THE IMPACT OF AEROSOLS ON SOLAR RADIATION: SOUTH AFRICAN CASE STUDIES

Hartmut Winkler

Department of Physics, University of Johannesburg, PO Box 526, 2006 Auckland Park, Johannesburg, South Africa;
Phone: +27-11-5594417; Fax: +27-11-5592339; E-Mail: hwinkler@uj.ac.za

Abstract

The paper describes the re-investigation of sunphotometer data collected at De Aar, a designated solar energy hub, in 2000, as well as similar data from another Karoo site. The previously published spectral and temporal direct radiation attenuation factors are here supplemented with corresponding characterisations of the diffuse irradiation, with and without its spectral dependence. The relation between the diffuse radiation strength and aerosol optical depth was quantified for the two sites and the fit parameters are presented for selected cases. The paper lists available ancillary data and describes procedures for estimating clear-sky direct and diffuse spectral irradiation parameters at South African locations considered for solar power station sites. The nature of the wavelength dependence and the application of these functions to determine solar potential and energy yields for the various solar power generating technologies is briefly discussed.

Keywords: Solar irradiation; direct radiation; diffuse radiation; South Africa.

1. Introduction and Theory

1.1. Solar potential in South Africa

South Africa has long been recognised as a location with abundant availability of solar irradiation. The South African energy crisis and the trend towards renewable energies have ensured that the exploitation of this resource has now become a high priority.

The construction of solar power stations on a massive scale is imminent in South Africa. In view of the associated large costs, it is imperative that the percentage of energy yielded per proposed station is maximised. This is done through suitable site selection, technology selection and through the optimisation of the equipment settings (e.g. the choice of tilt in the case of PV panels).

As long-term testing of the numerous sites under consideration is not always practical, decisions regarding the location and configuration of proposed solar power stations are often based on available solar irradiation maps. These are on the one hand the result of long-term irradiation measurements collected at some South African weather stations, or are the end product of the processing of satellite images.

In both instances the irradiation values identified for a site are prone to a considerable degree of uncertainty, either because these are interpolations based on rather distant measuring stations, or because the satellite data processing relies on calibration techniques that have usually been developed for different environments.

Another shortcoming of the available solar irradiation estimates is that they are in most cases cumulative values over the entire wavelength spectrum. As is discussed in this paper, however, the degree of convertibility of solar radiation into other energy forms is very much wavelength dependent.

1.2. Theoretical formalism

Solar radiation at the Earth’s surface is the sum of several parts: i) the direct beam of sunlight, ii) radiation from the rest of the sky, which is nothing but scattered sunlight and is referred to as diffuse radiation, and iii) radiation reflected off the ground. These components are conventionally recorded in units of power per surface area, and will in this paper be referred to as $F$ for the direct beam (as measured on a surface
perpendicular to the beam – also sometimes called DNI), \( D \) for the diffuse part and \( R \) for the reflected part.

The total power per surface area incident on a surface with a perpendicular making an angle \( \theta \) with the solar beam is known as the global irradiation, for which the symbol \( G \) is used here. It follows that the global irradiance is related to the other quantities by the relation

\[
G = F \cos \theta + D + R.
\]

In the event that the collecting surface is horizontal (as is most common for solar irradiance measurement instruments), the part of the radiation reflected off the ground is no longer measured, while \( \cos \theta \) now equates to the solar zenith angle. In that case \( G \) represents the global horizontal irradiance, or GHI, i.e.

\[
G = F \cos \theta + D.
\]

The direct beam weakens as it traverses the atmosphere. The fraction of the beam absorbed or scattered in a small path segment is proportional to the concentration of scattering elements encountered, leading to an exponential decline in the beam strength. The scattered part of the beam is either radiated back into space, or becomes part of the diffuse radiation at another location. There is therefore a correlation between the strength of the diffuse component and the amount of radiation attenuated from the direct beam.

The degree of attenuation is almost always a function of wavelength. It is therefore appropriate to model the beam intensity in terms of specific wavelengths. In particular, the radiation power per area per unit wavelength interval \( I(\lambda) \) inside the Earth’s atmosphere may be written in terms of \( I_0(\lambda) \), its value at the top of the atmosphere, and \( T(\lambda) \), the fraction of radiation at that wavelength transmitted through the atmosphere.

\[
I(\lambda) = I_0(\lambda) T(\lambda).
\]

We note that the transmittance function is itself the product of individual factors responsible for one particular attenuation mechanism (Rayleigh scattering, ozone, water vapour, aerosols and others), i.e.

\[
T(\lambda) = \text{Rayleigh}(\lambda) \times \text{O}_3(\lambda) \times \text{H}_2\text{O}(\lambda) \times \text{aerosol}(\lambda) \times \ldots
\]

We also note that the degree of attenuation/transmission depends critically on the solar zenith angle – the greater this angle, the more atmosphere is traversed by the incident beam and the greater the probability if interaction with particles and beam attenuation. The complex interdependent effects of the various atmospheric parameters have been the subject of extensive studies, a good summary of which is listed in the references [1].

Aerosol loading is commonly quantified by means of the aerosol optical depth \( \tau \), which is defined by the following expression:

\[
\tau = \exp(- \sec \theta).
\]

The diffuse radiation distribution is even more difficult to determine, as the angular distribution of the scattered radiation is dependent on the nature of the scattering particle, and as multiple scattering of a photon may also take place. This topic too has been studied in detail, and here again the reader is referred to a commonly quoted paper in the reference section [2].

1.3. Effect on the various solar energy generating technologies

The distinction between the direct and diffuse parts of the solar irradiance becomes critical when evaluating the yield solar energy generating technology considered at a particular site. Concentrated solar power technologies work on the basis that the direct beam is reflected onto an energy converting device using specific mirror alignments. These alignments however direct the diffuse radiation elsewhere, and this component is therefore not collected by the energy generating device.

Photovoltaic solar energy collectors, on the other hand, are irradiated by both the direct and diffuse beams. The diffuse component can in fact become stronger than the direct beam, even in clear conditions, if panels
are immobile and angle of incidence of the beam becomes large.

Another critical aspect needing to be considered when predicting the energy generating performance of a solar power plant is the spectral energy conversion efficiency. Photovoltaic devices, for instance, generally perform best when the wavelength of the incoming radiation corresponds to the wavelength characteristic of the gap between the valence and conduction energy bands of the material with which the photovoltaic cells were constructed. Photons with wavelength considerably longer than this optimal wavelength are generally not captured, and the same is true for a fraction of the light bluewards of the peak.

In the case of CSP, reflectance of light off the mirrors and the absorbance of the heat engines is also in general wavelength dependent.

For any particular solar energy generating device, it is possible to define its spectral efficiency \( \eta \), i.e. the fraction of radiation incident on the device at a specific wavelength that is converted into power by the device. Thus, for a specific device with a collecting surface aligned in a particular manner, the power \( P \) generated per unit collecting surface area equals

\[
\int I_G(\lambda)\,d\lambda = \cos \times \int I_F(\lambda)\,d\lambda + \int I_D(\lambda)\,d\lambda \quad \text{(for PV)}
\]

Note that, strictly speaking, the equation given for the photovoltaic case assumes a near-horizontal panel. When the panels become significantly inclined, a reflection term needs to be added, and the diffuse term will no longer include the entire hemisphere of the sky. An accurate treatment of these corrections will require knowledge of the angular distribution of the diffuse radiation, which in itself depends on the level of turbidity.

Knowledge of the spectral distribution of the direct and diffuse portion of the incident radiation is thus required to accurately determine the energy yield. Much work is still required to characterise these functions under atmospheric conditions as experienced at solar power generating sites in South Africa. These not only depend on location characteristics such as altitude, horizon profile and ground cover, but also on the prevalent climatic conditions and the nature and concentration of particles in the atmosphere, i.e. aerosols.

1.4. Effect of aerosols on the direct and diffuse radiation

This study seeks to empirically quantify the relationship between the aerosol concentration and the direct and diffuse radiation under clear skies in conditions characteristic of the South African interior regions where the biggest solar power stations are being planned.

With regards to the direct radiation, the study draws on previous work where the spectral attenuation due to aerosols has been measured over long time periods. Spatial irradiation maps may then be used to project the degree of attenuation at other sites in the region.

The spectral distribution of the diffuse radiation has not been sufficiently established in South Africa. To rectify this shortcoming, data in the possession of the author from two Karoo sites has been reanalysed and the procedure for the calculation of local estimates of this expression (as a function of aerosol concentration) is described here.
2. Available data

2.1. MFRSR data
The multifilter rotating shadow-band radiometer (MFRSR) is a class of sunphotometer that measure global and diffuse solar irradiation in seven narrow-band filters, spread throughout the optical and near-infrared spectral regions and each covering a wavelength range of ~10 nm in width. The instrument also records the broad-band irradiation (i.e. the sum over all wavelengths). Its operations and data reduction techniques have been documented by Harrison and collaborators [3]. By comparing the changes in spectral irradiance for a range of solar zenith angles, which in turn correspond to varying path lengths through the atmosphere, the aerosol optical depth may be estimated through the Langley technique.

The instrument was in operation in South Africa during three seasonal campaigns, in Sutherland during 1998 and 1999, as well as in De Aar during 2000. Irradiation data was continuously collected in all available filters at 1-minute time intervals for periods between six and nine months for each campaign. The purpose of these studies was to determine typical aerosol concentrations over these sites, and determine seasonal trends and variations. Results of these studies were published in two papers [4, 5].

These studies highlighted that turbidity levels were exceptionally low over the two sites. Enhanced concentrations were rare, and mainly occurred during the late winter/early spring months (August-October). Outside such events the aerosol transmittance was above the Rayleigh transmittance. It was further observed that the average turbidity levels at both sites were considerably lower than had been measured at South African sites further to the east [6].

The analysis of the data however restricted itself to evaluating the optical depths and analyzing these in terms of aerosol concentration and transport. Other properties of the data, such as the spectral characteristics of the diffuse radiation, were not carried out.

2.2. BSRN data
The period of sunphotometer data collection at De Aar coincided with a programme of solar irradiation monitoring at the very same location under the Baseline Surface Radiation Network (BSRN). The De Aar BSRN data extends over almost ten years, and includes global, direct and diffuse measurements at 1-minute time resolution, and has been presented in the compilation by Esterhuys [7].

The BSRN data is not spectrally resolved, but its broad-band global and diffuse measurements offer an ideal opportunity for checking the MFRSR broad-band filter calibration. The application of the MFRSR diffuse spectral distribution results furthermore enables the estimation of the wavelength dependence of the entire De Aar BSRN data set. The combination of the two data sets would provide a unique characterization of solar conditions in the important South African solar power nexus of De Aar, yielding spectral information and long-term seasonal trends.

2.3. SAFARI data
During 2000-2001 an intensive scientific campaign termed SAFARI’2000 took place in Southern Africa, aiming to determine aerosol generation, transport and deposition over the sub-continent [8]. The study highlighted the increase in atmospheric turbidity over the region during spring, which coincides with the end of the dry season. Extensive biomass burning in the tropics results in massive smoke plumes that circulate in an anti-clockwise direction over Southern Africa before dissipating or being drawn out into the atmosphere over the Indian Ocean.

The movement of aerosols in a general north-west to south-east direction over South Africa had been observed previously [9], and SAFARI confirmed and highlighted greater detail of this pattern. Valuable
information in this regard came from sunphotometers belonging to the AERONET collaboration [10], which were able to determine the spectral attenuation at a several sites (albeit well to the north-east of the sites investigated here) [6]. The AERONET and MFRSR data illustrated the gradual decrease in aerosol loading over South Africa from the north-east towards the south-west.

2.4. Irradiation maps
A range of irradiation maps are available and are popularly used to estimate solar irradiation values at pinpointed sites. The PVGIS data (http://re.jrc.ec.europa.eu/pvGIS) is based on the GRASS solar radiation model [11], while the Solar and Wind Energy Resource Assessment (SWERA – swera.unep.net) maps were developed from specific algorithms used to process multiple satellite images.

3. Analysis

3.1. Identification of ‘golden days’
To probe the relationship between turbidity and diffuse radiation, a set of half-days (referred to as ‘golden half-days’) were identified in both the Sutherland and De Aar MFRSR data during which no evidence of cloud was detected in both global and diffuse radiation time sequences. The golden half-days were in addition chosen in such a way that these covered the widest possible range of turbidity values.

3.2. Fitting of diffuse radiation curve
The broad-band and narrow filter diffuse readings for each minute during the golden half-day, from sunrise/sunset to local noon, were now plotted as a function of cos $\zeta$. These graphs were then fitted by means of polynomials. It was found that a very good fit was always possible by means of a 3rd order polynomial. Hence for each filter at wavelength $\lambda$,

$$I_D(\lambda) = a_{1,0}(\cos \zeta)^3 + a_{1,2}(\cos \zeta)^2 + a_{1,1}(\cos \zeta) + a_{1,0}.$$

3.3. The diffuse radiation-turbidity plots
Having defined the polynomial fits for each golden half-day, these were then used to determine the projected value of the diffuse irradiances at a specific cos $\zeta$ for that day, and these were then plotted against the turbidity, parameterised by previously known value of the aerosol optical depth in the 415 nm band. The same was done for all other golden half-days, using exactly the same value of cos $\zeta$.

Figure 1 illustrates one such plot, namely for cos $\zeta = 0.5$ at the De Aar station.
Fig. 1. Example of a plot of diffuse irradiation strength as a function of aerosol concentration (here for the De Aar station at $\cos \theta = 0.5$). The symbols signify the filters as follows: 415 nm – black diamonds, 501 nm – grey squares, 615 nm – grey triangles, 678 nm – black squares, 868 nm – grey diamonds.

Note how the curves reflect almost linear increases in diffuse radiation as a function of increasing optical depth, at least while the optical depths remain relatively small. Once the aerosol optical depth reaches about 0.15 (corresponding to a transmittance of ~0.75 at 415 nm), the curve flattens out, and even seems to decrease a little. The flattening is least pronounced with the curve corresponding to the longest wavelength (868 nm). Another feature worth noting in the graph is that the 415 nm diffuse curve grows less rapidly than the one for 501 nm.

A very similar pattern was observed with the Sutherland data (not shown here). There one day with exceptionally high turbidity (by the standards of the site) was recorded. On that day the diffuse radiation was however still considerably high – only a mild flattening of the curve had occurred.

3.4. Comparison of the diffuse radiation-turbidity fits

The data gathered enables the inter-comparison of fits to the diffuse irradiance vs. turbidity plots for a variety of parameters. Examples of such comparisons are listed in the table below. The entries in the last three columns are the quadratic equation coefficients, this equation taking the form

$$I_d(\lambda) = b_0 + b_1 \kappa(\lambda) + b_2 \kappa(\lambda)^2.$$
<table>
<thead>
<tr>
<th>Site, filter, cos $\zeta$</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>De Aar, 415 nm, 0.5</td>
<td>0.181</td>
<td>0.618</td>
<td>−0.905</td>
</tr>
<tr>
<td>De Aar, 868 nm, 0.5</td>
<td>0.013</td>
<td>0.146</td>
<td>−0.123</td>
</tr>
<tr>
<td>De Aar, broad-band, 0.5</td>
<td>25.3</td>
<td>203.2</td>
<td>−189.7</td>
</tr>
<tr>
<td>De Aar, 415 nm, 0.2</td>
<td>0.121</td>
<td>0.136</td>
<td>−0.247</td>
</tr>
<tr>
<td>De Aar, broad band, 0.2</td>
<td>18.2</td>
<td>106.4</td>
<td>−65.6</td>
</tr>
<tr>
<td>Sutherland, 415 nm, 0.5</td>
<td>0.180</td>
<td>0.623</td>
<td>−0.570</td>
</tr>
<tr>
<td>Sutherland, 868 nm, 0.5</td>
<td>0.012</td>
<td>0.120</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Table 1. Examples of quadratic fits to the (diffuse radiation) vs. (aerosol optical depth) curves. The units of the coefficients are W.m$^{-2}$

The $b_0$ values characterise the diffuse irradiance at zero turbidity, i.e. the ‘aerosol-free’ diffuse irradiation value at the specific cos $\zeta$.

The first two rows (and the last two rows) show how the blue diffuse irradiance differs from the diffuse irradiance in the near-infrared. The similarity between the two sites is illustrated by the correspondence of rows 1 and 6 (and 2 and 7). The effect of the zenith angle is shown by the inspection of rows 1 and 4 (or 3 and 5).

5. Discussion and Conclusion

The paper illustrates how to generate a relationship between the diffuse irradiance and the turbidity, in this case parameterised by the aerosol optical depth. The relationship between these two entities is determined by the solar zenith angle, the wavelength, and to a small degree also by the site. Specific relationships between any of these parameters can be determined from the data at will, and the corresponding effect on the direct and diffuse irradiance can hence be modelled.

The almost linear increase of diffuse irradiance with turbidity at small turbidity testifies to the steady growth of diffuse light with increasing light scatter in the atmosphere. The gradual flattening out of this trend is likely to be an indicator that increasing turbidity is now making multiple scattering significant, leading to a damping in the diffuse function growth.

The similarity between the graphs for De Aar and Sutherland, both locations in a large but climatically homogenous region, suggests that similar relationships also hold for other Karoo towns. Other future solar hubs, such as Kathu and Kimberley, are unlikely to differ very much from the two sampled sites either, though the average aerosol concentration is likely to be higher there due to their more north-easterly location. It is suggested that the clear-sky direct and diffuse irradiance for most of the dry north-west of South Africa can be estimated by using the De Aar results and adjusting these proportionally using the average irradiance differences between sites obtained from the various solar irradiance maps.

The ability to better approximate the spectral distribution of the diffuse radiation enables solar power station planners to develop more sophisticated estimates of the energy yield of photovoltaic panels, and to compare this yield to that associated with concentrated solar power devices. It furthermore allows a more accurate calculation of the optimal tilt angles and other operational parameters. It is a crucial component determining the power generated and expected profitability of a plant.
Acknowledgements

This study in part made use of data collected at the De Aar station of the Baseline Surface Radiation Network (BSRN) of the World Radiation Monitoring Centre. The author acknowledges Danie Esterhuyse for his effort in establishing and maintaining the De Aar BSRN site. The sunphotometer stationed at Sutherland in 1998-99 and De Aar in 2000-01 was made available by the Biogeochemistry division of the Max-Planck-Institut für Chemie in Mainz, Germany.

References