How local conditions affect solar irradiance and photovoltaic module performance in South Africa

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Abstract. Solar power generation efficiency is not only a function of the detector technology and configuration, but also depends on the amount, spectral distribution and angular profile of sunlight at ground level. This paper reviews some common techniques used to estimate the solar photon field at its interface with the detector. It examines the suitability of the associated light transmission and scattering models from a physical perspective under atmospheric conditions representative of the dry South African western plateau (where most local solar power stations are planned to be sited). The article concludes with a presentation of a simple ground-level spectral irradiance model formulation specific to South African condition that is readily adaptable to site conditions. Applied to the configuration and spectral responsiveness of a solar device this model is expected to yield better estimates of electricity generation than many internet-based tools commonly used for this purpose.

1. Introduction

South Africa is witnessing a massive growth in its solar energy generation capacity. This is manifested both by the construction of large solar power stations, as well as small scale installations such as rooftop photovoltaic modules and solar heaters [1].

Much research effort has been directed towards the achievement of greater energy solar conversion efficiency in the employed technologies, as well as improving the cost efficiencies. In comparison, relatively little work has focused on the determination of the available ground-level radiation and its spectral properties. The effect that these factors have on the determination of the energy yield of a solar power device is often not fully appreciated. The characteristics of the ground-level solar radiation are determined by the interplay between the solar photons and the atmosphere. The nature of the latter is to a significant degree location dependent, and also exhibits seasonal trends.

Atmospheric models used in solar irradiance calculations therefore need to be adapted to local circumstances, and this has only been done on a limited scale in South Africa. This paper seeks to summarize the main factors to be considered, and suggests parameters considered suitable for use in local irradiance modeling.

2. Theory

The solar irradiance measured at ground level is a function of both the solar zenith angle ζ (i.e. the angle the solar beam makes with the vertical), the height h of the site above sea level and the composition of the atmosphere above the site.

First and foremost, the zenith angle, in conjunction with a module tilt angle, determines the so-called cosine losses of the incident radiation [2]. Other physical parameters significant for such a study are summarized in the following sub-sections.

2.1. Airmass

The airmass m [3] represents the relative atmosphere traversed by the unscattered solar beam to reach ground level. It is measured in units of the equivalent of the medium crossed along the vertical path from the outer atmosphere to sea level. Therefore if the solar zenith angle is 0° at sea level, then $m = 1$. It is easy to show geometrically that for other zenith angles the airmass may be approximated by

$$m \cong \sec \zeta$$

The formulation above requires the assumption that we make a local 'flat Earth' approximation, as otherwise the Earth curvature causes this expression to gradually diverge from the true airmass with increasing ζ. For locations above sea level, the amount of atmosphere above the site is smaller. The fraction of atmosphere compared to the sea level atmosphere is sufficiently accurately described by the pressure ratio p/p_0, where p is the site atmospheric pressure and p_0 is the corresponding quantity at sea level. A good approximation of the atmospheric pressure as a function of h (when measured in meters) is given by the barometric formula

$$p = p_0 \exp(-h/8400) .$$

2.2. Optical thickness

The optical thickness indicates the degree to which a beam of light is attenuated when traversing a medium. If σ is the solar irradiance at the top of the atmosphere and the transmitted fraction is given by ϕ, then the direct beam irradiance I recorded at the solar power generating site is

$$I(\lambda) = \sigma(\lambda)\phi(\lambda, m) = \sigma(\lambda)\exp(-m\tau(\lambda))$$

The factor τ is a measure of the atmospheric turbidity, and is referred to as the optical depth. It turns out that this factor is the algebraic sum of the partial optical depths for each of the constituents accounting for atmospheric light beam attenuation:

$$\tau(\lambda) = \tau_R(\lambda) + \tau_O(\lambda) + \tau_G(\lambda) + \tau_W(\lambda) + \tau_A(\lambda)$$

where the subscripts represent Rayleigh scattering, ozone, other gases, water vapour and aerosols respectively, and these quantities may further be designated as follows [4].

- The Rayleigh optical thickness is strongly wavelength dependent, with $\tau_R(\lambda)$ very nearly proportional to λ^{-4} and the quantity otherwise only dependent on near-constant atomic parameters.
- The ozone optical thickness $\tau_O(\lambda)$ is very high at the violet end of the optical spectrum, but relatively insignificant at other wavelengths. It is a function of the atmospheric ozone concentration, which undergoes annual oscillations with an overall downward trend.
- The near-constant trace gas optical thickness $\tau_G(\lambda)$ includes the contributions due to spectral absorption by atmospheric gases such as N_2, O_2, CO_2 and CH_4. Only very few of these transitions are in the spectral range to which photovoltaic modules are sensitive.
- The water vapour optical thickness $\tau_W(\lambda)$ is a function of the amount of water vapour above a site, which is strongly dependent on meteorological conditions.
- The aerosol optical thickness $\tau_A(\lambda)$ depends on the particle type, size and optical properties in addition to the particle concentration. It is frequently parameterized in the form $\tau_A = \beta\lambda^{-\alpha}$, where β becomes a measure of the concentration, while α, which ranges between 0 and 4, becomes an indicator of the other aerosol properties. There have been determinations of representative α

values for common aerosol types, but these are associated with considerable uncertainty [5]. Atmospheric aerosols depend on processes and conditions at the sources of generation, as well as meteorological factors, and therefore this term is the most difficult to model. This term is as a result also the greatest contributor to uncertainty in the scattered light contribution.

2.3. Scattered light

In addition to photons from the direct solar beam, photovoltaic modules also receive a fraction of their incoming radiation from skylight, i.e. from photons deflected by scattering events elsewhere in the sky. This component is referred as the diffuse irradiance. The characteristics of this diffuse component thus also depend on local conditions.

The number of scattering events depends on the optical thickness for each attenuating process. In addition, one needs to look at the distribution of the angle of deflection for the scattering process. We can here differentiate between scattering due to small particles, and that involving larger particles.

When the scattering centre is significantly smaller than the wavelength, the beam experiences Rayleigh scattering for which the distribution of the scattering angle θ is described as follows:

$$\Phi_R(\theta)\ \mu\ (1+\cos^2\theta)$$

When however the particle size becomes comparable to the wavelength, the scattering process is referred to as Mie scattering, and the angular distribution probability is determined by the Henyey-Greenstein function [6]

$$\Phi_A(\lambda,\theta)\ \mu\ \frac{1-g(\lambda)^2}{\left(1+g(\lambda)^2-2g(\lambda)\cos\theta\right)^{3/2}}\ ,$$

where the asymmetry factor g depends on the particle type, but is normally in the range $0 < g < 1$.

3. PV module calibration procedures

Photovoltaic modules are rated according to illumination tests usually performed under laboratory conditions. In order to standardize the testing, the convention has been adopted to approximate the insolation conditions on the module as follows.

- The spectral distribution of the incident light should match what has become known as the AM1.5 spectrum, which has been adopted as a standard by the American National Renewable Energy Laboratory (NREL). It is supposed to approximate the sea level solar spectrum for an airmass 1.5 solar beam under typical conditions for that country.
- Furthermore, the total radiative power incident on the module should amount to 1 kW m^{-2} at a 90° angle to the surface.
- The PV module must be maintained at a temperature of 25°C throughout the test.

In practice it is practically impossible to reproduce the spectral characteristics of the solar spectrum in a laboratory. Hence lamps with different types of spectra are used, which must then be periodically calibrated against measurements of real sunlight, to ensure that the lamp calibrations can provide a realistic total (rather than spectral) measure of the power converted to electricity by the module.

4. Parameters appropriate for South African conditions

The irradiation of solar modules in South African conditions differs from the calibration environment in the following important respects. The local latitudes are such that the solar zenith angle near mid-day is smaller than for the northern mid-latitudes where the biggest concentrations of solar power installations are found. Much of South Africa also sits on a plateau, and large parts of the country are considered semi-arid as a result of low cloud frequencies. The vast oceanic areas to the west, east and south of the country contribute to overall lower concentrations of aerosols associated with fires, dust and human activity.

4.1. The characteristic airmass

The solar airmass is constantly varying with the changing solar position throughout the day, and the solar track across the sky is seasonally dependent. It is possible to determine a characteristic (daylight) solar airmass at a location by tracing the solar zenith angle as a function of time, and determine the median value of ζ over successive fixed time intervals. Multiplying this with the site relative zenith airmass (given by p/p_0), this leads to this representative site airmass value. Table 1 lists these values in the fourth column for a series of sites of interest, together with their geographical latitudes and altitudes above sea level. The first such site is the city of Washington in the USA, which is included here for comparison purposes. Then the table lists the three major South African urban centres. The final six rows in Table 1 present six of the new South African solar power plants (chosen to provide a wide spread in regional location and latitude).

Utilising the airmass values determined in this manner is slightly misleading for the type of analysis being carried out here. Crucially, the total amount of solar power collected is in most circumstances significantly lower when the Sun approaches the horizon (i.e. when ζ approaches 90°). This is particularly the case when photovoltaic technologies are employed that do not involve tracking the solar part. Even when this is the case though, the total light reaching the solar module becomes less at high zenith angles due to the greater atmospheric light losses.

If we analyse the case where PV modules are placed horizontally, the angle θ that the normal to the PV module makes with the solar beam becomes identical to ζ. If we ignore the decreasing transmissivity of the atmosphere at high ζ, and only apply the so-called cosine losses resulting from a misalignment of the module with the Sun, we find that the amount of solar energy collected is then equal to $\cos\theta$. It is therefore far more appropriate to introduce a weighting factor equal to $\cos\theta$ in our calculation of the average airmass. The weighted average airmass m_{weighted} was therefore determined using the formula

$$m = \frac{p}{p_0}\sec\left[\frac{\int_{year}\zeta(t)\cos\theta(t,\theta=\zeta)dt}{\int_{year}\cos\theta(t,\theta=\zeta)dt}\right].$$

This value has also been calculated for all the sites in Table 1, and is given there in the final column. It is probably not surprising that the value of this quantity for Washington DC amounts to almost exactly 1.5, which explains the choice of the AM1.5 model for the United States.

Table 1. Latitude and altitude for selected sites, together with average and weighted airmasses.

Site	Latitude (°)	Altitude (m)	$(p/p_0)\sec\langle\zeta\rangle$	m_{weighted}
Washington DC, USA	+38.889	9	1.923	1.502
Johannesburg CBD	–26.198	1732	1.364	1.104
Cape Town CBD	–33.930	27	1.806	1.433
Durban CBD	–29.859	8	1.732	1.390
Soutpan Solar (Limpopo)	–22.992	827	1.480	1.206
RustMo Solar (Marikana)	–25.738	1223	1.443	1.169
Kathu Solar	–27.601	1142	1.481	1.195
Khi Solar (Upington)	–28.540	839	1.549	1.247
Ilanga Lethemba (De Aar)	–30.595	1253	1.505	1.205
Vredendal Solar	–31.634	110	1.743	1.392

The South African sites however have significantly lower weighted average airmasses, due to their more equatorial latitudes and because of the high altitude of the South African plateau. This confirms that the AM1.5 is not the optimal spectral representation for South African conditions. A solar spectrum corresponding to $m \sim 1.25$ would be more typical of the irradiance experienced.

4.2. Ozone layer differences

The thickness of the ozone layer varies seasonally, with a minimum being recorded annually during the spring. Furthermore, the ozone concentration is also a function of latitude. In the polar regions of the southern hemisphere the layer can become particularly depleted, a phenomenon that has been termed the “ozone hole”.

The ozone optical depth is therefore often lower in South Africa than it would be in some northern hemisphere countries. This discrepancy is however only of minor significance, as the ozone mainly affects the light at the shortest wavelengths, which is in any case less likely to traverse the atmosphere, and also corresponds to that part of the spectrum to which a photovoltaic device is least sensitive.

4.3. Water vapour

Water vapour concentration in the atmosphere is strongly variable. It tends to be higher at tropical latitudes. While this is also true at high altitude over South Africa, humidity is low compared to other localities at ground level at most of the sites at which solar farms have been constructed – these are for obvious reasons preferentially set up in the most sunny and dry places.

Another factor worth noting when discussing the role of water vapour in solar energy is that the water vapour optical depth is highly wavelength dependent, and mainly affects the infrared. Most photovoltaic modules however do not absorb significant amounts of light from that part of the spectrum, as the really strong water vapour absorption features are all found redwards of 1 micron.

Because of this, and due to the strong variability, no quantification of any systematic differences in water vapour concentration over South Africa as opposed to conditions resulting in the AM1.5 spectrum will be attempted here.

4.4. Aerosols over southern Africa

Previous atmospheric studies have determined that aerosol loading over South Africa is low compared to other parts of the world [7,8,9]. Solar power stations have usually been constructed in the country’s interior, away from urban areas. At such locations atmospheric aerosol loading is generally only affected by dust at ground level and by seasonal biomass burning smoke residue at greater altitudes. In particular, aerosol turbidity due to the burning of vegetation occurs at the end of the winter dry season. It is only then that a higher aerosol optical depth is appropriate for irradiance calculations in South Africa.

The aerosols also play a crucial role in determining the diffuse irradiance. The fraction of the diffuse spectrum due to Rayleigh scattering is a function of solar position and height above sea level only. This is reproduced to a high degree of accuracy over time, and the scattered radiation from any particular part of the sky, at any specific time can be determined well using the Rayleigh scattering function. The diffuse fraction related to aerosols is however far more variable, depending not only on the concentration, but also on the aerosol scattering properties, such as the asymmetry factor g. A highly reliable South African solar irradiance model would need to incorporate that aspect.

4.5. The South African optimal ground level solar spectrum

As an illustration, this paper presents a concrete example of a representative South African ground-level solar spectrum. It has been determined for the central town of De Aar, near which numerous solar power stations are being constructed, and for which typical aerosol concentrations and optical properties have been previously derived with some confidence [9].

Figure 1 displays the direct irradiance spectrum for $m = 1.205$ earlier tabulated as best describing that site, with $\beta = 0.021$ [8,9] and other transmittances as in [4]. Also plotted there is the direct irradiance part of the AM1.5 spectrum as well as the solar irradiance at the top of the atmosphere. The much greater direct irradiance for De Aar is striking, and corresponds to a far higher solar yield for concentrated solar power technologies, which only process direct sunlight.

If a module spectral response function resembling an ideal PV cell (proportional to λ and zero beyond a cutoff set at 1 μm) is used, the comparative power increase achieved through illumination by a hypothetical AM1.205 lamp relative to the AM1.5 standard lamp was determined to be 34%.

For photovoltaic modules one must however also include the diffuse light contribution, i.e. the scattered radiation manifesting itself as skylight. This diffuse contribution increases with greater direct beam attenuation due to Rayleigh and aerosol scattering, the end result being that the global AM1.5 spectrum used for module characterization does not differ from the typical South African total irradiance spectrum by as much as figure 1 suggests.

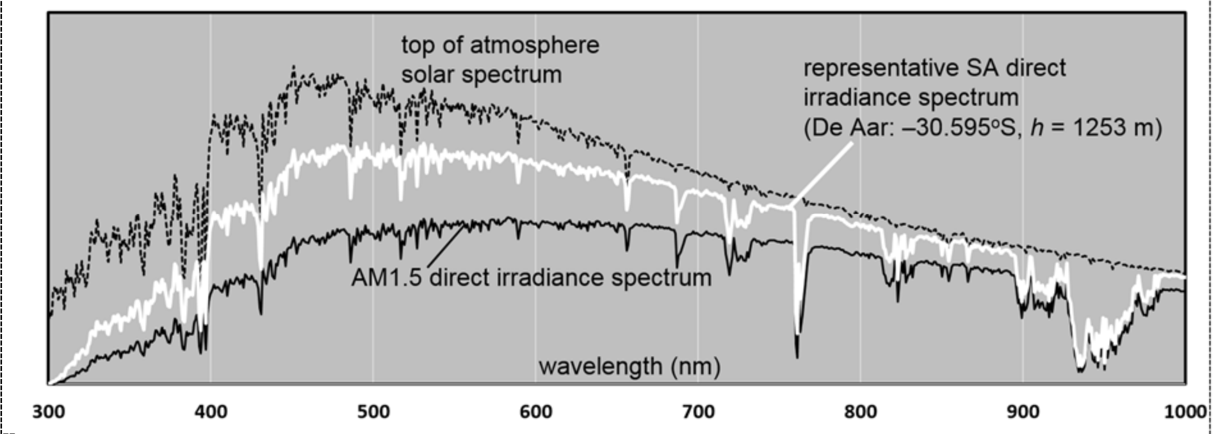

Figure 1. Comparison of the AM1.5 direct irradiance spectrum with an equivalent spectrum determined for the solar power generating location of De Aar, for the earlier determined weighted airmass of 1.205. The dotted line represents the solar spectrum above the atmosphere [10]. The plot only considers the wavelength range in which photovoltaic modules are sensitive.

5. Conclusion

PV modules in South Africa slightly exceed their suggested power ratings. The relative improvement factor is however much dependent on the time of measurement, module tilt, the presence and nature of module tracking mechanisms and current aerosol and water vapour characteristics. The projected solar installation power yield at a specific time and place can only be determined with confidence through calculation and projection of the appropriate ground-level solar spectrum onto a particular device. The mere crude application of the PV module power rating will produce a far less reliable energy yield.

References

[1] Walwyn D R, Brent A C 2015 *Renewable and Sustainable Energy Reviews* **41** 390
[2] Chang T P 2009 *Solar Energy* **83** 1274
[3] Kasten F, Young A T 1989 *Applied Optics* **28** 4735
[4] Gueymard C A 2001 *Solar Energy* **71** 325
[5] Dubovik O, Holben B, Eck T F, et al. 2002 *J. Atmos. Sciences* **59** 590
[6] Kocifaj M 2012 *Solar Energy* **86** 3575
[7] Formenti P, Winkler H, Fourie P, Piketh S, Makgoba B, Helas G and Andreae M O 2002 *Atmospheric Research* **62** 11
[8] Power H C, Willmott C J 2001 *Int. J. Climatology* **21** 579
[9] Winkler H, Formenti P, Esterhuyse D J, Swap R J, Helas G, Annegarn H J and Andreae M O 2008 *Atmos. Environment* **42** 1169
[10] Gueymard C A 2004 *Solar Energy* **76** 423