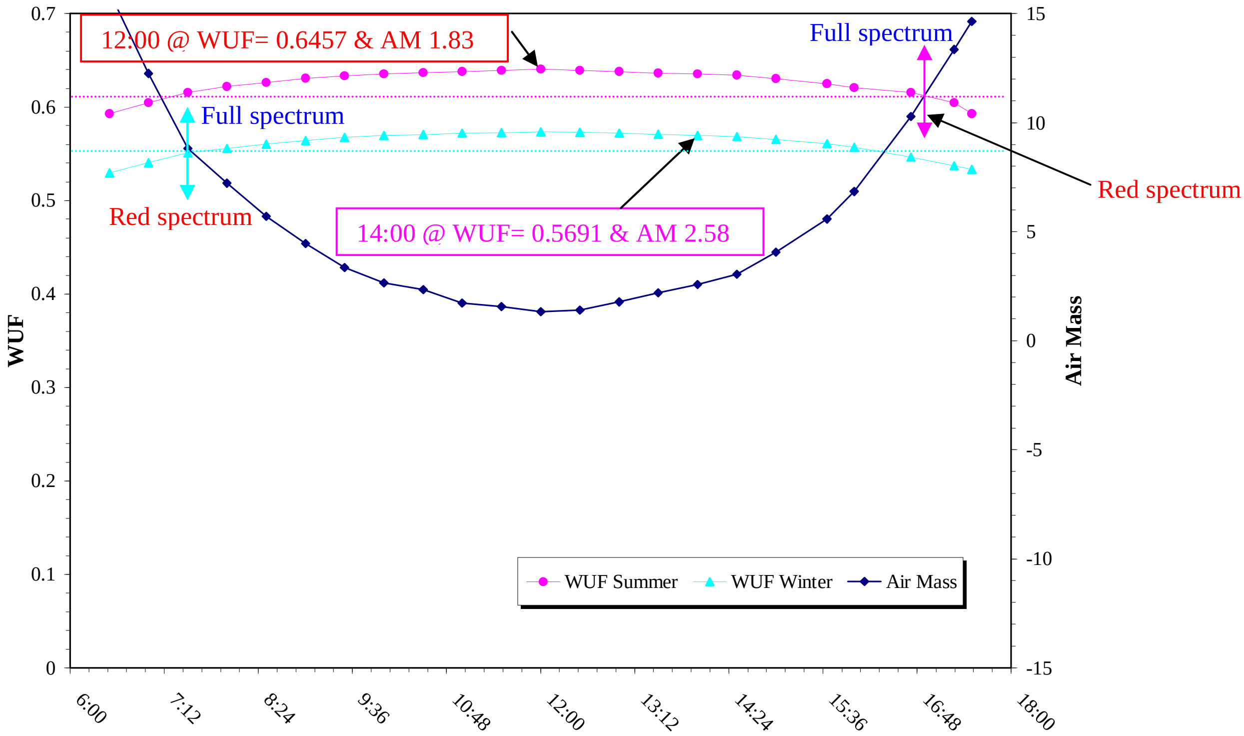

Figure 5.13: *Illustrates a typical daily WUF and air mass on clear summer and winter day for c-Si module.*

The same procedure adopted in figure 5.13 was also applied in analyzing the seasonal spectral effects on c-Si module. For summer period, it is deduced that for WUF < 0.61 is indicative of the red spectrum while WUF > 0.61 indicates a full spectrum. For winter season, WUF < 0.555 indicates a red spectrum and WUF > 0.555 is indicative of a full spectrum.

For summer seasons, the c-Si module "prefers" a spectrum characterized by low AM values (AM 1.83). This spectrum which peaks at 12h00 noon corresponds to the WUF = 0.6457. For winter season, the WUF was found to peak at 14h00 at a value of 0.5691, corresponding to AM 2.58. As evident in both seasons, the spectrum that is "preferred" by the c-Si module is different from AM 1.5.

Table 5.3 lists the parameters of c-Si module during summer and winter seasons.

Table 5.3: *Dependence of Fill Factor and Efficiency of mono-Si with outdoor spectrum as characterized by Weighted Useful Fraction in summer and winter seasons*

	$\sigma_{spectral\ range}$	WUF_{mean}	$FF_{Average}$	$\eta_{Average}$
Summer	0.41-0.895	0.6457	0.67	13.36
Winter	0.49-0.630	0.5791	0.67	13.67
% difference	71.13	12.31	0	2.27

The device spectral range ($\sigma_{spectral\ range}$) is wider in summer than it is during winter period. This results in 71.13% difference as the winter $\sigma_{spectral\ range}$ is reduced. The FF and efficiency still remains the same as indicated by a slight % difference, which is within experimental errors. The response of c-Si module to the outdoor changes due to season is not compromised although its spectral range has been affected.

5.3.3 Performance of poly-Si

Like other crystalline devices presented in section 5.3.1 and 5.3.2, the variation of the outdoor incident spectrum affect the device's I_{sc}. As mentioned earlier on in section 5.3.1, the variation of WUF versus AM depends on the characteristics of the PV module. It was considered important to analyze the effect of AM on WUF for pc-Si module for summer and winter season. Figure 5.14 illustrates the influence of air mass on device spectral variations for the pc-Si module.

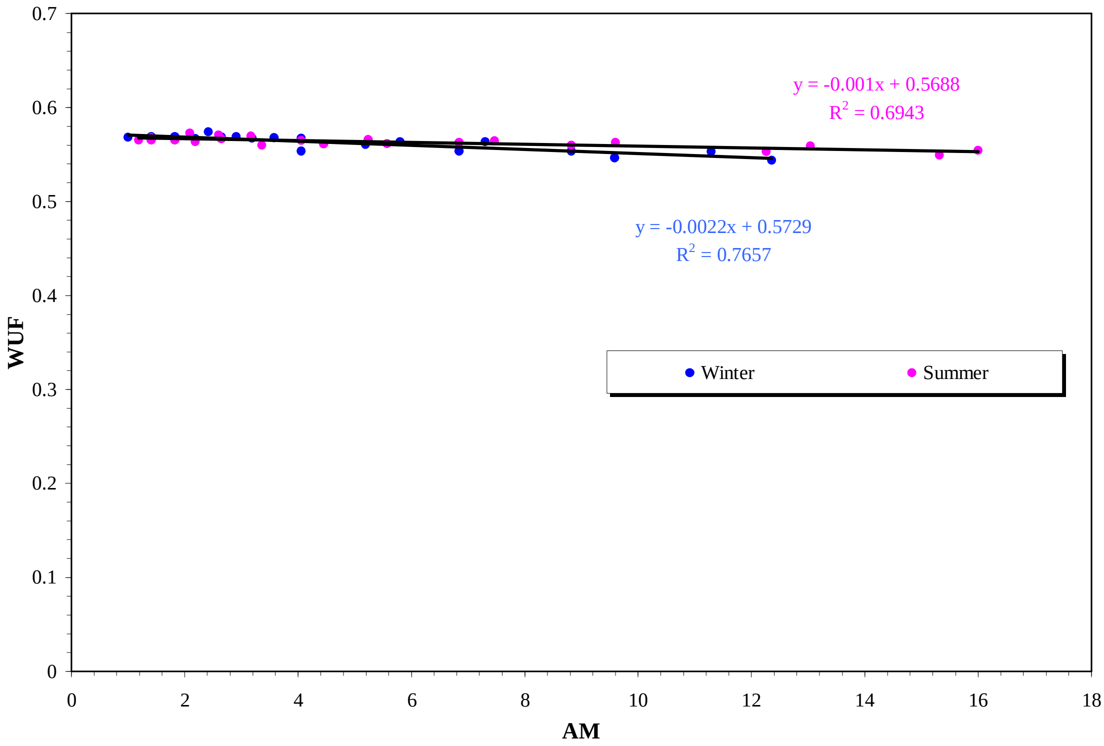

Figure 5.14: *Variation of WUF as a function of AM for summer and winter season for pc-Si module..*

The variation of WUF as a function of air mass for both winter and summer does not vary significantly as indicated by the slope of the two curves. Comparing figure 5.14 with figures 5.9 and 5.12, the pc-Si module's gradient is different. Figure 5.15 shows the summer and winter profiles in relation to AM for pc-Si module.

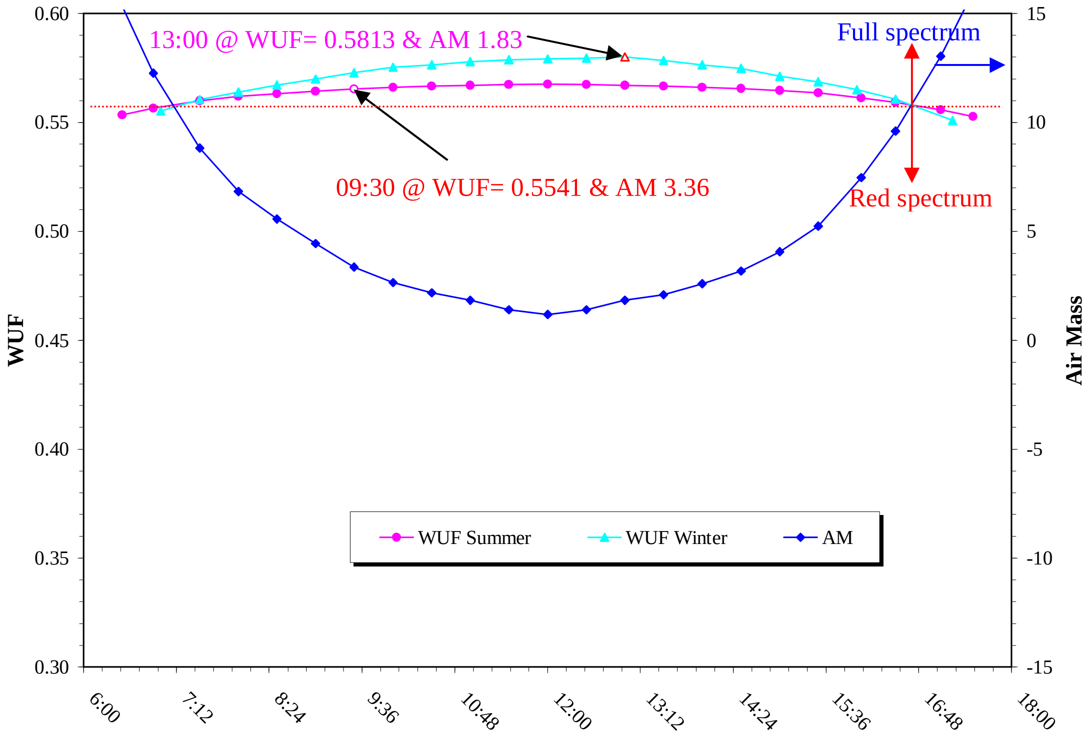

Figure 5.15: *Seasonal WUF summer and winter profiles for pc-Si.*

Notable from figure 5.15 are the low WUF values for the pc-Si module as compared to the other crystalline – Si modules. It is deduced from figure 5.15 that WUF < 0.551 for both summer and winter season is indicative of a "red" spectrum while WUF > 0.551 indicates a full spectrum. The WUF in summer peaks at 09h30 at a value of 0.5541 corresponding to an AM = 3.36, which is different from AM 1.5 expected at solar noon, 12h30 as mentioned in the section 5.4.1. For clear winter days, it was also observed that the WUF was found to peak at 13h00 at a value of 0.5813, corresponding to AM 1.83.

The efficiency of the device is analyzed for possible effect due to seasons. Table 5.4 illustrates the seasonal effect of WUF on module FF and efficiency.

Table 5.4: *Seasonal performance of poly-Si module due to spectral shift.*

	$\sigma_{spectral\ range}$	WUF_{mean}	$FF_{Average}$	$\eta_{Average}$
Summer	0.41-0.70	0.5541	0.713	7.21
Winter	0.47-0.66	0.5813	0.676	7.32
% difference	34.5	4.5	5.2	1.5

Poly-Si module's performance parameters are not significantly affected by the outdoor seasonal changes. The device average efficiency has a 1.5% difference which could be attributed by some errors associated with the measuring instruments. Although the device's $\sigma_{spectral\ range}$ had increased, this could not affect both WUF_{mean} and FF greatly.

5.4 SUMMARY AND CONCLUSION

Evident from the results presented in this study is that the spectrum received in sub-Sahara is totally different from the standard AM 1.5 spectrum than that received from the northern hemisphere regions. Also noted is that crystalline-Si modules are also affected as the spectrum shift during seasons although these devices are perceived (without outdoor data) that their performance is not influenced by the seasonal changes in outdoor spectrum. It has been showed that for summer season, mc-Si “prefers” to operate optimally at WUF = 0.8099, which is an indication of a full spectrum as defined in this study. For winter season the mc-Si module responds optimally at WUF = 0.7125 which corresponds to AM 2.19. It is evident that the change in outdoor spectrum due to seasons affects the module’s spectrum to which it best prefers and also the time of the day at the corresponding spectrum. Results for mono – Si module showed that the device performs best at WUF = 0.6457 which corresponds to AM 1.83 during summer season, while it operates optimally under a winter spectrum indicated by WUF of 0.5691 (AM 2.58). The seasonal changes resulted in the shift in day time corresponding to the “preferred” spectrum. This shift indicates that these devices should be rated using AM values that correspond to the WUF values under which the device operates optimal. For poly-Si, it was also observed the WUF values are lower than the other two crystalline-Si counterparts. The pc-Si was observed to prefer a low AM spectrum indicated by WUF = 0.5813 during winter season while for summer it prefers a spectrum characterized by WUF = 0.5541 at AM 3.36.

5.5 REFERENCE

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Gottschalg, R., et al. (2003), “Experimental study of variations of the solar spectrum of relevance to thin film solar cells”, Solar Energy Materials and Solar Cells, 79; 527 - 537.

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