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Effects of spectral albedo on solar photovoltaic devices

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ABSTRACT

Although the spectral effects of direct and diffuse radiation on solar photovoltaic (PV) performance are relatively well understood, recent investigations have shown that there can be a spectral bias introduced due to albedo from common ground surfaces that can impact the optimal selection of PV materials for a known location. This paper extends analysis to the effects of spectral bias due to the specular reflectivity of 22 commonly occurring surface materials (both man-made and natural) and analyzes the albedo effects on the performance of seven PV materials covering three common PV system topologies: industrial (solar farms), commercial flat rooftops and residential pitched roof applications. An effective albedo is found for each surface material and PV material combination, which can be used in lieu of broadband albedo values in PV simulations. These results enable PV material selection for specific environments enabling geographic optimization for the micro-environment, while at the same time assisting optimal surface selection in the vicinity of existing or planned PV arrays. This analysis is of particular significance for the modeling of performance of bi-facial PV modules and vertical BIPV.

1. Introduction

Given the earth's plentiful solar resource, solar photovoltaic (PV) energy conversion provides the largest potential of any sustainable energy source to mitigate greenhouse gas emissions [1] and the negative environmental [2], health [3], and economic [4] ramifications of anthropogenic climate change [5]. Although photovoltaic systems are becoming economically competitive with conventional fossil-fuel sources in an expanding list of geographic regions [6], cost remains a major barrier to abundant energy while remaining within the necessary physical limits of life cycle carbon emissions [7]. PV must grow from the tens of gigawatt-level to the terawatt level to halt the rise of CO_2 concentrations in the atmosphere [8,9]. In order to accelerate the diffusion of PV technologies, the electrical output on a per cost basis must be optimized.

One area of PV system optimization that has received relatively modest investigation in the past is the effect of spectral albedo on system performance. Different system topologies can result in significant contributions from reflected (albedo) irradiation. For example, systems which have a large tilt angle relative the ground can have a relatively large albedo contribution, especially if the area ahead of the module is unobstructed. Therefore, vertical PV systems (as have been seen in building integrated systems) and to a lesser extent high tilt angle ground mounted PV systems (as are installed at northern latitudes) can both be significantly impacted by albedo irradiation [10]. In addition, bi-facial modules rely heavily on the reflection of irradiation onto the rear plane of the module, which in some cases can be as high as 25% of incident irradiation on the front of the module [11]. Overall, these systems have been shown to utilize albedo to produce 120% more energy than a mono-facial unit, and therefore the optimization and modeling of these systems requires high-quality albedo predictions [12].

Albedo irradiation changes the spectral distribution of the incident irradiation on the surface of the PV device, which in turn affects system output. In general, PV modules based on commercial semiconductor materials are optimized under Standard Testing Conditions (STC), which are defined as 1000 W/m^2 irradiance with an AM1.5 spectrum at 25 °C [13]. This is not always a valid assumption, as there are long-established daily, locational and seasonal shifts in the spectral distribution of incident radiation at ground level [14–17]. Optimizing for STC can lead to modeling errors and sub-optimal system design as it produces an improper spectral weighting, which is used to calculate a PV device's response to irradiance.

In most PV system design tools the spectral distribution of albedo irradiation is ignored, and is assumed to be similar in

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composition to atmospheric irradiation, leading to the use of a spectrally averaged albedo in many simulations. The spectrally averaged albedo represents the albedo given by the broadband integration of a spectral albedo distribution, and typically for a single atmospheric spectrum [10]. In other words, if the spectrally distributed reflectivity is given by the function $A(\lambda)$, then the percentage of reflected light is generally measured as

$$\alpha = \frac{\int G(\lambda)A(\lambda)d\lambda}{\int G(\lambda)d\lambda} \tag{1}$$

which gives a constant value of albedo that is commonly extended to all spectral conditions. The reflected light (r_e) is then estimated by multiplying this constant albedo by the integrated broadband spectrum at this point.

$$r_e = \left(\frac{\int G(\lambda)A(\lambda)d\lambda}{\int G(\lambda)d\lambda}\right) \times \left(\int G(\lambda)d\lambda\right) = \alpha \times E \tag{2}$$

where $G(\lambda)$ is the broadband spectrum incident on the surface and E is the integrated broadband spectrum. This common formulation ignores the spectral complexity and assumptions made in the measurement of a single spectrally averaged albedo, and a more precise calculation of the reflected light should take into account the spectral variance in both the surface reflectivity and the light incident on the surface.

When taking this into account, it has been seen previously that surface materials can have a significant effect on not only the absolute amount of reflected light, but also in its spectral distribution. As an example, it has been found that snow will tend to bias its reflectivity towards the ultraviolet and "blue" side of the spectrum, whereas grass will tend to reflect preferentially after the "green" portion of the spectrum due to the effects of photosynthesis [10].

Given that PV materials have a defined spectral responsivity, these spectral biases can ultimately affect the power output of a PV device differently than would be assumed for a constant broadband albedo. This spectral biasing due to the surface reflectivity of common ground surfaces (snow and grass) has been shown to have a significant impact on PV output, depending on the type of PV material analyzed. Thus, it has been seen that consideration of the spectral contribution of the albedo is critical to the proper modeling of PV systems [10].

This paper extends the preliminary analysis in [10] to the effects of spectral biasing due to the albedo of a range of 22 environmental surface materials, and their effects on the performance of three common system topologies: industrial, commercial and residential. This analysis will enable PV material selection for specific environments enabling geographic optimization for the micro-environment, while at the same time assisting optimal surface selection in the vicinity of existing or planned PV arrays.

2. Methodology

2.1. Calculation of spectral effects on module performance

In this study, the short circuit current (I_{sc}) will be utilized as a proxy for panel performance. This study is primarily interested in defining the changes in effective irradiance on the surface of a module, which can be modeled accurately by considering only the I_{sc}. Implicit in this assumption is that the effects of increased module temperature due to thermalization and efficiency losses, which could effect the voltage of the system are ignored.

The I_{sc} output of a PV module is directly dependent on the spectrum of the incident radiation and the spectral response of the module.

$$I_{sc} = \int SR(\lambda)G_{tot}(\lambda)d\lambda \tag{3}$$

where $SR(\lambda)$ is the spectral response of the module and $G_{tot}(\lambda)$ is the combination of all sources of irradiation on the surface of the module. Therefore, in order to define the effective albedo, it is useful to define the albedo of a material as the ratio of I_{sc} developed due to albedo irradiation to the I_{sc} developed from all other sources of irradiation, as shown in [10], which define a spectrally responsive albedo (α_{SR}) as

$$\alpha_{SR} = \frac{\int A(\lambda)SR(\lambda)G_{tot}(\lambda)d\lambda}{\int SR(\lambda)G_{tot}(\lambda)d\lambda} \tag{4}$$

In order to calculate the effective albedo for a given surface/PV material combination, reflectance data for the surface materials,

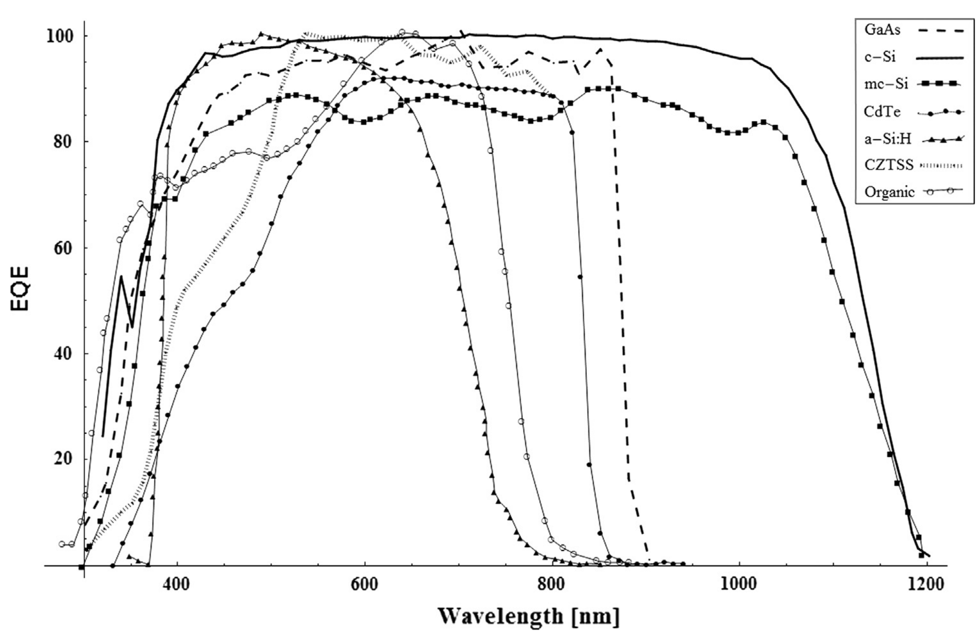

Fig. 1. The normalized EQE of the seven PV materials: (1) crystalline silicon (c-Si), (2) multicrystalline silicon (mc-Si), (3) hydrogenated amorphous silicon based (a-Si:H), (4) cadmium telluride (CdTe), (5) (CZTSS), (6) gallium aresenide (GaAs) and (7) organic PV.