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Optical losses of photovoltaic modules due to mineral dust deposition: Experimental measurements and theoretical modeling

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ABSTRACT

Deposition of particles on photovoltaic (PV) modules has the potential to increase costs of solar energy production and maintenance and to affect grid-connected energy forecasting. Particles deposited on PV modules can reduce the optical transmission to the PV semiconductor significantly ($>50\%$) due to absorption and scattering. Although there are many previous studies of PV module efficiency losses with respect to exposure time, angle tilt of the PV module, and other environmental factors, there has been little study of PV module efficiency losses with respect to the optical characteristics of the deposited particles (e.g., refractive index, optical depth). Here, we deposited two types of dust onto glass slides, optically absorbing dust and optically non-absorbing dust. We systematically increased the mass per unit area deposited onto the glass slides and measured the optical depth and total transmission (i.e., direct plus diffuse light) using a spectrophotometer with an integrating sphere detector system. Our experimental measurements were compared with a two-stream radiative transfer model, and with Monte Carlo radiative transfer calculations, yielding good agreement for both absorbing and non-absorbing dust. Our results indicate that total transmission decreases approximately linearly as a function of dust mass deposited per unit area, with the slope being highly sensitive to the absorptivity of the dust. The obtained results and models used in this study can be used in conjunction with deposition models to predict the degradation of the optical transmission of PV modules with respect to mass per unit area dust loading.

1. Introduction

Solar photovoltaic (PV) modules are exposed to the environment, and aerosol particles, including mineral dust, can deposit on them. Experimental studies have revealed that dust deposition can significantly ($> 50\%$) degrade the power output of PV modules (Sayyah et al., 2014; Sulaiman et al., 2014). These deposited particles cause output power losses for the PV module due to reduced irradiance interacting with the PV module semiconductor, and we shall henceforth refer to these optical losses simply as efficiency losses. Although some experimental work on PV module efficiency losses as a function of environmental factors (e.g., exposure time, wind speed, relative humidity, PV module tilt angle) has been done (Etyemezian et al., 2017; Maghami et al., 2016; Mani and Pillai, 2010), very few experiments have studied PV module efficiency losses as a function of deposited aerosol optical depth τ_0, the key parameter quantifying optical transmission through a layer of particles. In recent years, there has been growing interest in reducing solar energy costs in order to compete with energy generated from fossil fuels. For this reason, one of the important current goals of the U.S. Department of Energy is the reduction of cost of PV solar energy to $\sim$\$0.08 per kilowatt-hour (Fu et al., 2017). Similarly, there has been growing interest in energy forecasting given the increasing penetration of grid-connected solar power (Inman et al., 2013). One important factor influencing solar energy costs as well as solar energy forecasting is the reduced efficiency of PV modules with particle deposits on their surfaces (Costa et al., 2017; Gholami et al., 2017). Deposited aerosol particles extinguish irradiance directed towards the PV semiconductor due to scattering and absorption (Moosmüller et al., 2009), but mathematical modeling of these mechanisms is lacking. Among one of the very few modeling studies, Al-Hasan (1998) developed a model for reduction of transmission of direct radiation onto a PV module, with experimental validity of up to 50% transmission reduction. Building on this work, there have been recent studies modeling direct transmission reduction for PV modules with low soiling loadings on the order of $\sim 0.2\,\mathrm{g/m^2}$ (Sun et al., 2017). Similarly, our group has conducted a theoretical study of the optical losses due to scattering and absorption of radiation by particles deposited onto PV modules. This previous study (Piedra and Moosmüller,

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2017) considered that optical losses are fundamentally due to scattering into the backward hemisphere direction and due to absorption, but that forward hemisphere scattering still reaches the PV semiconductor. This work was limited to small ($\tau_0 \ll 1$) optical depths of deposited aerosol and did not include any comparison with experimental results. In addition, we do not know of any models of PV module efficiency losses as a function of optical depth that consider both the direct beam (defined here as the part of the transmitted solar radiation unaffected by deposited dust) as well as the diffuse radiation (defined here as the part of the transmitted solar radiation scattered by deposited dust).

Here, we develop an optical model based on the two-stream approximation (Bohren, 1987) to calculate the optical losses due to deposition of aerosols onto PV modules that includes direct and diffuse radiation. In addition, we present calculations of optical losses using Monte Carlo techniques (e.g., Wang et al., 1995). The validity of our models is examined by experimentally depositing suspended dust onto glass slides acting as surrogates for PV modules. The models presented here assume normally-incident, monochromatic light. They can be expanded to different incidence angles by discretization of directionality, for instance by the discrete-ordinate method (Liou, 2002) and to the spectrum of incident solar radiation by integration over the relevant wavelength region with a spectral sensitivity function for the PV module of interest. These optical models can be used in conjunction with deposition models, relevant to the location of interest, to predict optical efficiency losses of PV modules due to aerosol deposition. The potential use of these models for forecasting applications is described in Section 5. Abbreviations used in this publication are listed in Table 1 in order of appearance.

Similarly, mathematical symbols used are listed in Table 2 in order of appearance.

2. Experimental measurements

In the following section, we describe a suspension-deposition experiment that was conducted to suspend mineral dust and subsequently allowing it to settle gravitationally onto glass slides that are used as surrogate for PV module surfaces.

2.1. Mineral dust suspension and deposition

We suspended absorbing and non-absorbing mineral dust samples with a mass of ~20 g sample placed into a sample flask. The absorbing dust consisted of pure hematite (Fe_2O_3) particles (Powder Technology Inc.). The non-absorbing dust was an off-white lakebed deposit, diatomaceous shale, consisting of plagioclase, quartz, and lesser amounts of clay, collected as part of a recent study on the characterization of mineral dust (Engelbrecht et al., 2016; Moosmüller et al., 2012). Pressurized air was injected into the sample flask, entraining the sample and transporting it through a tube into the deposition chamber where it consequently gravitationally settles and deposits onto glass slides placed horizontally at the bottom of the deposition chamber (see Fig. 1). We systematically increased the amount of mass per unit area ρ_m deposited on our glass slides by increasing the time that pressurized air was injected into the flask. Dust deposited onto the horizontal glass slide. However, for optical characterization of the glass slide plus deposit, the glass slide with deposit had to be rotated into a vertical position. This limited our deposition mass density ρ_m because above a certain mass density, dust would fall off the slide when positioned vertically. The limits observed were $\rho_m \approx 14\ \mathrm{g/m^2}$ for the absorbing sample and $\rho_m \approx 9\ \mathrm{g/m^2}$ for the non-absorbing sample. These limits are consistent with a PV module's cumulative dust loading over more than 100 days of exposure in Doha, Qatar (Javed et al., 2017). We obtained size distributions for the deposited mineral dust particles from digital image analysis of scanning electron microscope (SEM) images of the deposits. For this analysis, we used dust depositions with nearly equal, low area mass density (i.e., $0.43\ \mathrm{g/m^2}$ for non-absorbing dust and $0.44\ \mathrm{g/m^2}$ for absorbing dust). The particles' longest dimensional lengths (the "diameter") yielded a histogram that was fitted with a log-normal number size distribution $n(D)$ given by

$$n(D) = \frac{1}{C\sigma D\sqrt{2\pi}}\exp\left[-0.5\left(\frac{\ln D-\mu}{C\sigma}\right)^2\right], \tag{1}$$

where D is a free variable used to represent the longest length of the particles as a continuous probability distribution function, σ is the standard deviation of $\ln D$, μ is the mean of $\ln D$, and C is a scaling constant used to normalize the probability distribution such that the integral of $n(D)$ over the D domain is one. The normalized histograms and curve-fits can be seen in Fig. 2, including its fitting parameters. The peak or mode of the log-normal distribution for the absorbing samples was located at ~1.3 µm, while the peak of the non-absorbing sample was located at ~0.8 µm.

Table 1
List of abbreviations used.

Abbreviation	Meaning
PV	Photovoltaic
SEM	Scanning Electron Microscope
SIS	Spherical Integrating Spectrophotometer
AOD	Aerosol Optical Depth
SSA	Single Scattering Albedo

2.2. Optical characterization of deposited dust

The optical properties of mineral dust samples deposited on glass slides were characterized with a Perkin Elmer 1050 UV/Vis/NIR spherical integrating spectrophotometer (SIS) equipped with a detector system consisting of a 150-mm diameter integrating sphere with InGaAs/PMT detectors covering the 250 to 2500-nm spectral range (Padera, 2013). This SIS system has two measurement ports: a transmission port located in front of the sphere, and a reflection port located at the back of the sphere (Figs. 3 and 4). It allows for measuring either the scattering into the forward hemisphere (Fig. 3) or the total transmission into the forward hemisphere, which is the sum of direct beam transmission and scattering into the forward hemisphere (Fig. 4).

We have normalized our measurements of dust-deposited (dirty) glass slides transmission T so that the non-deposited (clean) glass slide transmission $T_{clean\ raw}$ is normalized to $T_{clean} = 1$. The normalized transmission T_{norm} of the particles-glass slide system is obtained from a raw measurement T_{raw} normalized with respect to the raw measurement of a clean glass slide transmission $T_{clean\ raw}$ as

$$T_{norm} = \frac{T_{raw}(\lambda)}{T_{clean\ raw}(\lambda)}. \tag{2}$$

This normalization isolates the effect of deposited dust on optical transmission. In our experiments, $T_{clean\ raw}$ ranged from ~0.91 to ~0.93, comparable to the normal incidence ~0.92 transmission through an air-glass-air system with glass refractive index of 1.5, where losses are caused by Fresnel reflections from two surfaces. All transmission measurements discussed in the following discussion have been normalized with Eq. (2).

2.2.1. Forward-Hemisphere scattering measurement

The SIS spectrometer can be used to selectively measure the transmission of light scattered into the forward hemisphere T_{fwd} by locating the sample in the transmittance port in front of the SIS and eliminating the direct beam power through absorption by a non-reflecting (black) surface (Fig. 3).