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DETERMINING GROUND ALBEDO IN PV PLANTS VIA GROUND MEASUREMENTS AND DECIMETER-RESOLUTION SATELLITE IMAGES

Summary

Accurate modelling of a bifacial photovoltaic (PV) power plant can require spatially resolved albedo information within the partly-built area of the plant as several surface types (like bare soil and grass) are mixed frequently. We present a novel approach to combine highly-resolved satellite images and ground measurements to retrieve decimeter-resolution ground albedo maps which can exclude disturbances caused by the PV rows and their shadows. We demonstrate the approach and evaluate its potential using remotely sensed images with 0.2- to 0.5-m resolution of four plants in Germany and Spain. Our approach avoids errors in the estimated ground albedo in the range of -0.098 to 0.041 compared to a remotely sensed albedo with the resolution of MODIS and -0.08…+0.09 compared to a single albedometer placed within the solar field. These deviations, which are avoided by our approach, translate into avoided errors of -1.9…+2.1% in the PV yield modelled based on the albedo.

Keywords: Ground albedo, bifacial photovoltaics, WorldView, bifacial gain, MODIS, Sentinel, rear-side

Field of application: Solar Resources and Energy Meteorology: Solar Resource Assessment, Remote Sensing

Addressed audience: Investors, EPC companies, O&M providers, PV software developers, planners, scientists

1. Introduction

Bifacial photovoltaics (PV) modules have become standard in utility-scale PV installations as they generate additional yields over monofacial modules. At the same time, this creates the need for accurate methods to determine ground albedo and ground-reflected irradiance within the partly built areas of PV plants. State-of-the-art methods are only partly suitable for the task and can exhibit systematic deviations, see e.g. Blum et al. (2025). Due to this, performance models for bifacial PV plants can exhibit notable deviations which affect tasks like planning, acceptance testing and fault detection. Thus, there is a strong uncertainty among users on the energetic and economic benefit of bifacial PV. Variations of ground albedo are frequent in PV plants: temporally as vegetation recovers from construction works and due to seasonal changes as well as spatially as different surface types can be present in a PV plant. Different rock types, sand, vegetation of different type, height and stage (e.g. green grass and light-colored hay) are present frequently.

Albedometers with ground-facing pyranometers only measure the albedo within their limited fields of view. Spatial variations of ground albedo within a PV plant are therefore not captured. Additionally, shading of the ground surface monitored by the albedometer needs to be avoided as far as possible. In practice, this leads to the selection of non-representative measurement locations outside the solar field. On the other hand, albedo derived from satellite images so far has a coarse spatial resolution (ground sampling distance [GSD]) of at least 10 m, usually 500 m, which makes it very difficult to separate the ground albedo from the one of the PV modules.

Multiple low-earth-orbit (LEO) satellite constellations are operational that provide satellite images with a ground sampling distance (GSD) of around 15-50 cm in multiple bands. For example, WoldView-3 covers the wavelength range from 400 nm to 1050 nm with 8 bands. The benefit of highly-resolved (HR) satellite images (GSD < 1 m) has not been investigated for the application yet. We close this gap with a current research activity. Our contribution presents first results of a combined estimation of the spatial distribution of ground albedo in PV plants from decimeter-resolution satellite images and point-wise measurements of ground albedo. The study demonstrates the current status of our algorithm and gives an estimation of the potential value of this data source to enable a more accurate performance assessment and fault detection for bifacial PV plants.

Figure 1: Raw WorldView image of a PV plant near Tabernas, Spain (left), ground albedo map (center) and albedo map in which PV modules and shades were removed (right). The solar field's footprint is indicated by a blue dashed polygon.

Our case study includes exemplary green-field photovoltaic (PV) plants in Spain and Germany and remotely-sensed images with a GSD of 20-50 cm.

2. Method

From the satellite images, ground albedo and surface type are estimated for each pixel enhancing pipelines from coarser-resolved satellite products based on the Sentinel/MSI and MODIS imagers. Fig. 1 shows exemplary intermediate products of the process, with the original WorldView-2 image on the left. The five bands beyond RGB are not shown. The resolution of the image is high enough to distinguish PV modules, areas shaded by PV modules and unshaded ground between the PV rows. This allows us to determine ground albedo only from suitable, unshaded pixels rejecting all other areas. Our workflow is as follows. Top-of-atmosphere (TOA) radiance is calculated from the WorldView Imager's known calibration. TOA reflectance is calculated based on the current sun geometry. An atmospheric correction yields Bottom-of-atmosphere (BOA) reflectance. A machine-learning-based semantic segmentation determines the surface type in each ground pixel. A BRDF (bidirectional reflectance distribution function) is parametrized based on empirical relationships between BRDF and surface type. Finally, based on the local BRDF and BOA reflectance in the eight wavelength bands respectively, broadband ground albedo is determined (Fig. 1, center). Ground areas obscured or shaded by PV modules and other obstacles are detected by a separate machine-learning method. Such areas receive albedo information from surrounding pixels via an inpainting approach (Fig. 1, right). This is an approximation which is expected to be acceptable as shaded areas usually contribute a small share to the ground-reflected irradiance received by PV modules.

The satellite-based albedo map is calibrated with local measurements. These are also used to generate a temporal update of the satellite-based albedo map. In the present evaluation, the calibration of the albedo map with measurements is simulated by assigning ground albedo from the literature in two points respectively where the surface type is known.

To investigate the potential decimeter-resolution imagery, we model the annual production of the PV plants detected in the satellite images using PVWatts (NREL, 2025). We model these plants as bifacial and estimate plant properties (DC capacity, efficiency, module tilt, tracking etc.) based on the satellite images. In the PV simulations we apply ground albedo from different sources and compare the results. This way we identify the albedo sources' potential impact on PV performance modelling and fault detection tasks. Albedo from different sources is modeled based on the high-resolution albedo maps. A ground albedo comparable to one from MODIS [1] is calculated as average over 500 m x 500 m windows covering the evaluated PV plant. Only in this case, PV modules and their shadows are included in the estimated albedo. Ground-based albedo measurements are simulated as follows. The range of detected albedo values is discretized into 5 bins divided by the 20th, 40th, 60th, 80th percentiles. 5 albedo zones each representing 20% of the PV plant's area are then formed from pixels falling into the same bin. As a simplification, the average albedo calculated over all pixels in the same zone simulates an albedo measurement. Finally, in the PV simulation based on high-resolution (HR) data, a representative albedo is calculated as average over all albedo map pixels inside the PV plant's footprint (e.g. blue contour in Fig. 1). As the amount of available satellite data was still limited when this evaluation was carried out, we used aerial images (BVV, 2025; CNIG, 2025) with a GSD of 20-22 cm to represent decimeter-resolution satellite data at three additional sites in Germany and Spain. Aerial images will be replaced with satellite images in the full contribution.

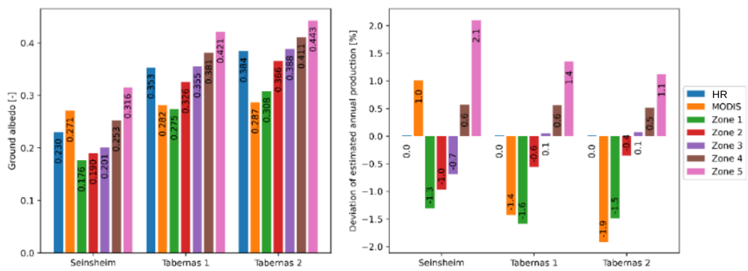

Figure 2: Ground albedo from the different sources (left) and resulting modelled annual PV production (right)

3. Results

As shown in Fig. 1 (right column) the satellite image gives a plausible indication of the ground albedo and its variability within the tested PV plant. Already from the comparison of the left and center columns of Fig. 1 it is apparent that a low-resolution satellite-based ground albedo is prone to errors as PV modules and their shadows affect the detected ground albedo and as the area surrounding a PV plant can have a very different ground albedo than the PV plant. Accordingly, Fig. 2 (left) shows that the 'MODIS' albedo deviates notably from HR. At the sites Tabernas 1 and 2, albedo is strongly underestimated by 0.072 and 0.098. For Tabernas 1 (1.4 MW), a nearby dark green olive grove and other vegetation dominates the 'MODIS' albedo. In the case of the comparably large PV plant Tabernas 2 (22 MW), the dark PV modules and their shades are a strong influence. For Seinsheim (6 MW), 'MODIS' overestimates the albedo by 0.041 as the high albedo of nearby plowed fields affects the 'MODIS' albedo. Figures 2 (left) also shows that a wide range of albedo values is present at each of the studied sites. Depending on the zone in which an albedometer is placed, the measured ground albedo can deviate by up to -0.08…+0.09 from the representative HR albedo. The selection of a representative measurement point for ground albedo and the adequate weighting of multiple albedo measurements into a representative average can be difficult in practice.

Figure 2 (right) summarizes the results of the annual PV production simulations based on the different ground-albedo sources. The predicted PV production can deviate notably from case HR (-1.6…+2.1%) if ground albedo is received from an albedometer. Please note that each of the 5 zones represents 20% of a PV plant's area. Based on that, 40-60% of the measurement points in the studied PV plants will lead to absolute deviations of the modeled PV production of ≥1%. With the 'MODIS' albedo, the predicted PV production deviates by -1.9…+1% from HR.

4. Conclusions and outlook

Our study shows the current status of a novel method to analyze ground albedo from decimeter-resolution satellite images and local measurements. It estimates the potential of decimeter-resolution ground albedo to avoid errors present in state-of-the-art approaches to determine ground albedo and resulting PV production. The combination of local measurements and satellite data brings a number of advantages. The calibration with local measurement increases the method's accuracy. Additionally, the presence of clouds, the revisit times of satellites and economic considerations limit the temporal coverage of satellite images. In our system, the local measurement is therefore used to generate a temporal update of the satellite-based albedo map. Our full contribution will be based on a larger fleet of PV plants to validate the deviations found here. Aerial images used partly in this abstract will be replaced with WorldView images. We will also analyze the influence of seasonal phenomena on ground albedo and PV production. In particular, we will include satellite images taken in winter time as snow can strongly influence the bifacial gain.

5. References

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