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ASPIRE – A TOOL TO INVESTIGATE SPECTRAL EFFECTS ON PV DEVICE PERFORMANCE

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ABSTRACT

A new model for calculating spectral irradiance from standard meteorological inputs is presented, named ASPIRE (All-sky Spectral IRadianceE). The Bouger law-based transmittance approach for modelling clear-sky spectra has been augmented with an extended empirical process to account for variation with cloud cover. Unlike previous clear-sky models, this new tool separates the effects of air mass from cloud cover within the clearness index by comparing measured solar spectra with the results of clear-sky modelling.

The intended use of the ASPIRE model is to allow investigation of spectral effects on PV device output under realistic operating conditions, for which measured spectral irradiance data is rarely available. These investigations are important to refine the energy yield calculations for PV systems operating under seasonally varying spectra, especially wide band gap materials.

1 INTRODUCTION

The spectrum of incident irradiance has become an important factor in the performance of photovoltaic (PV) devices, since many emergent thin film technologies are highly spectrally selective. This can give rise to significant variations in performance as the spectrum changes. Such variation occurs on a daily and a seasonal basis, in a manner and magnitude determined by location and local atmospheric effects. For sites with significant spectral variation and devices with high spectral selectivity, it was shown that this is an important input parameter [1]. Figure 1, for example, shows the seasonal patterns of irradiance availability within the absorption band of a typical single-junction amorphous silicon (a-Si) device, which impacts directly on the efficiency.

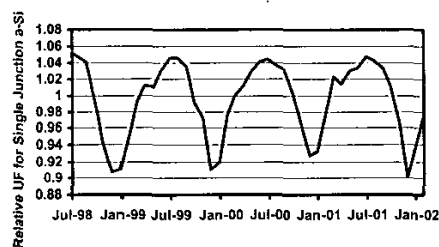


Figure 1: Seasonal Variation of Spectrum

Temperature and total irradiance effects on performance have been the focus of research for some time. Combined with the fact these parameters can be measured rather easily, their effects can be modelled and quantified. Measurement of spectral irradiance poses more

problems, such as the higher cost of equipment. This results in spectral measurement systems making a balance between accuracy and measurement time and can lead to either inadequate resolution, or measurements that have been distorted by variation in the spectrum during the acquisition period.

To circumvent these issues and enable studies of spectral irradiance at sites where no measured data exists, various spectral irradiance models have been developed, based on input from meteorological parameters [2-4]. Despite the limitations of such a simple approach, these models have proven to be accurate enough to benefit PV system analysis routines. The main drawback of such models is that they only hold for clear sky situations, i.e. with no cloud present. In the locations where these models have been applied, it has been argued with reason that the contribution to total energy production, over say a year, from the PV system operating in cloudy conditions is not significant. However, PV is now accepted as having a valuable role in locations which do not enjoy the highest levels of insolation, such as those at higher latitudes, or those with maritime climates or similarly mixed weather. In the UK for example, about one quarter of annual solar energy is delivered under cloudy skies, hence it is important to be able to characterise these conditions and determine how they affect PV device performance. This paper presents work on a tool for modelling the spectrum of incoming solar radiation for all sky conditions, under development at the Centre for Renewable Energy Systems Technology (CREST) in the UK.

2 CLEAR-SKY MODEL

First, the clear-sky irradiance spectrum is modelled, before correcting it for cloud cover. The clear-sky spectral model employed comprises three parts: the calculation of beam irradiance normal to the Sun, the horizontal diffuse irradiance calculation, and the translation of the two components to global irradiance in the tilted plane required. The spectrum is modelled in the range 300 to 1700nm, since this covers the response of all terrestrial PV devices and matches the measurement capability of the system at CREST. The spectral beam transmittance is derived for each wavelength (in 10nm intervals) as the product of the extra-terrestrial spectrum (considered stable) and the transmittance fractions associated with various atmospheric absorption/scattering processes:

$$I_{B\lambda} = DI_{ET\lambda} \tau_{ra} \tau_{aa} \tau_{oa} \tau_{wa} \tau_{mg\lambda} \quad (1)$$

where D is the seasonal Earth-Sun distance correction, $I_{ET\lambda}$ is the extraterrestrial radiation at wavelength λ , and the τ 's are the transmittance fractions associated with each

of the scattering and absorption processes (Rayleigh and Mie scattering and absorption by ozone, water vapour and other gases). The diffuse spectrum is determined from the scatter fractions and directions calculated during the beam modelling:

$$I_{D\lambda} = I_{r\lambda} \times I_{a\lambda} \times I_{gs\lambda} \quad (2)$$

where $I_{r\lambda}$, $I_{a\lambda}$, and $I_{gs\lambda}$ are the contributions due to Rayleigh scattering, aerosol (Mie) scattering and reflections between the ground and sky, respectively.

The beam and diffuse components for each wavelength are finally combined on a tilted plane to give the global spectral irradiance required, using the algorithm of Hay and Davies (tested comparatively against similar models in [5]) for the diffuse irradiance.

The transmittance sub-models used here most closely match those employed in Chris Gueymard's SMARTS2 code [4, 6], developed from the rigorous multi-layer algorithms of the LOWTRAN/MODTRAN family. The named sources differ for the extra-terrestrial spectrum and gas absorption data, which for this work are taken from [7], but overall this has little influence for the present engineering application. More significant is the selection of the aerosol model, since the scattering and absorption of radiation by aerosols is one of the most variable factors in the beam calculation. This also has a large influence on the diffuse component, which is based entirely on scattering effects. Aerosols are highly site dependent, being affected by local climate and pollution levels, both of which change over time. This is a difficult challenge to overcome in the development of a model designed to be widely applicable with a minimum of inputs and results in an unavoidable compromise. The parameters used here come from a maritime climate model and are held constant throughout the year. If complexity is not a problem, there are methods discussed in [6] to elaborate the detail of the aerosol model and include time dependence.

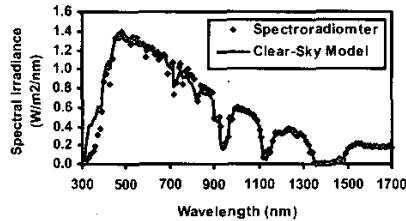


Figure 2: Clear-Sky Model Performance Under Clear Skies

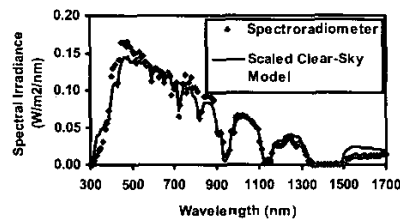


Figure 3: Scaled Clear-Sky Model Performance Under Cloudy Skies

Figure 2 shows a typical example of the clear-sky model performance against measured spectra, taken from cloud-free skies. Figure 3 shows that, even with normalising the modelled spectra to the same broadband irradiance value as measurements taken under cloudy skies, the clear-sky model does not satisfactorily reproduce the energy distribution of the cloudy spectrum. This is due to the fact that attenuation due to cloud cover is not uniform over wavelength [8].

For locations such as the U.K., where a significant proportion of solar energy is delivered under non-clear skies, it is apparent that the effect of cloud on the spectrum and hence on PV device performance should be taken into account.

3 CLOUD MODEL

To date, the only effort to model cloudy-sky spectra involved fitting spectral measurements to a clear-sky model to generate a correcting polynomial function of clearness index (k_T) [9]. The clearness index, k_T is defined as the ratio of measured terrestrial irradiance on a horizontal surface to the top-of-atmosphere irradiance incident on a horizontal surface. As such, it has an inherent dependence not only on atmospheric opacity, but also on air mass. This does not make it the ideal parameter for characterising irradiance conditions since the same value of k_T can be attributed to quite dissimilar spectral environments. Instead, a clear weather index (CWI) parameter has been defined as the ratio of measured terrestrial irradiance on a horizontal surface to simulated clear-sky terrestrial irradiance on a horizontal surface. In this way, the air mass can be used to parameterise spectral variation due to atmospheric path length and the CWI can be used to parameterise spectral variation due to atmospheric opacity.

Separate adjuster functions are developed for the beam and diffuse spectra, based on air mass and clear weather index. These are implemented as reducers for each component, based on a Liu-Jordan assumption on isotropy of diffuse irradiance [10], giving the irradiance at wavelength λ incident on an arbitrary plane as:

$$G_\lambda = B_\lambda \times \cos(\varphi) + D_\lambda \times F_s \quad (3)$$

Where B_λ is the spectral beam irradiance normal to the Sun, φ is the angle of the Sun to the plane, D_λ is the hemispherical spectral diffuse irradiance, and F_s is the fraction of the sky to which the plane has a view.

The cloud adjuster for the in-plane spectral irradiance is defined:

$$AdjG_\lambda = ModG_\lambda - MeasG_\lambda \quad (4)$$

Where $ModG_\lambda$ is the clear-sky modelled irradiance at wavelength and $MeasG_\lambda$ is the measured spectral irradiance at λ . Combining (3) and (4) yields for the individual component adjusters:

$$AdjG_\lambda = AdjB_\lambda \times \cos(\varphi) + AdjD_\lambda \times F_s \quad (5)$$

Five months of spectral irradiance measurements (taken every ten minutes with the monochromator-based spectroradiometer at CREST) were used to fit the

empirical adjusters for the cloud module. The data would ideally cover at least a year, however this dataset was chosen because it has been logged since an upgrade of the CREST measurement system, which includes better irradiance stability checks. Since the spectroradiometer takes approximately two minutes to complete a scan of the spectrum, which can vary quite rapidly under certain weather conditions, the advantages in being able to screen spectra for integrity were believed to outweigh the cost in volume of data.

For each measured spectrum, the clear weather index (CWI) is calculated from the ratio of total measured irradiance in the horizontal (from a corresponding pyranometer measurement) to total modelled irradiance in the horizontal (using the integrated output of the clear-sky spectral model). The air mass (AM) is also calculated from the date, time and site location and the measurements are binned in these two parameters.

For each AM-CWI bin, data are compared on the basis of the solar angle to the plane of spectral measurement (latitude tilt of 53°). In this way, pairs of data are identified where the AM and CWI conditions are similar and the solar angles are significantly different. It has been assumed that each combination of AM and CWI gives rise to a unique perturbation of the clear sky spectrum, hence the same adjustment for cloud should be valid in each bin. By then considering two different angles of incidence on the inclined spectral measurement system, beam and diffuse components can be inferred and separate adjustments to the beam and diffuse spectra can be determined from (5):

$$\begin{aligned} AdjG_{\lambda|1} &= AdjB_{\lambda|1} \cos(\varphi)_{\lambda|1} + AdjD_{\lambda|1} F_S \\ AdjG_{\lambda|2} &= AdjB_{\lambda|2} \cos(\varphi)_{\lambda|2} + AdjD_{\lambda|2} F_S \end{aligned} \quad (6)$$

Where the subscripts 1 and 2 specify the two measurements of the couplet. The following assumptions are made on the basis that the two measured spectra are from the same bin with nearly the same conditions:

$$\begin{aligned} AdjB_{\lambda|1} &= AdjB_{\lambda|2} \\ AdjD_{\lambda|1} &= AdjD_{\lambda|2} \end{aligned} \quad (7)$$

Eliminating and rearranging (6) yields the adjuster for the beam component:

$$AdjB_{\lambda} = \frac{AdjG_{\lambda|1} - AdjG_{\lambda|2}}{\cos(\varphi)_{\lambda|1} - \cos(\varphi)_{\lambda|2}} \quad (8)$$

Substituting back into either of the pair in (6) yields the adjuster for the diffuse component:

$$AdjD_{\lambda} = \frac{AdjG_{\lambda} - AdjB_{\lambda} \times \cos(\varphi)}{F_S} \quad (9)$$

The above procedure is performed for each bin and repeated as each data point is paired with every other in the bin to give several calculations of the adjusters, with each corresponding CWI taken to be the average of the pair. The results from all CWI bins are lumped for each

AM bracket and $AdjB_{\lambda}$ and $AdjD_{\lambda}$ are fitted against CWI through a standard minimisation process (Levenberg-Marquardt, as implemented in [11]). These parameterised functions are implemented with the clear-sky model to form the ASPIRE package. The complete data set required for the model comprises air temperature, pressure and relative humidity, which do not vary drastically over short distances allowing nearby meteorological stations to be used for data, and broadband irradiance, which is required from the site of interest.

4 VALIDATION AGAINST MEASURED SPECTRA AT CREST

The ASPIRE model has been validated against measured spectra from Loughborough. Examples of how the complete model performs against clear-sky (Figure 4) and cloudy (Figure 5) conditions are also shown.

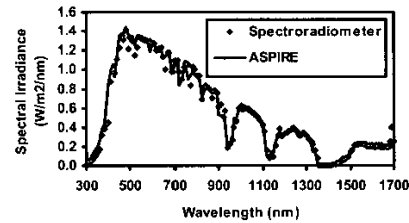


Figure 4: ASPIRE Performance Under Clear Skies

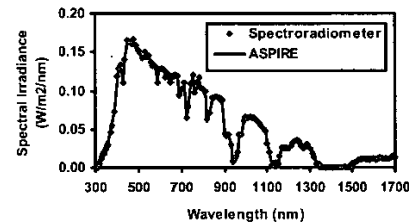


Figure 5: ASPIRE Performance Under Cloudy Skies

Through comparison of Figure 3 and Figure 5 it can be seen that the fitted adjustment made for cloud cover accurately simulates the spectral attenuation effect of decreasing clearness. Comparison of Figure 2 and Figure 4 shows that this has not been at the expense of performance under clear conditions. The overall performance of the model for the full validation data set is summarised in Figure 6.

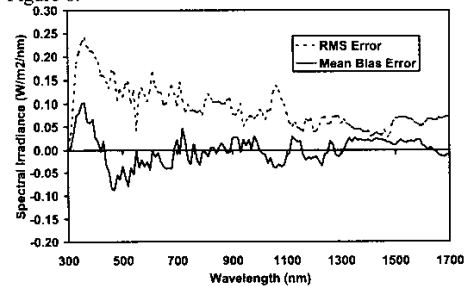


Figure 6: ASPIRE Performance Over Full Validation

The total RMS errors for the dataset are approximately 10% of the magnitude of the standard AM1.5G spectrum across the spectral range considered. For very low irradiance spectra, measured under extremely heavy cloud cover, the simulation errors appear larger, however for PV applications such times are not so significant to the overall energy production. The mid-cloud regime, under which a large share of annual insolation is delivered, is well simulated. More significant is the bias error, since systematic errors of this type will bias the results of any simulation work using the model. The separation of beam and diffuse spectra has improved the model in this respect compared to a total spectrum adjustment.

The largest errors occur at the smallest wavelengths. This is thought to be related to the performance of the measurement system, which is known to lose accuracy in this area. It is possible that there are contributing factors from some system configuration issues which have recently come to light, such as the need to know a more precise fraction of the sky obscured by nearby objects, and these are currently under investigation. A study of the mean bias error on a monthly basis has determined that it is largely consistent, hence it should not affect the capability of the model to simulate the seasonal spectral changes shown in Figure 1.

5 CONCLUSIONS

The ASPIRE model has been presented as a useful tool to facilitate the modelling of spectral irradiance effects on PV devices. The reliance on a minimum of meteorological inputs has sacrificed accuracy in modelling instantaneous spectra, yet makes the tool simple to use and widely applicable. The seasonal variation of the solar spectrum and the impact on PV is well simulated, allowing the variation of PV system output to be quantified.

Development work is ongoing and currently focuses on the problems associated with the underprediction in the blue end of the diffuse spectrum. A solution here should improve the model performance when applied to instantaneous spectral simulation, yet even now accuracy of order 10% is achievable.

6 ACKNOWLEDGEMENTS

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