Spectral Effects on CIS Modules While Deployed Outdoors

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1. Introduction

The effect of spectral distribution on the performance of photovoltaic (PV) modules is often neglected. The introduction of multi-junction devices such as Copper Indium Diselenide (CIS) necessitated a concerted investigation into the spectral response on these devices. In part this attributed to the wider spectral response resulting from a combination of different energy band gaps. This in turn implies that the device should have a relatively lower dependence on outdoor spectral content, which depends on a number of factors such as year time, location, day time and material composition in the atmosphere.

The availability of outdoor spectral data, which in most cases is not available, allows for the evaluation of the outdoor response of the CIS technology as the spectrum shifts during the course of the day, during cloud/clear sky condition and seasons. This study reports on the effect of outdoor spectrum, which is different from the reference AM 1.5, on the CIS performance parameters.

2. Different outdoor methodologies currently adopted

2.1 The concept of average photon energy

In trying to quantify the 'blueness' or 'redness' of outdoor spectrum, Christian *et. al.* adopted the concept of Average Photon Energy (APE) as an alternative (Christian et al., 2002). He defined APE as a measure of the average hue of incident radiation which is calculated using the spectral irradiance data divided by the integrated photon flux density, as in equation 1.

$$APE = \frac{\int_a^b E_i(\lambda)d\lambda}{q_e \int_a^b \Phi_i(\lambda)d\lambda} \qquad (1)$$

where :
q_e = electronic charge
$E_i(\lambda)$ = Spectral irradiance
$\Phi_i(\lambda)$ = Photon flux density

As an indication of the spectral content, high values of average APE indicate a blue-shifted spectrum, whilst low values correspond to red shifted spectrum. Although this concept at

first approximation characterizes the spectral content at a particular time-of-the day, no direct feedback of the device information is obtained since it is independent of the device. The concept of Average Photon Energy (APE) has also been adopted to illustrate the seasonal variation of PV devices (Minemoto et al., 2002; Christian et al., 2002).

2.2 The Air Mass concept

The mostly commonly adopted procedure (Meyer, 2002; King et al., 1997) is to calculate the Air Mass (AM) value at a specific location and relate the module's electrical parameters. It is standard procedure for PV manufacturers to rate the module's power at a specific spectral condition, AM 1.5 which is intended to be representative of most indoor laboratories and is not a typical spectral condition of most outdoor sites. The question that one has to ask is, why then is AM 1.5 spectrum not ideal? What conditions were optimized in the modeling of AM 1.5 spectra? What are the cost implications on the customer's side when the PV module is finally deployed at spectra different from AM 1.5?

The modeled AM 1.5 spectrum commonly used for PV module rating was created using a radiative transfer model called BRITE (Riordan et al., 1990). The modeled conditions used for example the sun-facing angle, tilted 37º from the horizontal, was chosen as average latitude for the United States of America. The 1.42 cm of precipitable water vapor and 0.34 cm of ozone in a vertical column from sea level are all gathered from USA data. Ground reflectance was fixed at 0.2, a typical value for dry and bare soil. In principle this spectra is a typical USA spectrum and therefore makes sense to rate PV modules which are to be deployed in USA and the surrounding countries.

AM is simply defined as the ratio of atmospheric mass in the actual observer - sun path to the mass that would exist if the sun was directly overhead at sea level using standard barometric pressure (Meyer, 2002). Although the concept of AM is a good approximation tool for quantifying the degree of 'redness' or 'blueness' of the spectrum, the major draw back is that it is applied under specific weather conditions, i.e., clear sky, which probably is suitable for deserts conditions.

2.3 The spectral factor concept

Another notion also adopted to evaluate the effect of outdoor spectrum, is the concept of Spectral Factor. As described by Poissant (Poissant et al., 2006), Spectral Factor is defined as a coefficient of the short-circuit current (I_{sc}) at the current spectrum to the short-circuit current at STC (I_{STC}).

$$m_t = \frac{I_{sc}}{I_{STC}} \cdot \frac{\int_{\lambda_1}^{\lambda_2} E_{STC}(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E(\lambda)d\lambda} \tag{2}$$

From equation 2, the I_{sc} and the I_{STC} is obtained using the equation 3 and 4 respectively.

$$I_{sc} = \int_{\lambda_1}^{\lambda_2} E(\lambda)R_t(\lambda)d\lambda \tag{3}$$

$$I_{STC} = \int_{\lambda_1}^{\lambda_2} E_{STC}(\lambda)R_t(\lambda)d\lambda \tag{4}$$

where: $E(\lambda)$ = Irradiance as function of wavelength

                        $E_{STC}(\lambda)$ = Irradiance at STC

                        $R(\lambda)$ = Reflectivity

The spectral factor quantifies the degree of how the solar spectrum matches the cell spectral response at any given time as compared to the AM1.5 spectrum.

2.4 The useful fraction concept

With regard to changes in the device parameters, the concept of Useful Fraction used by Gottschalg et al (Gottschalg et al., 2003) clearly demonstrates the effect of varying outdoor spectrum. Useful fraction is defined as the ratio of the irradiance within the spectrally useful range of the device to the total irradiance.

$$UF = \frac{1}{G} \int_0^{E_g} G(\lambda)S(\lambda)d\lambda \tag{5}$$

Where E_g is the band-gap of the device (normally the cut - off wavelength) and G is the total irradiance determined as:

$$G(\lambda) = \int_0^{\lambda_{cut-off}} G(\lambda)d\lambda \tag{6}$$

where $G(\lambda)$ is the spectral irradiance encountered by a PV cell.

3. Methodology used in this study

Before the CIS module was deployed outdoors, the module underwent a series of testing procedures in order to establish the baseline characteristics. Visual inspection was adopted to check for some physical defects e.g. cracks, and incomplete scribes due to manufacturing errors. Infrared thermography revealed that no hot spots were present before and after outdoor exposure. These procedures were used to isolate the spectral effects with respect to the performance parameters of the module. To establish the seasonal effects on the module's *I-V* curves, three *I-V* curves were selected. One *I-V* curve for a winter season and the 2nd *I-V* curve for summer season were measured. The 3rd *I-V* curve was used to establish whether the module did not degrade when the winter curve was measured. All curves were measured at noon on clear days so that the effect of cloud cover would be negligible. For accurate comparison purposes all *I-V* curves had to be normalized to STC conditions so that the variations in irradiance and temperature would be corrected. Firstly the I_{sc} values were STC corrected by using equation 1 (Gottschalg et al., 2005).

$$I_{sc} = \left(\frac{I_{sc}}{G} \times 100\right) + \left(25 - T_{module}\right) \times \alpha \tag{7}$$

where *a* is the module temperature coefficient [A/ºC].

Each point on the *I-V* curve had to be adjusted according to equation 8.

$$I_2 = I_1 + I_{sc} \times \left[\left(\frac{1000}{G} \right) - 1 \right] + \alpha \left(25 - T_{\text{mod }ule} \right) \tag{8}$$

where: I_1 =   measured current at any point
                       I_2 =   new corrected current
                       G =   measured irradiance

The corresponding voltage points were also corrected according to equation 9.

$$V_2 = V_1 - R_s \times \left(I_2 - I_1 \right) + \beta \times \left(25 - T_{\text{mod }ule} \right) \tag{9}$$

where: V_1 =   measured voltage at a corresponding point for I_1
                       R_s =   internal series resistance of the module [Ω]
                       β =   voltage temperature coefficient of the module [V/°C]
                       V_2 =   new corrected voltage

The outdoor spectrum was also measured for winter and summer periods in order to compare them for possible changes in the quality of the two spectra (figure 5). With regard to changes in the device parameters, the concept of Weighted Useful Fraction (WUF) (Simon and Meyer, 2008; Simon and Meyer, 2010) was used to clearly demonstrate the effect of varying outdoor spectrum. This concept was developed due to some limitations noted with other outdoor spectral characterization techniques (Christian et al., 2002).

The methodology used by Gottschalg et al (Gottschalg et al, 2002) makes use the assumption that the energy density (W/m²/nm) within the spectral range of the device at a specific wavelength is totally absorbed (100%). But in reality the energy density at a specific wavelength has a specific absorption percentage, which should be considered when determining the spectral response within the device range. It was therefore necessary to introduce what is referred to as the Weighted Useful Fraction (WUF) (Simon and Meyer, 2008; Simon and Meyer, 2010).

$$WUF = \frac{1}{Gtot} \int_0^{E_g} G(\lambda) d(\lambda) SR(\lambda) \tag{10}$$

where: $G(\lambda)$ is the integrated energy density within device spectral range with its corresponding absorption percentage evaluated at each wavelength.

As a quick example, at 350 nm for a-Si device, its corresponding energy density (W/m²/nm) is 20% of the irradiance (W/m²) received which contribute to the electron-hole (e-h) creation and for mc-Si at the same wavelength, 60% is used to create e-h pairs. But the concept of Useful Fraction considers that at each wavelength, all the energy received contributes to the e-h, which is one of the short comings observed from this methodology. The idea of using Weighted Useful Faction was to address these short falls which tend to over estimate the overall device spectral response.

The data obtained using the concept of Weighted Useful Fraction represents a statistical phenomenon of occurrences. Therefore the Gaussian distribution as a statistical tool was used to interpret the data simply because of a mathematical relationship (Central Limit Theorem). In this case the theorem holds because the sample is large (major condition of the theorem) and therefore the Gaussian distribution is suitable to be applied. In this study, the

3rd parameter Gaussian distribution function was used to describe the distribution pattern and to accurately determine the variance of points from the peak value (central value). The peaks of the Gaussian distribution was obtained by firstly creating frequency bins for the WUF and determine the frequency of the points in each bin expressed as a percentage. The bins were imported into SigmaPlot 10 and the peak 3rd Gaussian distribution function was used to accurately generate the peak WUF. Figure 1 illustrates the frequency distribution bins for a-Si:H module.
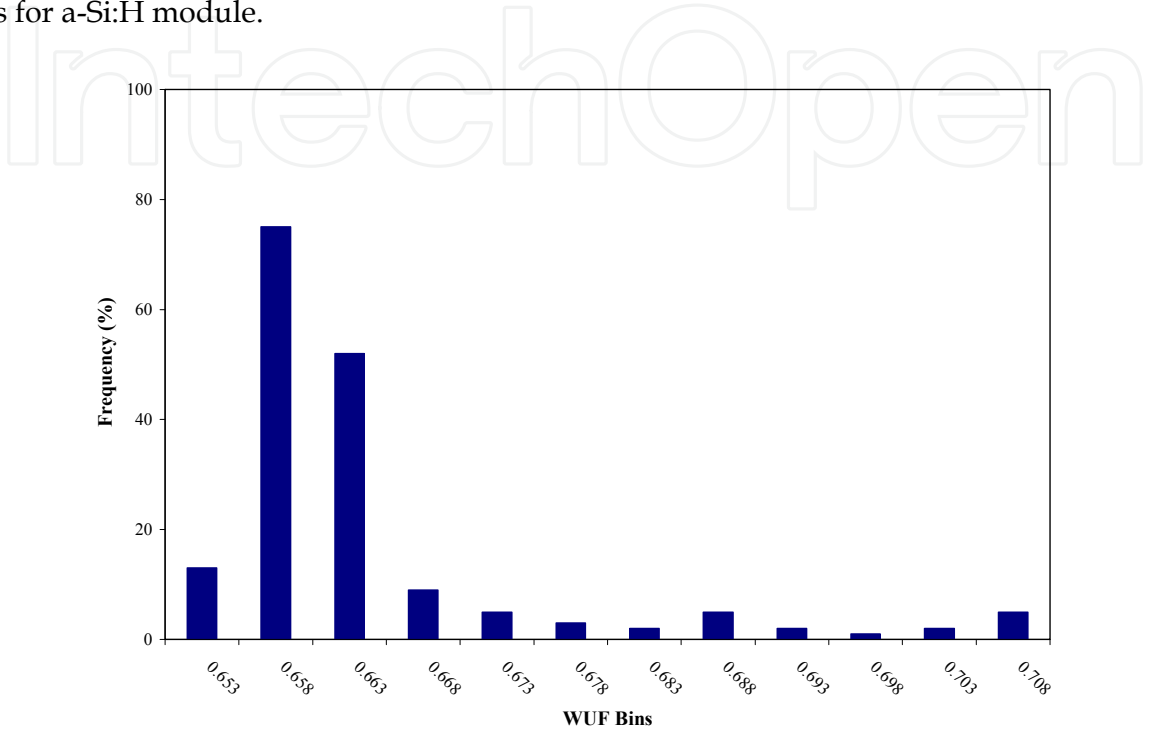
Fig. 1. Frequency distribution of WUF for a-Si:H module

Evident from figure 1 is an increase in WUF frequency at specific WUF value. This percentage frequency represents the number of data points measured at a specific WUF during the study period.

The centre of the points, which corresponds to the spectrum the device "prefers" most, was obtained using the peak Gaussian distribution of the form:

$$f = a\exp\left[-0.5\left((x - x_o)/b\right)^2\right]$$ (11)

where: a = highest frequency

       x = WUF value

       x_o = WUF centre value

       b = deviation (2σ)

Figure 2 illustrates a typical Gaussian distribution used to accurately determine the mean Weighted Useful Fraction.

Also illustrated is the width of the distribution as measured by the standard deviation or variance (standard deviation squared = σ^2). In order to interpret the results generated from each Gaussian distribution, two main terminologies had to be fully understood so that the results have a physical meaning and not just a statistical meaning. The standard deviation (σ) quantifies the degree of data scatter from one another, usually it is from the mean value.

In simple statistics, the data represented by the Gaussian distribution implies that 68% of the values (on either side) lie within the 1st standard deviation (1σ) and 95% of the values lie within the 2nd standard deviation. The confidence interval level was also analyzed when determining the mean value. The confidence interval quantifies the precision of the mean, which was vital in this analysis since the mean represents the WUF spectrum from which the devices responds best during the entire period of outdoor exposure. The increase in standard deviation means that the device spends less time on the corresponding WUF spectrum. Ideally it represents the error margin from the mean value. The percentage frequency value corresponding to the mean WUF value represents the percentage of the total time of outdoor exposure to which the device was responding best to that spectrum.
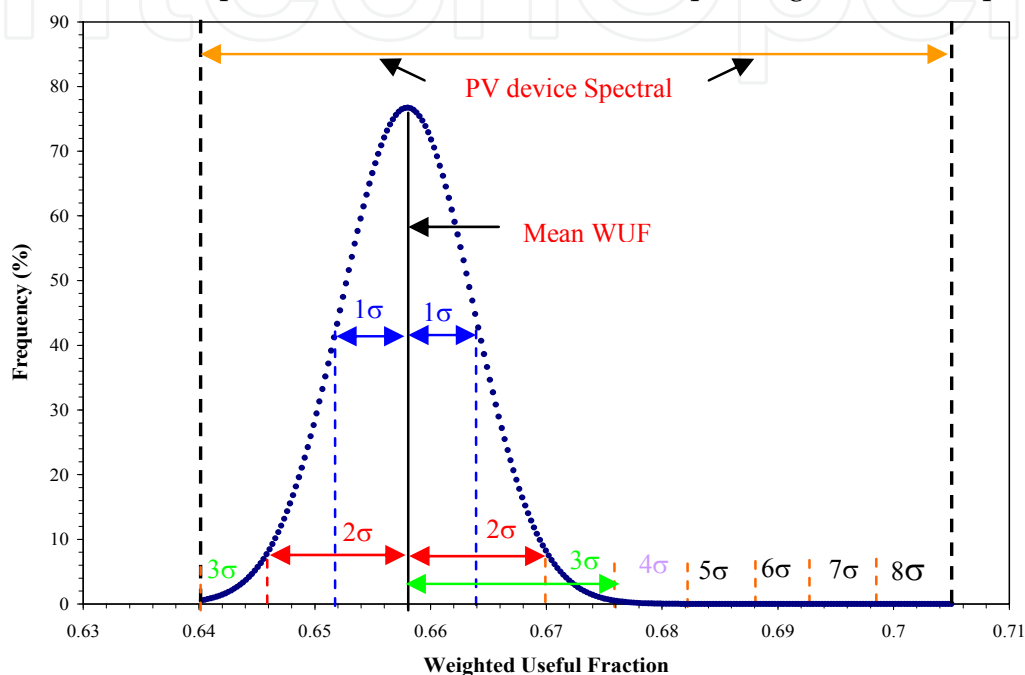

Fig. 2. Illustration of Gaussian distribution used to determine the mean WUF.

Depending on how the data is distributed, the Gaussian curve 'tails' differently from each side of the mean value. The increase in σ in this case reveals two crucial points regarding the statistical data in question. Firstly, it quantifies the total time spent at a specific spectrum as the σ increases during the entire period of monitoring. Secondly it reveals the entire spectral range to which PV devices respond. From figure 2, the standard deviation increases from 1σ to 8σ on one side of the mean WUF and from the other side varies from 1σ to 3σ. The total range of the WUF is from 0.64 to 0.7 although it spends less time from spectral range where standard deviation σ is greater than a unit. A high confidence level of each Gaussian distribution indicates the accuracy of the determined mean. All results presented in this work showed a high confidence level.

Normalization of I_{sc} was achieved by dividing the module's I_{sc} with the total irradiance within the device spectral range ($G_{Spectral\ Range}$). The commonly adopted correlation existing between the module's I_{sc} and back-of-module temperature is of the form $I_{sc} = (C_0 + C_1 T_{device}) \times G_{SpectralRange}$ (Gottschalg et al., 2004). Firstly, the relationship between $I_{sc}/G_{SpectralRange}$ (which is referred to as $\varphi_{SpectralRange}$ from this point onwards) is plotted against back-of-module temperature. The empirical coefficient C_0 and C_1 are obtained. The second

aspect is to plot $\varphi_{SpectralRange} \div (C_o + C_1 T_{device}) = f(WUF)$ versus the Weighted Useful Fraction (WUF), from which the predominant effect of the spectrum can be observed and analyzed. Due to a large number of data obtained, all results analyses were made using only data corresponding to global irradiance (G_{global}) > 100 W/m². This was done to reduce scatter without compromising the validity of the results

4. Results and discussion

Although the outdoor parameters might 'mimic' the STC conditions, the performance of the PV device will not perform to that expectation. By analyzing the effect of outdoor environment, the spectrum received is largely influenced by solar altitude and atmospheric composition, which in turn affect device performance.

Figure 3 illustrates the seasonal effects on the CIS module current-voltage *(I-V)* characteristics when deployed outdoor, first on 31 January 2008 and later on 12 June 2008.

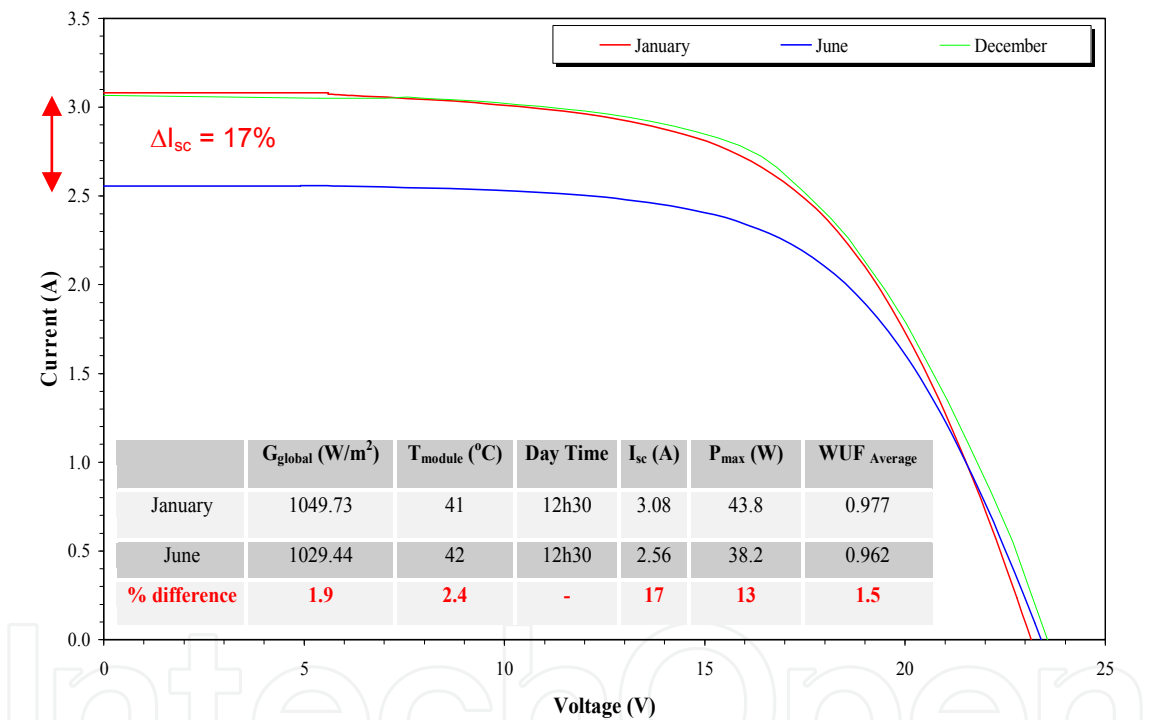|	G_{global} (W/m²)	T_{module} (°C)	Day Time	I_{sc} (A)	P_{max} (W)	WUF Average
January	1049.73	41	12h30	3.08	43.8	0.977
June	1029.44	42	12h30	2.56	38.2	0.962
% difference	1.9	2.4	-	17	13	1.5

Fig. 3. Comparison of the CIS I-V characteristics for a typical summer clear sky and winter clear sky. The accompanying table lists the conditions before corrections to STC.

The January *I-V* curve was taken a few days after deployment of the modules while operating at outdoor conditions. Two aspects needed to be verified with this comparative analysis of the I-V curves for that time frame: Firstly the state of the module, i.e. whether it did not degrade within this time frame needed to be ascertained so that any effect on device I_{sc}, FF and efficiency would be purely attributed to spectral effects. Secondly, this was done to see the effect of seasonal changes on the *I-V* characteristics. Since the outdoor conditions are almost the same when the measurements were taken, the I-V curves were normalized to STC conditions using the procedure mentioned in section 2. Since the 3 *I-V* curves had been corrected for both temperature and irradiance, therefore any

modification or changes on the I_{sc} values is purely due to spectral effect. The difference in module's I_{sc} is largely attributed to the outdoor spectral composition, which as have been mentioned earlier on, depends on season and time of the year amongst other factors. The CIS module was also simulated using Solar Studio Design. At each AM value, the module's *I-V* curve was obtained. Figure 4 illustrates the effects on the simulated CIS *I-V* curves as the Air Mass was varied.
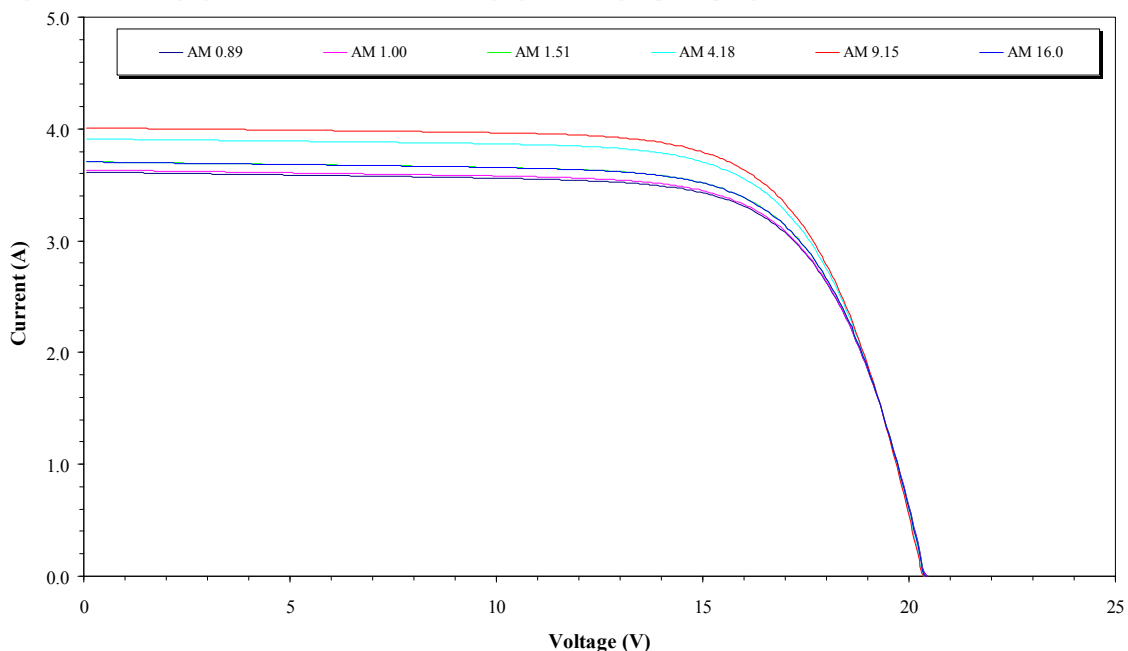

Fig. 4. The effect of varying Air mass on the simulated CIS module.

The change in outdoor spectrum as characterized by the AM values affect the module's *I-V* curves, mostly the I_{sc}. Although this module is rated at STC using the AM1.5 spectrum, the CIS module is performing less at AM1.5 as compared to AM 9.15. The *I-V* curve at AM 1.5 coincides with the *I-V* curve at AM 16.0. It should be noted that the change in AM value is an indication of the spectral content dominating. The ΔI_{sc} = 7.5% difference between I_{sc} at AM 1.5 and I_{sc} at AM 9.15 is purely due to spectral changes. Returning back to figure 1, the difference in I_{sc} between winter and summer spectrum is due to spectral changes. The typical winter and summer spectra were compared with the view of finding any variation in the profiles. All values were divided by the highest energy density in each curve so as to normalize them. Figure 5 presents the normalized spectral distribution corresponding to the two *I-V* curves in figure 3.

Clearly there is a difference in the spectral content primarily due to the difference in solar altitude and hence air mass. In the absence of the device degradation, similar irradiance and module temperatures, the reduction in module performance is attributed to the difference in spectral distribution associated with the seasonal variation. To further verify whether indeed the reduction in the module's I_{sc} was due to spectral changes associated with seasonal changes, the device WUF for the entire year was analyzed. The monthly average WUF was considered to be sufficient to provide evidence, if any in its profile. Figure 6 shows the evolution of the monthly average WUF of the CIS module.
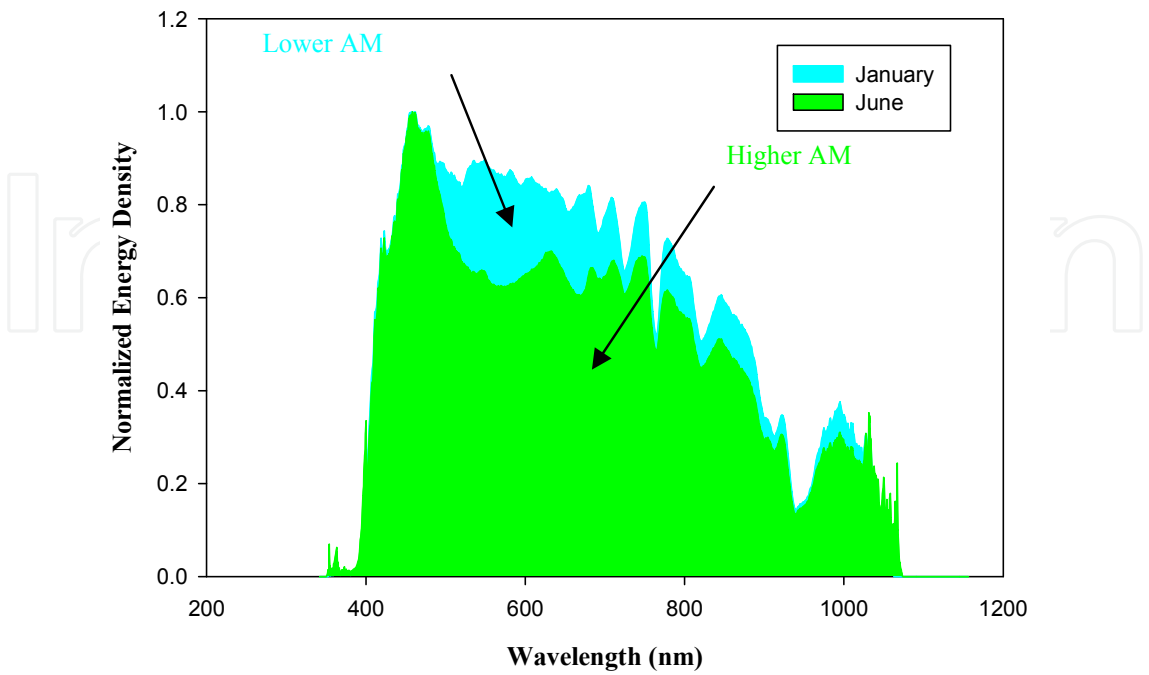
Fig. 5. Normalized spectral distribution for January and June months.
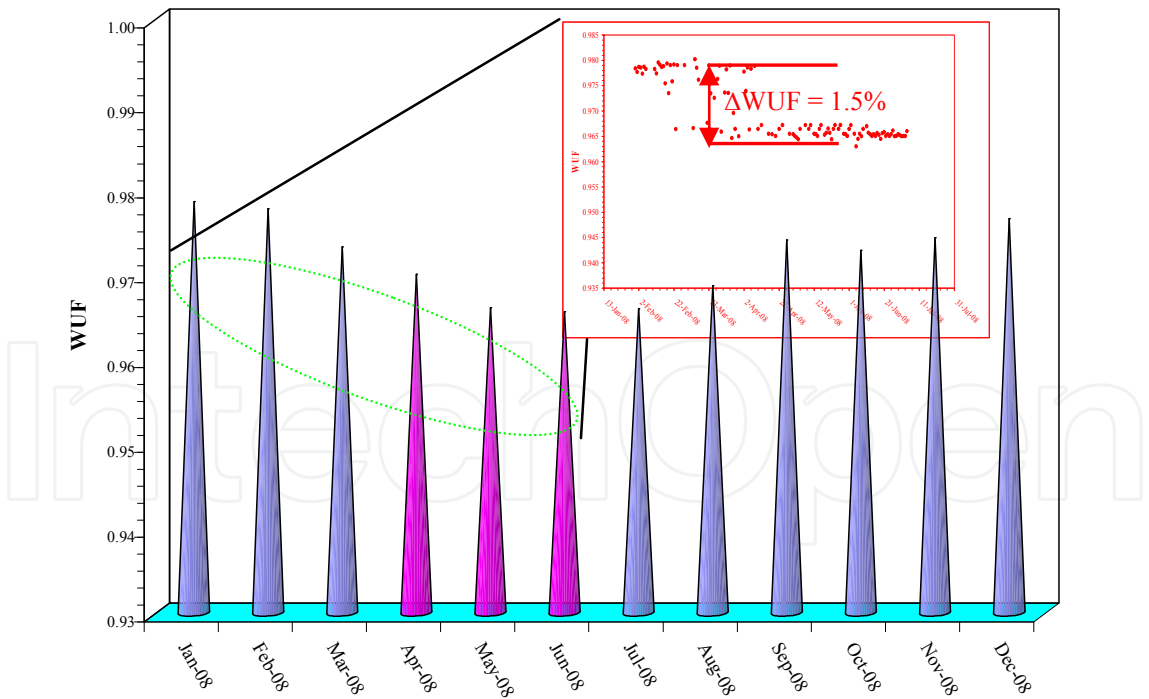

Fig. 6. Evolution of daily average Weighted Useful Fraction versus timeline. Inset is an average daily profile for the period from January to June 2008.

Evident from figure 6 is the high values of CIS WUF for the entire period which indicates that the device performs well under full spectrum. Taking the average values of the upper

(summer) and the lower for winter, a 1.5% drop in WUF is noticed (inset figure). A small change in WUF results in large change of the device's I_{sc}. In order to verify this assumption, the change in WUF versus Air Mass was established as is presented in figure 7.
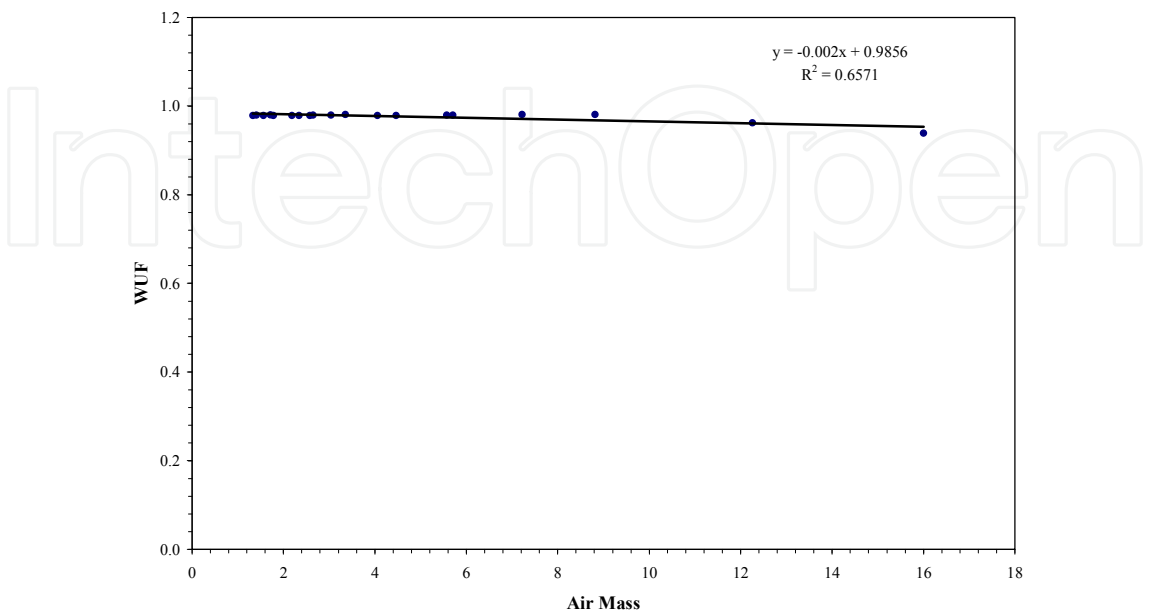
Fig. 7. Influence of the air mass on device spectral variations as characterized by WUF for CIS module.

The relationship established in figure 7 was used to calculate the change in WUF at different Air Mass values, a typical change in season. Values for low air mass (indication of a summer spectrum) and high air mass (indication of winter) were used to calculate the % change in WUF and later compared to the simulated % change in I_{sc} at different AM values, the same values that has been used in previous calculation. Equations 12 and 13 illustrate the equations used for this calculation.

$$WUF_{1.0} = -0.002 \times AM1.0 + 0.9856 \tag{12}$$

$$WUF_{9.15} = -0.002 \times AM9.15 + 0.9856 \tag{13}$$

where: $WUF_{1.0}$ is the calculated value of WUF at AM 1.0 and the $WUF_{9.15}$ is the calculated value of WUF at AM 9.15.

From figure 4 the value for I_{sc} (AM 1.0) and I_{sc} (AM 9.15) were used to calculate the % change in I_{sc} as the spectrum changes. The $\Delta WUF = WUF_{1.0} - WUF_{9.15}$ expressed as a %, was found to be 1.66%, while the $\Delta I_{sc} = 11.88\%$. From this analysis, one can conclude that a small % change in ΔWUF result in large % difference of the module's I_{sc}, which explains the 17% decrease in I_{sc} due to a ΔWUF of 1.5%. The slight difference in the two results is due to the difference in the actual operating conditions in which case the simulated conditions are different from the actual conditions when the two I-V curves in figure 4 were measured.

A 10 point moving average was applied so that a clear correlation can be seen. By fitting a 3rd order polynomial fit, a functional relationship between FF and WUF is observed. The FF of the device is an indication of the series and junction quality of the device cells; therefore

by plotting the FF with WUF a functional relationship can be established. Figure 8 shows the slight increase in FF as the WUF varies.
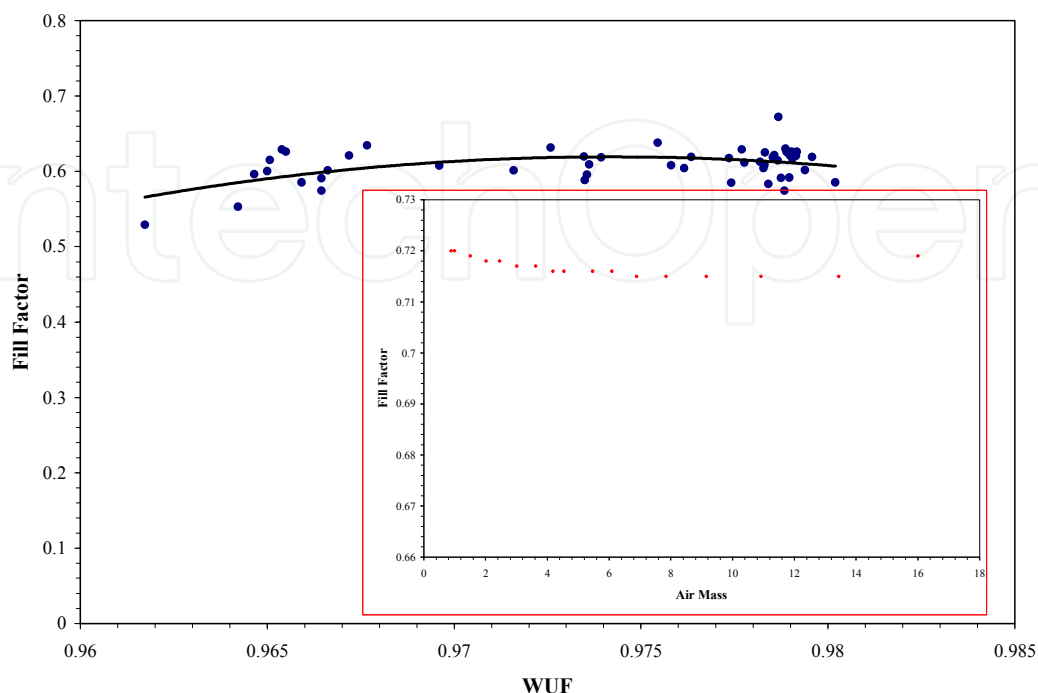

Fig. 8. Effect on CIS average Fill factor due to outdoor irradiance and spectral changes. Inset is the variation of FF vs. Air Mass for the same device.

Observed from figure 6, a 6.5% increase in FF is observed within the WUF range 0.960 - 0.983 (considering the % difference between the averages of the upper and low values of the FF). It should however be noted that this percentage increase value is just an indication of the change in FF. The increase in FF as observed is attributed to the quality of the spectrum dominating which result in 'supplying' sufficient energy for the electron-hole creation, with less energy losses, which in most cases is dissipated as heat. From the inset figure, a decrease in FF as AM values increase from AM 1.5 is evident. Closely analyzing the two graphs, the spectrum dominating under the WUF range of the CIS module is a blue rich spectrum which explains a slight increase in FF. From the inset figure, the FF is higher at AM 1.5 and decrease as the spectrum becomes longer wavelength dominated. Clearly the change in outdoor spectrum has an effect on the FF of the CIS module. Often reported is the relationship between efficiency and global irradiance as measured by the pyranometer. For CIS module, the variation of aperture efficiency with WUF is visible described by a logarithmic fit into the scattered data. Both WUF and irradiance affect device performance with the same magnitude. Gottschalg et al., (Gottschalg et al., 2004) established a relationship for device aperture efficiency and Useful Fraction (UF). The efficiency is described by $\eta \approx \frac{\alpha}{A} UF$ which when interpolated to our concept of Weighted Useful Faction (WUF) the device efficiency would be described by $\eta \approx \frac{\alpha}{A} WUF$: where $\alpha = Power(P)/Spectral\,\mathrm{Re}\,sponsiveRange(UI)$, is roughly a constant. This relationship exhibit a

linear trend of efficiency with WUF in our case. The other key performance indicator in PV analysis is the device aperture efficiency. The efficiency of CIS module was also analyzed using the same procedure for FF analysis. Figure 9 indicate the efficiency versus WUF of the CIS device.
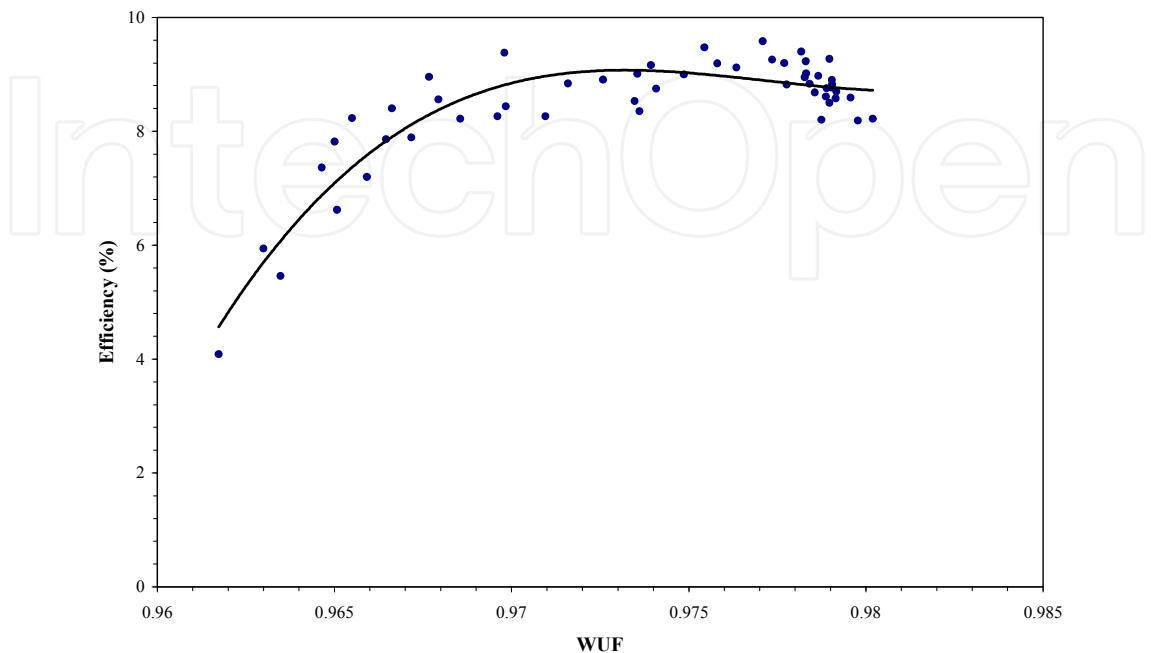

Fig. 9. Correlation between aperture efficiency versus outdoor WUF of the CIS module.

The efficiency increases logarithmically with an increase in Weighted Useful fraction (WUF > 0.960), which do not agree with the theoretical relationship illustrated in the previous section ($\eta \approx \frac{\alpha}{A} WUF$). One can attribute this discrepancy of the measured data and theory as follows: The α in the equation above is assumed to be a constant, but in actual fact it is strongly dependant on the irradiance available within the denominator function (UI). The irradiance within the Responsive Spectral Range (UI) is assumed to be a constant, a single value to be precise. In reality the irradiance does fluctuates within this range, rendering the α not to be a constant parameter. However the device efficiency exhibits a logarithmic increase as a function of WUF, due to the irradiance variations, resulting in α not to be a constant. The effect of season on device efficiency was also investigated; the results are shown in figure 10.

It is observed from figure 10 that the device efficiency is stable for both summer and winter. The PV module's performance parameters e.g. I_{sc}, V_{oc}, FF and η are characterized by what is referred to as temperature coefficients. Temperature coefficient is described as the rate of change (derivative) of the parameter with respect to the temperature of the PV device performance parameters (King et al., 1997). For PV system sizing and design, knowing the device temperature coefficient plays a very critical role. Quantifying the spectral effects on its own has proved to be a challenge; as a result no temperature coefficient with respect to outdoor spectrum has been documented. In figures 11 and 12, the relationship between outdoor spectral effects (WUF) and the average back - of module temperature is presented. Using a linear fit to the data, a spectral temperature coefficient is obtained. Figure 11 illustrates the relationship between WUF and temperature for a winter period.
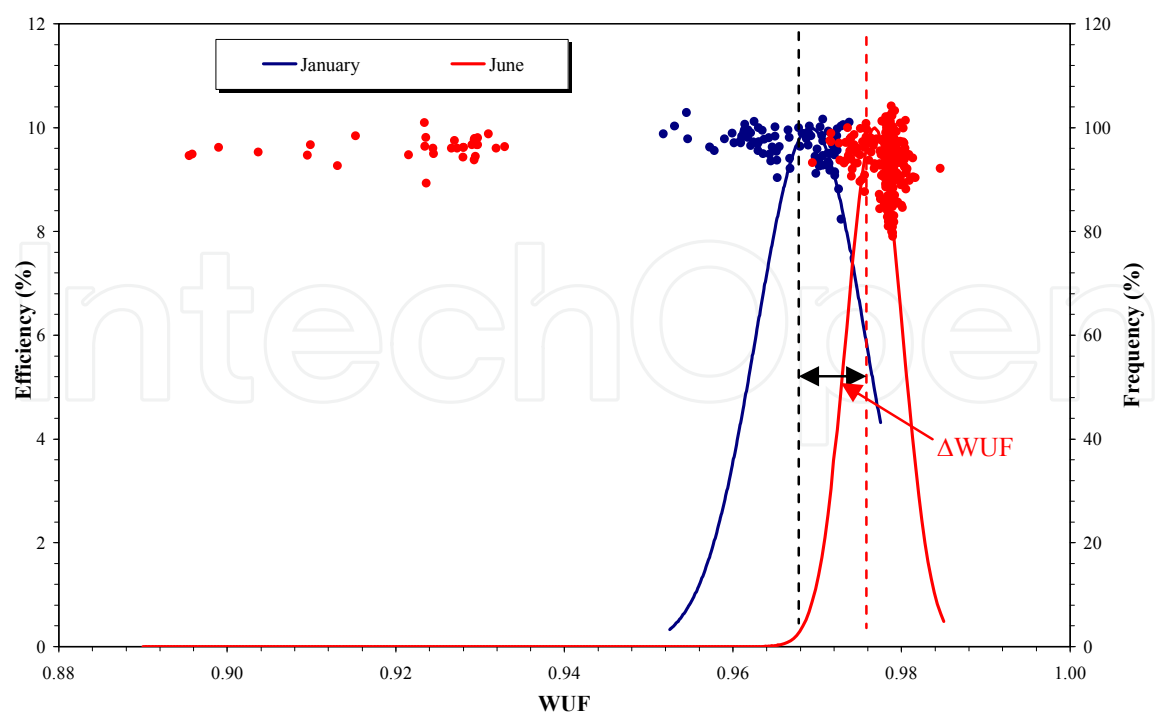
Fig. 10. Average outdoor aperture efficiency as a function of WUF of CIS module for both winter and summer period.
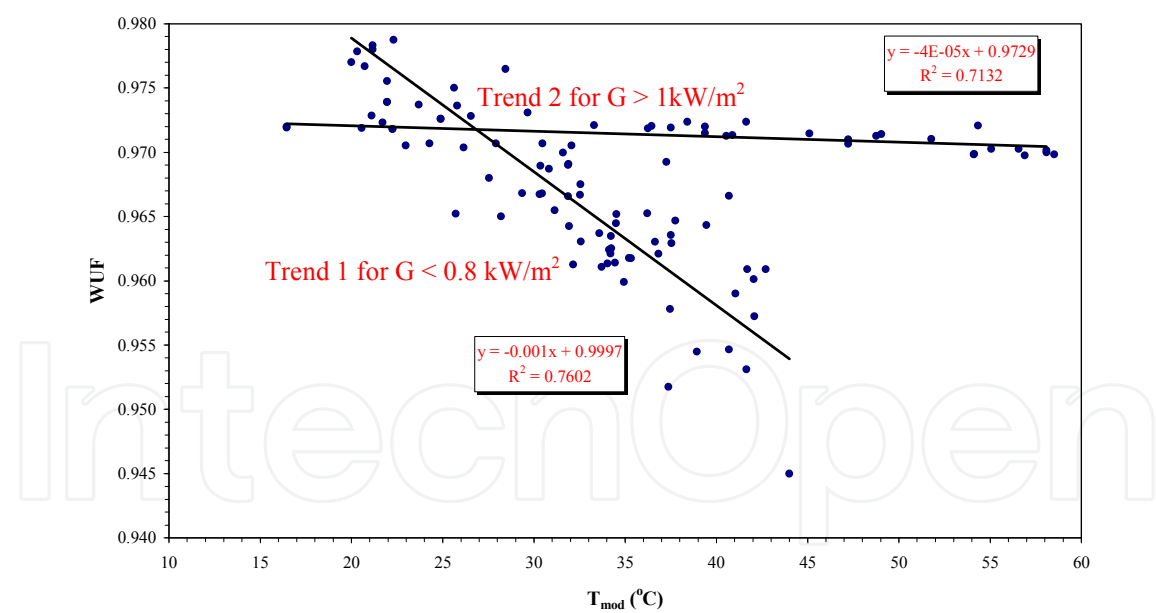

Fig. 11. Relationship between the outdoor WUF and back of module temperature of the CIS module during winter period.

Observing the results in figure 11, two temperature coefficients for WUF are obtained during the winter period. This trend in behaviour could have been attributed to the different outdoor weather patterns observed for winter period. Some days even during winter, the outdoor climatic conditions would resemble a typical clear sky summer season, indicated by

very high temperature (indicated by trend 2), while the rest of the days would be for typical winter season, normally characterized by mostly low temperature. In both cases, a negative WUF temperature coefficient is observed, with trend 1 being -0.001/^{o}C and for trend 2 being -0.4×10^{-5}/^{o}C.

The same procedure was also used to find the effect of temperature on WUF for summer months of CIS module. Figure 12 shows the WUF versus temperature relationship.

Interesting to note from figure 12 is that the spectral effect temperature coefficient for summer period is the same as the one obtained during winter, clear sky (trend 2) although for summer the highest temperature reached was above 60°C while for trend 2 (figure 11), the highest was less than 60°C. From the two figures, it has been shown that temperature coefficient due to spectral effect (WUF$_\beta$) can be obtained once the outdoor spectrum data for a device is correctly calculated using the Weighted Useful Fraction (WUF) concept. Like other performance parameters, whose temperature coefficients are equally important in PV characterization and system design, the WUF should be also be considered as this might help to minimize some of the system sizing errors, which in most instances lead to under performance, unreliable and financial repercussions.
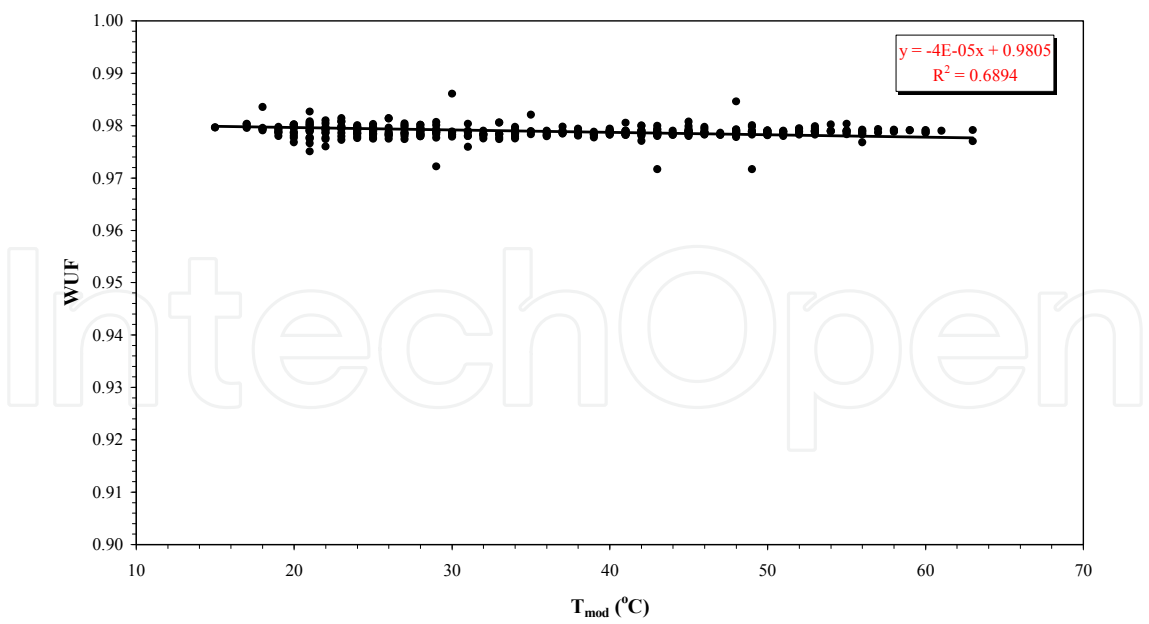

Fig. 12. Relationship between the outdoor WUF and back of module temperature of the CIS module during summer period.

5. Conclusion

The outdoor spectral effects using the Weighted Useful Fraction (WUF) of CIS module was analyzed. Observed was a 17% decrease in the device short - circuit (I_{sc}) current attributed due to a change in season. The change in season (summer/winter) result in the outdoor spectrum to vary by ΔWUF = 1.5%, result in the decrease in the device I_{sc}. From the analysis done, it was concluded that a small percentage change in ΔWUF resulted in large % difference of the module's I_{sc} as the outdoor spectrum changed during the course of the day, which confirmed that the 17% decrease in I_{sc} was due to a ΔWUF of 1.5 %. A strong correlation between FF and the WUF exists for CIS module. It is observed that the FF increases by 6.5% as WUF increases. The temperature coefficient of a device is one of the important concepts for characterizing device performance parameter. A close correlation between WUF and temperature was established. Temperature coefficients for spectral induced effect (WUF) were found to be -0.001/°C for winter period and -4×10^{-5}/°C for summer seasons. This difference in WUF$_\beta$ for summer and winter indicated that the temperature coefficients obtained in controlled environment (indoor procedure) can not be truly dependable for modeling purposes or system sizing since the outdoor conditions has an effect also. It should also be noted that the temperature coefficient for spectral effect is indeed an important parameter to consider.

6. References

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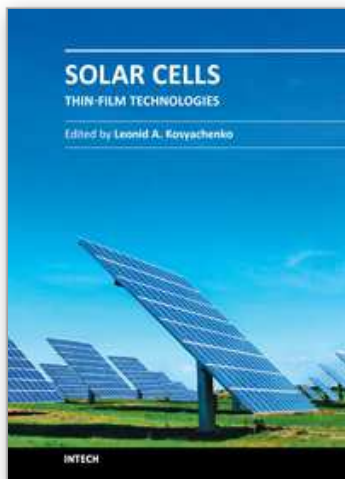
Solar Cells - Thin-Film Technologies

Edited by Prof. Leonid A. Kosyachenko

The first book of this four-volume edition is dedicated to one of the most promising areas of photovoltaics, which has already reached a large-scale production of the second-generation thin-film solar modules and has resulted in building the powerful solar plants in several countries around the world. Thin-film technologies using direct-gap semiconductors such as CIGS and CdTe offer the lowest manufacturing costs and are becoming more prevalent in the industry allowing to improve manufacturability of the production at significantly larger scales than for wafer or ribbon Si modules. It is only a matter of time before thin films like CIGS and CdTe will replace wafer-based silicon solar cells as the dominant photovoltaic technology. Photoelectric efficiency of thin-film solar modules is still far from the theoretical limit. The scientific and technological problems of increasing this key parameter of the solar cell are discussed in several chapters of this volume.

How to reference

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Michael Simon and Edson L. Meyer (2011). Spectral Effects on CIS Modules While Deployed Outdoors, Solar Cells - Thin-Film Technologies, Prof. Leonid A. Kosyachenko (Ed.), ISBN: 978-953-307-570-9, InTech, Available from: http://www.intechopen.com/books/solar-cells-thin-film-technologies/spectral-effects-on-cis-modules-while-deployed-outdoors

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