EFFECTIVE SPECTRAL ALBEDO FROM SATELLITE DATA FOR BIFACIAL GAIN CALCULATIONS OF PV SYSTEMS

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ABSTRACT: A key requirement for increasing the accuracy of energy yield modelling is the accurate estimation of the ground albedo value of a potential site. As most natural surfaces are not white, the colour as well as irradiance of reflected light needs to be considered. In this work we use spectral ground reflectance datasets from satellite data and ground-based stations in order to extract effective spectral albedo values and their uncertainties for bifacial PV system energy yield modelling. We demonstrate satellite spectral reflectance data as a realistic case for bifacial gain calculations and validate them with the ground-based data. An effective albedo calculation methodology is introduced, where the spectral albedo dataset, spectral irradiance and spectral response of the PV module type of the potential system are considered. Comparing 20 different locations and 3 different bifacial module types, we show that it is critically important to account for diurnal and seasonal variations in spectral albedo in bifacial gain calculations. We also show that there can be significant differences between front side and rear side spectral response in silicon bifacial PV modules which can lead to differences of greater than 20 % in the effective value of ground reflected irradiance.

Keywords: Albedo, Bifacial PV Module

1 INTRODUCTION

Bifacial PV modules have the potential to generate 5 – 15 % more energy than equivalent monofacial modules [1], offering the potential to reduce levelized cost of energy (LCOE). Nevertheless, there is a high uncertainty in predicting this “bifacial energy gain” (BEG) using current modelling software. This uncertainty adds financial risk to new bifacial PV projects and deters investment. Calculations for modelling BEG are tightly connected to with the measurement or estimation of the ground albedo value for a given PV system and its spectral profile.

Albedo depends on the lighting conditions (angle of Sun, amount of diffuse light) and the reflectance properties of the surface, which vary with weather and seasons. The albedo of natural surfaces also has strong spectral dependence. Previous work on spectral albedo for bifacial gain calculations has looked into the spectral profile of specific common surfaces [2-4]. These found significant corrections were needed to account for PV modules’ spectral response to the reflected spectra. However, for real sites, spectral albedo values are a unique time-varying combination of spectral profiles. Thus, a first step towards reducing bifacial gain uncertainties is to determine a reliable source of spectral-albedo information for the target site with well-defined uncertainties.

Ground-based measurements are the most accurate source of ground reflectance data. However, it is impractical to survey a complete site for many years before constructing a PV system. Where ground-based data are available, they typically cover only a small area for a limited time.

On the other hand, Earth observation satellites provide global measurements of surface reflectance with decades of historical data freely available. Such data provide valuable information relevant to long-term BEG assessment. But these satellites were not designed for this application; each has limitations in terms of spectral coverage, spatial resolution or observation frequency. Furthermore, the conversion of top-of-atmosphere observations to surface reflectance and albedo requires intricate modelling that introduces further uncertainty.

In this work, we analyse the potential use of satellite data as a source of spectral reflectance information for the modelling of BEG. An effective albedo calculation methodology is introduced, where the spectral albedo dataset for a given location, spectral irradiance and spectral response of the PV module type of the potential system are considered. The use of satellite data for generating effective albedo datasets is validated against ground-based measurements at two sites. Finally, effective albedo data are created for all combinations of 20 globally distributed sites and 3 bifacial module types to investigate the impact of spectral and seasonal variations on bifacial gain modelling and system performance monitoring.

2 METHOD

2.1 Effective albedo

Albedo, defined as the ratio of upwelling reflected irradiance to downwelling incident irradiance on the ground, is a complicated variable. It can be represented by an onerous multidimensional integral of the product of incoming light angular and spectral distribution and the surface’s angularly and spectrally resolved bidirectional reflectance distribution function (BRDF). For simplicity, it is convenient to separate into two components: White-sky albedo α_{ws} and black-sky albedo α_{bs}, representing diffuse and direct components respectively. α_{ws} is calculated from a bi-hemispherical integral of the surface BRDF assuming an isotropic light source. α_{bs} is calculated from a single hemispherical integral of the BRDF assuming that all incoming light is from a single direction. α_{bs} is a function of solar zenith angle θ_{Sun}, whereas α_{ws} is independent of the Sun’s position.

Common modelling packages such as PVsyst [5] or Bifacial Radiance [6] calculate rear-side irradiance using view-factor or ray-tracing simulations as a precursor to BEG assessment. These take albedo α as an input parameter and assume that the ground is an isotropic (Lambertian) scattering surface and spectrally flat. To account for spectral, diurnal and seasonal effects, we propose replacing α with *effective albedo*:

$$\alpha_t' = \frac{\sum_i \int S_{rear}(\lambda)\left[E_{sun,i}(\lambda)a_{bs,i}(\lambda) + E_{sky,i}(\lambda)a_{ws,i}(\lambda)\right] d\lambda}{\sum_i \int S_{rear}(\lambda)\left[E_{sun,i}(\lambda) + E_{sky,i}(\lambda)\right] d\lambda},$$

where $S_{rear}(\lambda)$ is the PV module's rear-side spectral responsivity at wavelength λ, $E_{sun,i}(\lambda)$ and $E_{sky,i}(\lambda)$ are the instantaneous direct and diffuse horizontal spectral irradiance, $a_{bs,i}(\lambda)$ and $a_{ws,i}(\lambda)$ are the instantaneous black-sky and white-sky spectral albedo profiles. The latter are determined at intervals i determined by the frequency of the available irradiance data (typically 1 minute). It is averaged over time intervals t, typically hourly, daily or monthly, suitable for input to yield modelling software.

For a given site, time-series effective albedo data can be generated either as a *historical* or *typical* dataset provided that the variables in the above equation can be measured or estimated. We have compared multiple possible sources for these data.

One caveat in the definition of effective albedo above is that is assumes a PV module that has no angular-dependent reflection losses and is mounted horizontally. It also neglects the fact that shading from a PV array can influence the ratio of direct to diffuse irradiance on the ground as viewed by a module. For isotopically scattering surfaces, these do not matter in the calculation of effective albedo; they will be accounted for in the system ray-tracing or view-factors optical model. In the case of some surfaces (particularly deserts) however, accounting for these geometric effects can necessitate modification of the effective albedo calculation. As this is a system-design dependent feature and adds considerable complexity, we do not include these corrections in this paper.

2.2 Satellite reflectance data

The NASA Moderate Resolution Imaging Spectroradiometer (MODIS) MCD43 products [7] provide measurements of surface reflectance at a resolution of 500 m in 7 narrow spectral bands from 455 – 2155 nm. Data are available for any global location from the year 2000 to present day. They provide daily outputs, each day taken from a weighted average of measurements over a 16-day period. Over this period, observations are made from multiple observer angles and Sun angles, enabling information to be captured on the angular distribution of reflectance. We use this product to generate daily white-sky albedo values and solar-zenith dependent black-sky albedo values for each of the 7 bands using a validated method [8]. Solar zenith angles calculated using the NREL SPA algorithm [9] are used to create a diurnally varying black-sky albedo value for each band.

Banded albedo values are converted into continuous spectra by interpolation before integration. This is discussed further in section 3.2 below.

Snow cover presents an additional challenge to BEG modelling. In this paper we do not address this issue and remove data from days where snow is present.

2.3 Ground-based reflectance data

For validation of satellite-derived effective albedo data, we use two example sites of the Radiometric Calibration Network (RadCalNet) at Gobabeb, Namibia and at La Crau, France [10]. These are a desert and temperate site respectively. Measurements of surface reflectance are taken at half-hour intervals using spectroradiometers covering the range 400 – 1810 nm at 10 nm resolution. Instead of albedo measured over a complete hemisphere, the output is reflectance measured over a small solid angle at nadir (vertical) orientation. Nevertheless, nadir reflectance can be used to validate MODIS data by generating equivalent effective nadir reflectance values from the satellite data.

Figure 1 shows an example of a single measured reflectance spectrum at the Gobabeb site compared to the reflectance values calculated from MODIS data for the same time and location.

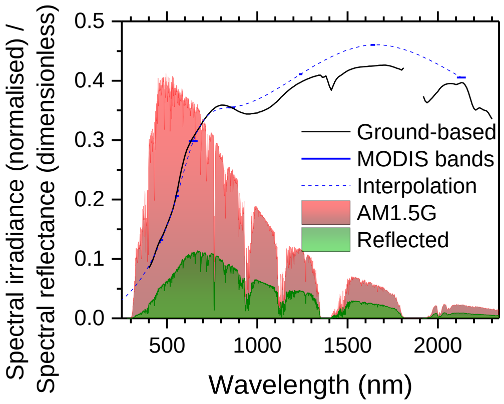

Figure 1 An example of a ground-based nadir spectral reflectance measurement (Gobabeb, 12:00, 16/03/2019) (black line), compared to the same modelled from MODIS satellite data in 7 bands (blue bars) and synthesised spectrum (blue dashed) from interpolation of MODIS bands.

2.4 Irradiance data

The ratio of direct and diffuse horizontal irradiance is needed for the correct weighting of the black-sky and white-sky components of albedo. Furthermore, irradiance is used to weight instantaneous effective albedo values in the generation of average α_t' values for intervals (hourly, daily, monthly). In this work we use two sources of irradiance data: The Bird clear-sky model [11], which is simple but ignore the effects of cloud cover, and the Baseline Surface Radiation Network (BSRN) [12]. The latter provides historical measurements of direct and diffuse horizontal irradiance at more than 70 locations worldwide, some dating back to 1992.

For all calculations, the normalised AM1.5G reference spectrum is used for both diffuse and direct spectral irradiance. The effect of using synthesised weather-dependent spectral irradiance instead of a constant spectrum was investigated but found to have negligible impact on the results. The AM1.5G reference spectrum is shown in Figure 1 along with the reflected spectrum observed at nadir simulated by multiplying the reference spectrum by the measured reflectance spectrum.

2.5 Module spectral responsivity data

Spectral responsivity data were obtained from three bifacial PV modules with different cell technologies measured at the Fraunhofer Institute for Solar Energy as part of an interlaboratory comparison exercise [13]. These are shown in Figure 2. A spectral responsivity curve taken from the datasheet for a reference cell and a pyranometer are also used.

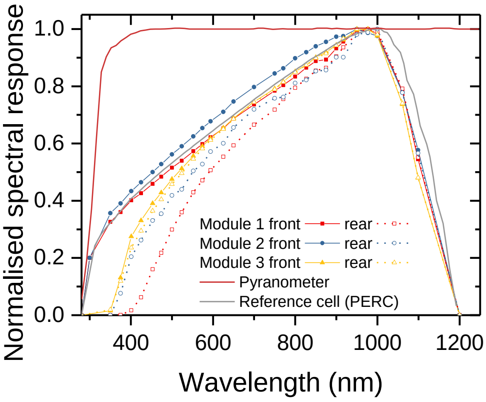

Figure 2 Normalised spectral responsivity curves for devices used in this work. They include 3 bifacial modules based on different silicon cell technologies (n-PERT, PERC, heterojunction, respectively) [13] and an example pyranometer and silicon PERC reference cell spectrum taken from datasheets.

3 RESULTS

3.1 Validation against ground-based measurements

Figure 3a) shows effective nadir reflectance values created from MODIS data and clear-sky irradiance model at Gobabeb and La Crau sites for a 10-year period using the reference cell spectral responsivity curve compared to same from ground-based spectral reflectance measurements measured over a shorter period. The figure shows data generated at half-hour intervals from 09:00 – 15:00 each day. The satellite-based date reproduces well both the average values of effective reflectance and the seasonal variations due to changes in vegetation and the angle of the Sun.

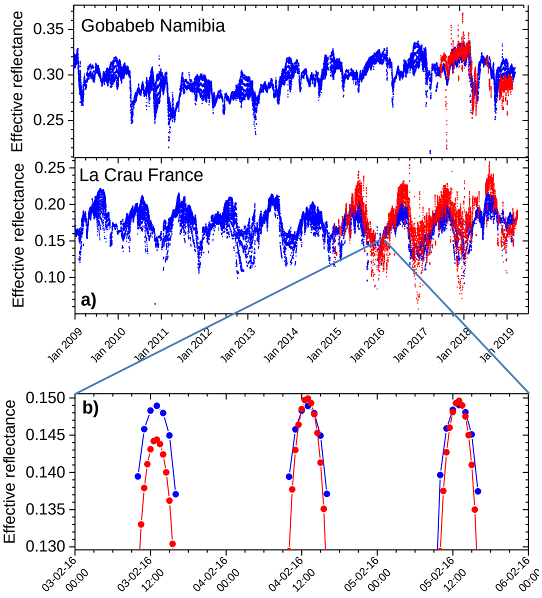

Figure 3 Historical spectrally corrected nadir reflectance values generated at half-hour intervals from ground-based spectral reflectance measurements (red dots) and from MODIS satellite measurements (blue dots). **a)** a 10-year period at Gobabeb, Namibia and La Crau, France. **b)** a 3-day period at La Crau highlighting diurnal variation.

Figure 3b) shows a close-up of the results at La Crau for a 3-day period. It shows that the diurnal variation in reflectance, caused by the changing angle of the Sun combined with the anisotropic scattering of the surface, is well reproduced in the MODIS data model. This diurnal behaviour is critical to accurate BEG calculations; significant errors may result if albedo is assumed to be constant within a day. Note that the diurnal behaviour of nadir reflectance is inverted from the behaviour of albedo, which usually reaches its daily minimum value at noon.

Table I gives statistical measures of the relative difference between using satellite and ground-based measurements. These show that the satellite data and model are able to recreate the measured reflectance with a typical accuracy of about 5 % at the desert site and 10 % at the temperate site. The bias in long-term average values is very small, indicating the suitability of historical satellite reflectance data for long-term BEG assessment accounting for seasonal, diurnal and inter-annual variations in spectral albedo. These errors are consistent with other validation studies of satellite-based measurements for other applications [14-16].

Table I Normalised root mean square error (NRMSE) and bias (irradiance-weighted mean error) in instantaneous (half-hourly frequency) and daily-averaged mean reflectance comparing satellite-derived against ground-based measurements for two sites.

Error in reflectance (satellite versus ground)	Gobabeb	La Crau
Half-hourly NRMSE	4.7 %	10.3 %
Daily NRMSE	4.5 %	9.2 %
Relative bias	+ 2.0 %	- 3.9 %

The short-term (instantaneous and daily) random error arises primarily from three sources:

1. MODIS data are averaged over a 16-day period, so daily values fail to respond quickly to sudden changes in reflectance from *e.g.* rain or rapid vegetation growth,
2. Uncertainty in MODIS data on some days caused by a shortage of good observations, usually due to cloud cover, and
3. Variations in weather and optical effects that are not accurately modelled by the simplified reflectance model.

Long-term bias in satellite data arises from:

1. Spectrometer calibration error,
2. Uncertainties in the atmospheric transmission model used to convert top-of-atmosphere measurements to bottom-of-atmosphere values,
3. Spatial variation around the site (the viewing area of the ground-based instruments is much smaller than a MODIS pixel), and
4. Error due to sparse spectral information available in the 7 MODIS bands and their interpolation.

3.2 Validation of spectral interpolation

The above results suggest that interpolation of 7 MODIS spectral bands, only 4 of which are within the absorption range of silicon PV modules, is a sufficiently accurate for effective albedo at the two RadCalNet sites. Here we generalise that conclusion to other surface types and PV modules.

The US Geological Survey Spectral Library [17] contains about 2500 high-resolution reflectance spectra measured on different surface types. From this library, we selected 93 spectra classed as “vegetation” or “soils and mixtures” for which data are available in the 300 – 3000 nm range. For each of these spectra, we first calculate the “true” effective albedo corresponding to each of the devices shown in Figure 2 assuming isotropic scattering. To simulate MODIS sampling, we subsample each spectrum at the 7 MODIS spectral bands and then interpolate to generate synthetic MODIS-derived spectral reflectance. The synthetic MODIS effective albedos are then compared to those from the “true” effective irradiance. The average errors arising from spectral interpolation are shown in Figure 4. The average error across all surface and PV module types is about 1 %, confirming that the 7 MODIS bands are sufficient for generating effective albedo for BEG assessment.

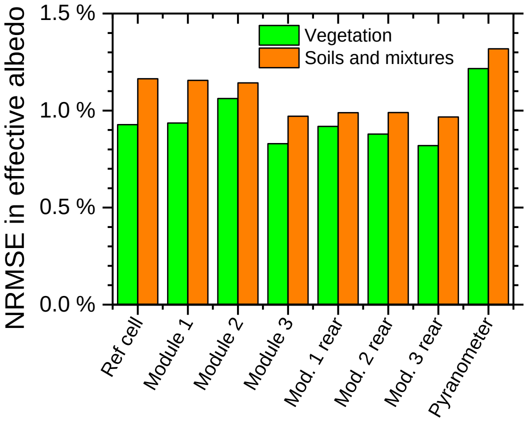

Figure 4 Estimated normalised errors in effective albedo due to spectral interpolation from MODIS bands for vegetation and soil surface types from USGS library.

3.3 Impact of module spectral responsivity

Having validated the use of MODIS satellite data for generating effective albedo quantities, we extend our study by adding a further 18 sites around the globe from the BSRN network. For each of these sites, historical irradiance data are available for at least 10 years. This was used to generate 10-year effective albedo time series for each device shown in Figure 2 at each site. The sites are broadly categorised into desert sites, sites with strong seasonal variations in vegetation cover, and sites which densely vegetated all year round.

Figure 5 shows example statistical output for two locations and two PV module spectral responsivities. The two sites shown are extreme examples: Gobabeb, being a sandy desert site, has the lowest seasonal variation of any site while Bondville has the strongest seasonal variation due to growth of soybean and corn crops at that location.

There is a remarkably strong difference in $\boldsymbol{\alpha}_t'$ values between using the front-side and rear-side response spectrum of Module 1. This is a result of the difference in response to blue light between the two sides of the module. As most blue light is absorbed by the ground, module rear-sides exhibiting poor blue response perform relatively better in reflected light compared to the reference AM1.5G spectrum under which module bifaciality is measured. The use of the effective albedo $\boldsymbol{\alpha}_t'$ enables this effect to be incorporated into BEG assessments.

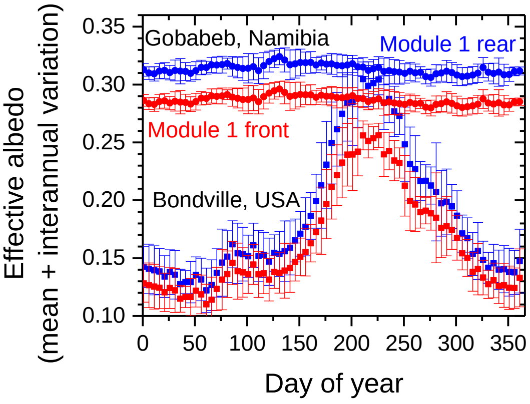

Figure 5 Examples of mean (symbols) and interannual standard deviation (error bars) of daily $\boldsymbol{\alpha}_t'$ by day of year over 10 years (2010-2019) using MODIS satellite data. Two sites are shown, Gobabeb, Namibia (circles) and Bondville, Illinois (squares), calculated for the module spectra from the front (red symbols) and rear (blue symbols) sides of the same bifacial PV module.

The magnitude of the spectral correction effect can be summarised by a spectral correction factor f_{SR}, being the ratio of $\boldsymbol{\alpha}_t'$ divided by the equivalent $\boldsymbol{\alpha}_t'$ calculated with a flat spectral response ($S(\lambda) = 1$). The average values of f_{SR} calculated for all sites is presented in Figure 6. f_{SR} is strongly dependent both on the choice of PV module and the amount of vegetation at a location. For some densely vegetated locations values of f_{SR} greater than 1.3 are seen. For these cases, not compensating for spectral effects may lead to underestimation of BEG by up to 30 %. Therefore, it is critical to accurate BEG calculations that the rear-side spectral responsivity of a candidate module is known, as this influences module choice. Note, however, that this effect is diluted somewhat at high PV array tilt angles as PV modules’ rear sides are exposed to sky as well as ground-reflected light.

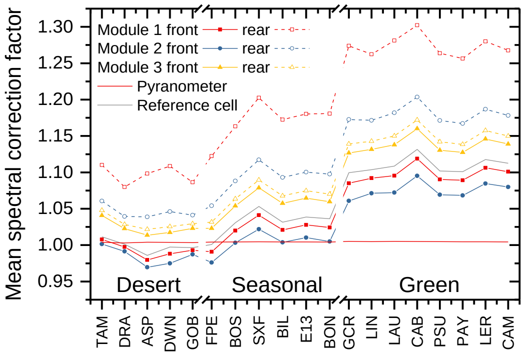

Figure 6 Effective albedo spectral correction factor f_{SR} calculated for each device spectral responsivity and each BSRN location (denoted by 3-letter code on horizontal axis) relative to broad band flat spectral response. The irradiance-weighted mean over a 10-year period is shown.

To illustrate this, BEG assessments were calculated with PVSyst [5] for an example horizontal single-axis tracker bifacial PV system using α_t' calculated from MODIS at Gobabeb and La Crau sites. Even though these sites experienced relatively small spectral corrections, the difference between the front-side and rear-side spectral response curves of Module 1 resulted in absolute and relative differences in BEG of 0.43 % and 6.5 % respectively at Gobabeb and 0.45 % and 10.2 % respectively at La Crau. For more densely vegetated sites this effect would be much larger.

Differences in f_{SR} are also critical for PV system monitoring. Pyranometers, reference cells or photodiodes are used to measure rear side irradiance on bifacial PV arrays. When the spectral response of these sensors is not matched to the spectral response of the rear side of the PV module, a mismatch error will arise depending on the difference in f_{SR}. The results in Figure 6 show that this error could be as large as 30 %, for example, if a pyranometer is used to monitor the rear side of Module 1. The pyranometer would massively underestimate the rear-side effective irradiance. This would make the PV array appear to be performing better than expected and may lead to underperformance being unnoticed. Furthermore, it is not possible to correct for this effect by applying a constant mismatch correction factor, as the magnitude of the mismatch has a seasonal and diurnal variation (as much as 35 % in some cases). This mismatch error was described recently by Gostein *et al.* [4], who concluded that a reference cell should be used instead of a pyranometer for monitoring rear-side irradiance. Our results confirm this, but also suggest that mismatch error of 15 % may still be present with some module types unless the reference cell is spectrally matched to the *rear-side* response of the PV array.

4 CONCLUSIONS

Spectral albedo effects are often ignored in the modelling of bifacial energy yields. We have demonstrated that these spectral effects significant and should be considered. We have demonstrated a method of using satellite-derived spectral reflectance measurements to generate effective albedo values that account for these spectral effects and can be used as an input for bifacial system modelling software. The satellite data were validated against ground-based high-resolution spectral reflectance measurements for two sites. The method is suitable for extension to other sites globally, provided that uncertainty sources such as local variations in surface properties are taken into account. Although the MODIS satellite data has sparse spectral coverage, the error in effective albedo due to interpolation between MODIS spectral bands is only about 1 %.

We have considered multiple locations and module types, showing that diurnal and seasonal variations in albedo and ground-reflected spectrum can be very large and need to be considered for accurate bifacial gain calculation. The consideration of modules' rear-side spectral response is of critical importance. Unfortunately, the difference between front and rear side spectral response is often overlooked both in modelling and in module datasheets. Its measurement is currently not required for procedures such as IEC TS 60904-1-2:2019 (Measurement of current-voltage characteristics of bifacial PV devices). We recommend that more effort is made to disseminate measurements of bifacial modules' rear side responses. Spectral matching of reference cells to the rear side of PV module also needs to be considered for accurate monitoring of bifacial PV systems.

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