CHAPTER 3

METHODOLOGIES FOR OUTDOOR SPECTRUM EVALUATION

3.1 INTRODUCTION

The outdoor environment to which Photovoltaic (PV) devices are subjected is a complex entity in its own right. Attempting to analyze the different phenomena and how they influence each other has proven to be rather challenging. How does each of those environmental factors influence the performance of these devices? Is it possible to isolate each of these factors and evaluate its impact on PV performance? These are some of the challenges that are associated with outdoor monitoring procedures.

The benchmark rating of PV devices is done under reference conditions of AM 1.5 Global spectrum, 1000 W/m^2 and 25^{o}C. Research has shown that G(λ) = 1000 W/m^2 as measured by a pyranometer in the field, does not indicate that G(λ) (Field) ≡ $G_{AM\ 1.5}$(λ) [Gottschalg, et al., 2005], since the field spectrum shape is strongly dependent on many factors such as time of the year, sun elevation, metrological conditions and incident angle [Gottschalg, et al., 2005]. Figure 3.1 illustrates the difference between a typical sub-Sahara spectrum and the AM 1.5G.

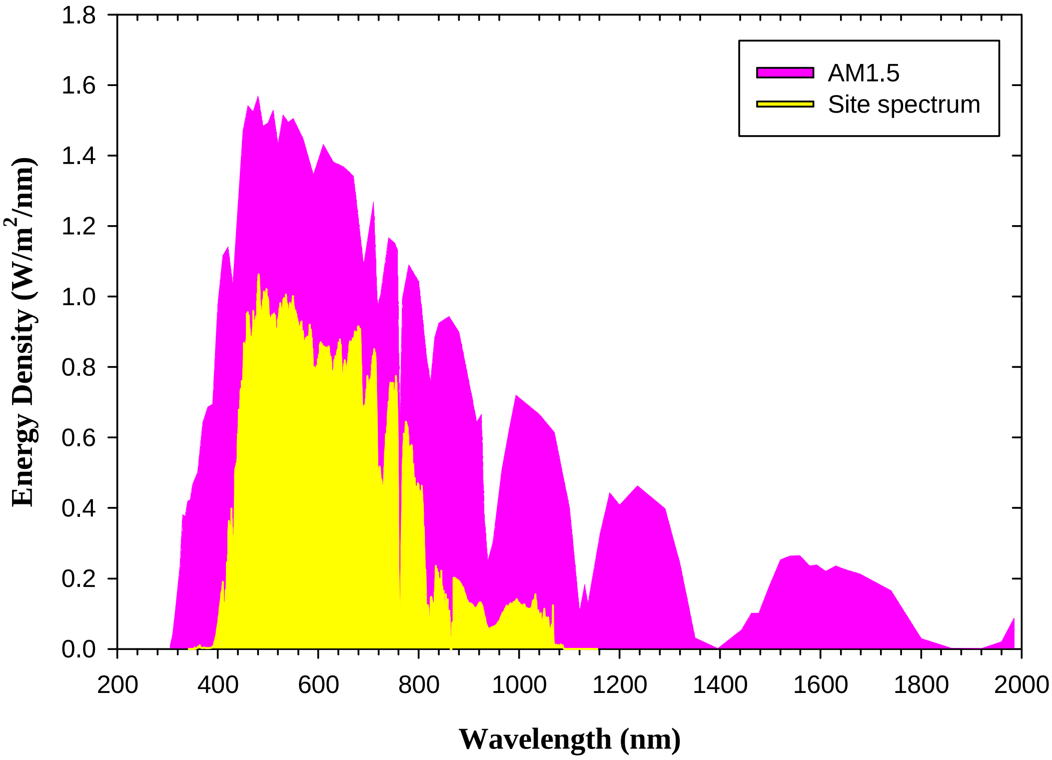

Figure 3.1: *Site - dependant spectrum compared to AM1.5G.*

Although it is well known that the changes in outdoor spectrum affect device performance, little work has been conducted to support this hypothesis. This is probably due to lack of spectral data or in certain instances where data is available, little knowledge of interpreting that data. The outdoor spectral data that one obtains in the field does not lend itself to simple interpretation. Different analytical interpretation procedures have been proposed, all trying to explain and quantify the spectral influence on PV devices. In the following sections, four concepts used to quantify and interpret outdoor spectral data are discussed including their perceived limitations. One outstanding fact is that all these concepts have been used to interpret data obtained in the Northern hemisphere, with no results for Southern hemisphere to date.

3.2 THE CONCEPT OF AVERAGE PHOTON ENERGY

In trying to quantify the ‘blueness’ or ‘redness’ of outdoor spectrum, Christian Jardine adopted the concept of Average Photon Energy (APE) as an alternative [Christian, et al., 2002]. APE which is defined as a measure of the average hue of incident radiation is calculated using the spectral irradiance data divided by the integrated photon flux density, as in equation 3.1.

$$APE = \frac{\int_a^b E_i(\lambda)d\lambda}{q_e\int_a^b \Phi_i(\lambda)d\lambda} \qquad \text{...........3.1}$$

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., 2007; Christian, et al., 2002].

3.3 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 as done in chapter 2, section 2.6.3 for Alice town, South Africa. 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, 1990]. The modeled conditions used for example the sun-facing angle, tilted 37^{o} 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.

3.4 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 (www.cete-vareness.nrcan.gc.ca), 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}).

$$m_t = \frac{I_{sc}}{I_{STC}} . \frac{\int_{\lambda_1}^{\lambda_2} E_{STC}(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} E(\lambda) d\lambda} \qquad \text{...........3.2}$$

From equation 3.2, the I_{sc} and the I_{STC} is obtained using the equation 3.3 and 3.4 respectively.

$$I_{sc} = \int_{\lambda_1}^{\lambda_2} E(\lambda) R_t(\lambda) d\lambda \qquad \text{...........3.3}$$

$$I_{STC} = \int_{\lambda_1}^{\lambda_2} E_{STC}(\lambda) R_t(\lambda) d\lambda \qquad \text{...........3.4}$$

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

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

$R(\lambda)$ = *Reflectivity*

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

3.5 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., 2005] clearly demonstrate 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.

$$UF = \frac{1}{G} \int_{0}^{E_g} G(\lambda) d\lambda \qquad \text{...........3.5}$$

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

$$G = \int_0^\infty G(\lambda) d\lambda \qquad \ldots\ldots\ldots\ldots 3.6$$

where *G(λ)* is the spectral irradiance encountered by a PV cell.

One major assumption made with this methodology is that the energy density ($W/m^2/nm$) 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, et al., 2008].

$$WUF = \frac{1}{G} \int_0^{E_g} G_w(\lambda) d(\lambda) \qquad \ldots\ldots\ldots\ldots 3.7$$

where: $G_w(\lambda)$ 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 ($W/m^2/nm$) is 20% of the irradiance (W/m^2) 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 Useful Fraction mentioned in equation 3.5 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 3.2 illustrates the frequency distribution bins for a-Si:H module.

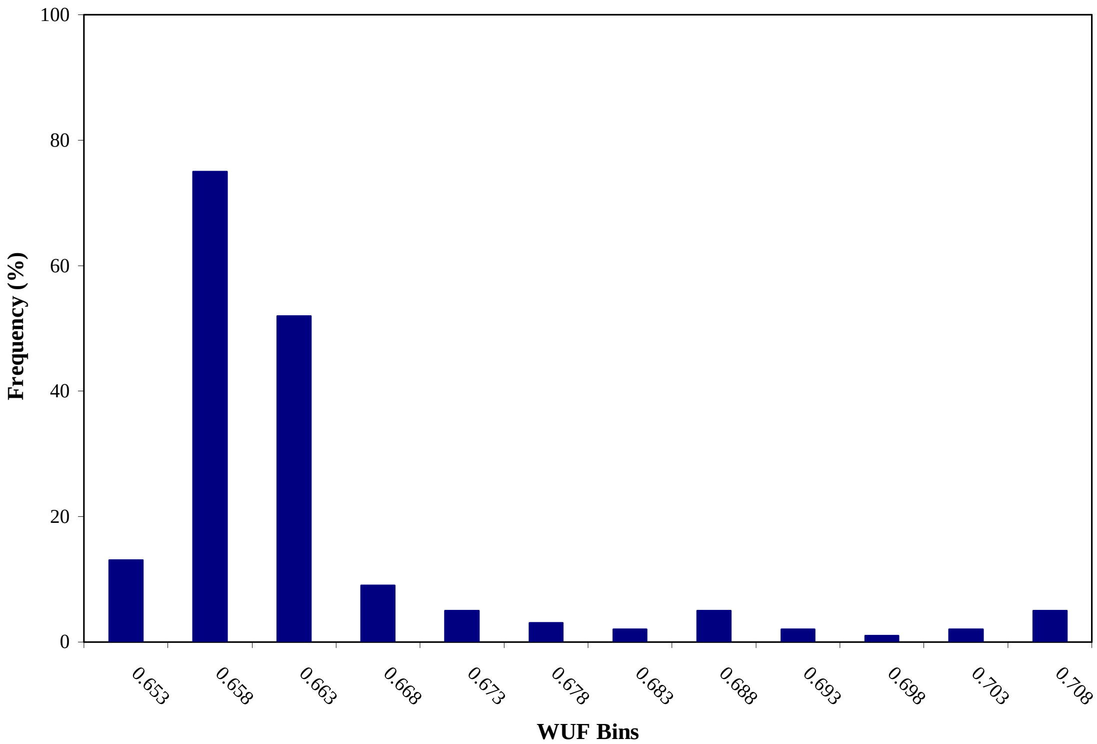

Figure 3.2: *Frequency distribution of WUF for a-Si:H module*

Evident from figure 3.2 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:

$$f = a\exp\left[-0.5\left((x - x_o)/b\right)^2\right] \qquad \text{...........3.8}$$

where: a = highest frequency

x = WUF value

x_o = WUF centre value

b = deviation (2σ)

Figure 3.3 illustrates a typical Gaussian distribution used to accurately determine the mean Weighted Useful Fraction.

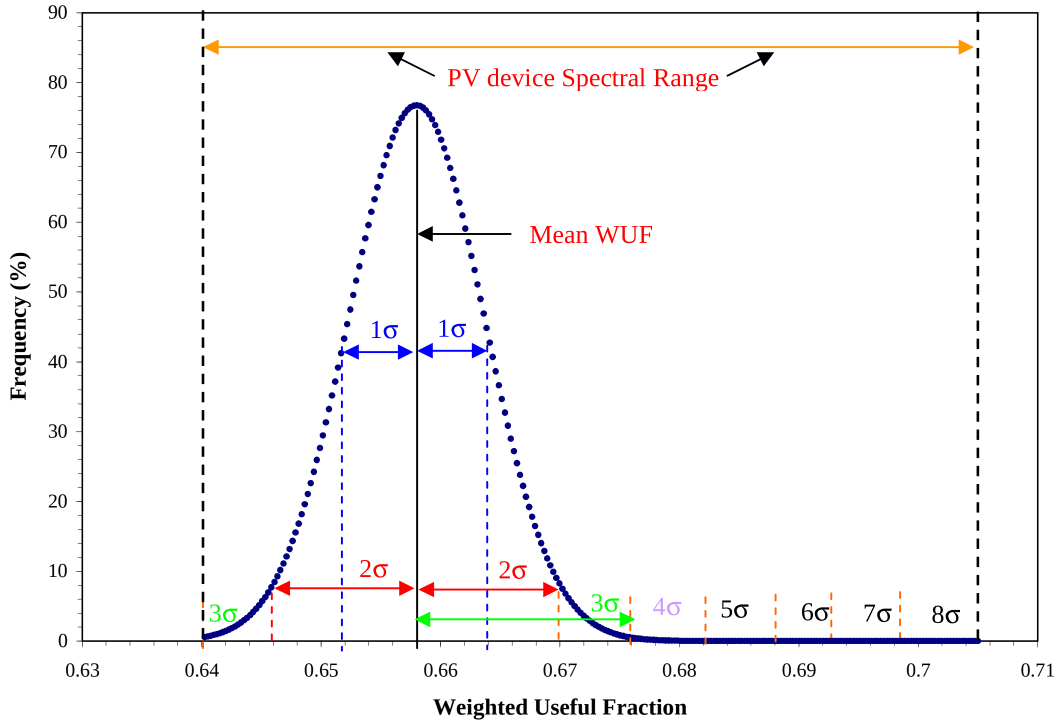

Figure 3.3: *Illustration of Gaussian distribution used to determine the mean WUF.*

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.

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 3.3, 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 $I_{sc} = (C_0 + C_1 T_{device}) \times G_{SpectralRange}$ [Christian, 2002]. Firstly, the relationship between $I_{sc}/G_{SpectralRange}$ (which is referred to as $\phi_{SpectralRange}$ 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 $\phi_{SpectralRange} \div \left(C_o + C_1 T_{device}\right) = f(WUF)$ 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/m^2. This was done to reduce scatter without compromising the validity of the results

3.6 CONCLUSION

This chapter has discussed different methodologies adopted for evaluating the effect of outdoor spectrum. Some shortfalls of each method were also highlighted from which the concept of Weighted Useful Fraction was developed. An analysis and a full description of the Weighted Useful Fraction were clearly elaborated. A Gaussian distribution curve fitting was used to accurately determine the mean WUF of each device. The mean WUF represent the preferred spectrum to which the device responds best during the entire period of outdoor exposure. A figure clearly illustrating the physical meaning of the statistical terms associated with the Gaussian distribution and how the terms were used to interpret the WUF data was discussed. It is evident from the above discussion that the concept of WUF is indeed useful in interpreting outdoor spectral data, which so far does not have a standard methodology.

3.7 REFERENCE

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