Determination of a Minimum Soiling Level to Affect Photovoltaic Devices

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***Abstract*—Soil accumulation on photovoltaic (PV) modules presents a challenge to long-term performance prediction and lifetime estimates due to the inherent difficulty in quantifying small changes over an extended period. Low mass loadings of soil are a common occurrence, but remain difficult to quantify. In order to more accurately describe the specific effects of sparse soil films on PV systems, we have expanded upon an earlier technique to measure the optical losses due to an artificially applied obscurant film. A synthetic soil analogue consisting of AZ road dust and soot in acetonitrile carrier solvent was sprayed onto glass coupons at very brief intervals with a high volume, low pressure pneumatic sprayer. Light transmission through the grime film was evaluated using a QE test stand and UV/vis spectroscopy. A 0.1 g/m^2 grime loading was determined to be the limit of mass measurement sensitivity, which is similar to some reports of daily soil accumulation. Predictable, linear decreases in transmission were observed for samples with a mass loading between 0.1 and 0.5 g/m^2. Reflectance measurements provided the best means of easily distinguishing this sample from a reference.**

***Index Terms*—Photovoltaic cells, surface contamination, performance loss, standardized test methods, soiling**

I. INTRODUCTION

SLOW soil accumulation on photovoltaic (PV) modules presents a challenge to long-term performance prediction and lifetime estimates due to the inherent difficulty in quantifying small changes over an extended period. Most of the available information on the effects of soil has been collected during the operation of installed arrays. Predictive estimates are not typically available for specific sites, so rough estimates are used in long-term models [1]. Thevenard and Pelland [1] noted that uncertainty in the performance evaluation of large systems is particularly problematic to assessing economic viability. The authors selected a 3% derate factor with 2% uncertainty, but noted that their estimates could be improved with a better understanding of soiling losses. An upper limit to the loss in transmission due to soiling was reported by [2]. After a certain threshold, the surface is sufficiently saturated to make the effect of additional particulates insignificant. The upper limit observed by [2] has been experimentally described by [3] as a function of particle stacking. The authors applied sand particles in a narrow size distribution to glass surfaces. They found that particle clustering influences the total obscured area of the slide as an exponential function. This clustering effect is likely responsible for the observation by [4], who note that "dust promotes dust".

Except in the case of extreme weather conditions [5], it is unlikely that fielded PV systems would be allowed to reach a saturated loading condition. Low soil mass loadings represent a much more common; albeit difficult to quantify, occurrence. Models appropriate for heavy mass loadings do not agree well with models describing lighter loadings [6]. Measurements of light transmission through soiled glass (haze) have been described by [7] as dependent upon the density of the accumulated soil film. Sparse soil films exhibited a non-linear change in haze, making prediction difficult at low mass loadings. Measurements on assembled PV modules would likely be more difficult, as direct transmission measurements are not feasible. Reflectance measurements on module surfaces have been reported [8], [9]; however, a direct correlation between the amount of soil and reduction in performance was not made.

In order to more accurately quantify the specific effects of sparse soil films on PV systems, we have expanded upon an earlier technique [10], [11] to measure the optical losses due to an artificially applied obscurant film. Two significant factors must be considered to effectively evaluate light transmission through thin soil films. First, accurate measurement of the mass and obscured area is essential. Secondly, the optical effects of the soil and cover glass must be considered. We have found that accurate measurement of soil on glass coupons can provide detail to 0.1 g/m^2. While not yet directly correlated to PV performance, surface reflectance is the simplest characterization technique for low mass coatings.

II. EXPERIMENTAL METHODS

Light transmission through very low mass loadings of soil was evaluated by examining glass coupons with a known quantity of grime obscuring the surface. Spectral transmission measurements were complimented with spectral reflection measurements.

A. Grime Application

The clean test coupon was weighed with a 0.00001 g resolution balance (Mettler Toledo XP205) and placed at a 45° angle inside a filtered spray chamber. A synthetic soil, termed grime, consisting of AZ road dust and soot in acetonitrile carrier solvent [10] was sprayed onto the test coupon at very brief intervals. The base, non-spectrally responsive grime [10] was used in order to establish a baseline for particle size effects

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and area coverage. Suspension densities from 10 g/l to 20 g/l were used to control the particle deposition rate on each coupon. Dense solutions resulted in spotted patterns, while dilute solutions produced a lighter, more uniform pattern. In earlier work [11], the spray applicator was swept from right to left to apply a uniform, heavy coat across the entire surface of a large coupon (13.5 × 5.5 cm) This step has been modified in the present work to produce very light coatings. Instead of sweeping the applicator, it was held over the center of a smaller (4.5 × 5.5 cm) coupon while a brief spray (∼ 1 sec) was applied. The acetonitrile carrier solvent evaporated quickly, ensuring a very uniform particle dispersion over the glass surface, when desired. Coupons were weighed in triplicate and averaged.

The area of each glass coupon was determined by imaging the sample with a 1:2 mm drafting scale included in the field of view. Each image was imported into ImageJ [12] and calibrated using the length of the drafting scale in the image. The auto-level and auto-contrast adjustments were used to enhance the edges of the sample. The glass was outlined by hand, and the area was calculated, as illustrated in Fig. 1b. Each image was re-opened, calibrated, and measured in triplicate to provide a sample standard deviation. The area coverage was determined by imaging the top, middle and bottom region of each coupon. Images were collected at 2.52x magnification using an Olympus IX71 microscope equipped with a DP72 camera. Area coverage was determined using an automated image analysis script to locate and measure each particulate.

B. Testing

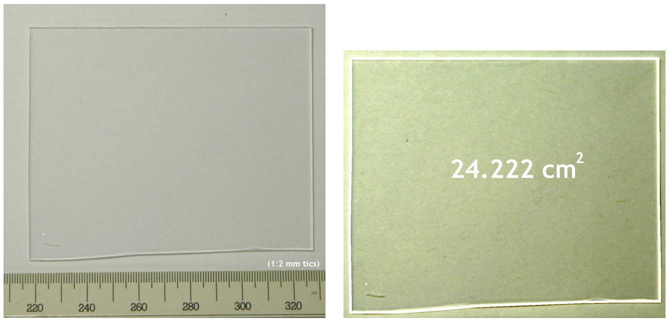
Light transmission through the grime film was evaluated using a Quantum efficiency (QE) test stand and UV/vis spectroscopy. QE measurements were collected with three readings per wavelength on a PV Measurements QEX-10 at 10 nm increments over an interval from 300 to 1250 nm. The stage height was adjusted to 21.6 cm in order to focus the sample spot on a multicrystalline Si cell with a baseline efficiency of η = 16%. Triplicate measurements were collected by positioning the coupon in various positions over the test device.

Spectral transmission and reflection measurements were collected with a Varian Cary 5000 UV/vis/NIR spectrophotometer equipped with a DRA-2500 diffuse reflectance accessory. The instrument was operated at 1 nm resolution in the UV/vis range (300-800 nm, 600 nm/min) and 4 nm resolution in NIR range (800-1200 nm, 2400 nm/min). The slit bandwidth was fixed at 3 nm for UV/vis, while the NIR energy was set at 10. Data collection was repeated in triplicate for each coupon.

III. RESULTS AND DISCUSSION

A. Low Grime Loading

Due to the very small sample mass, accurate measurements were essential to this study. Each coupon was weighed in triplicate, and the specific area of the glass coupon was determined by image analysis as shown in Fig. 1. The repeatability of the area measurement was determined by re-calibrating and measuring the same image in triplicate. Since the soil coating was so light, automated analysis by image contrast was not feasible. The area was outlined by hand, then measured using ImageJ.



(a) Raw image of soiled coupon (b) Processed image showing outline

Fig. 1. Images of soiled coupons were collected (a) and analyzed in ImageJ (b) to find the total area of the glass.

Particle size was not directly controlled in this study. Instead, a single test grime was diluted in varying amounts of carrier solvent to control particle agglomeration on the glass surface. This practice emulates natural soil accumulation under both gradual and forced (i.e. light rain) deposition regimes.

B. Measured Response to Low Mass Loadings of Grime

The transmission through applied grime films was evaluated using QE and UV/vis spectroscopy. Each instrument provided spectral behavior at each of the points interrogated by the instrument beam. In order to compare between the two techniques (Fig. 2), the spectral data (Fig. 3) was integrated to provide a single value. Any point with a standard deviation greater than 25% of the average value was not included. As a result, reliable measurements could not be obtained for mass loadings below 0.1 g/m^2. As we noted earlier [11], reflectance measurements are much more sensitive to very small changes in surface contamination than transmission measurements. The spectral response (Fig. 3) showed a distinct delineation between each trace. While reflectance does not directly correlate to flat plate PV performance, it may be a useful field measurement technique.

Measurements were also collected with a one-sun simulator, but the repeatability was very poor for samples between 0 and 0.35 g/m^2. In contrast, the repeatability of the QE measurements collected for the same samples was very good. These results illustrate a significant point regarding minimum soiling levels. With proper hardware, a minimum soiling threshold can be determined and used as an input to estimate losses with a very fine detail. However; the utility of this level of detail must be matched to other uncertainties in the system.

C. Grime Patterning and Measurement Uncertainty

Reflectance measurements were shown to be the easiest determination of soil on glass coupons. Work by Murphy et al. [8] used a glossmeter to determine soil loading, reported only in terms of measured gloss. These measurements were

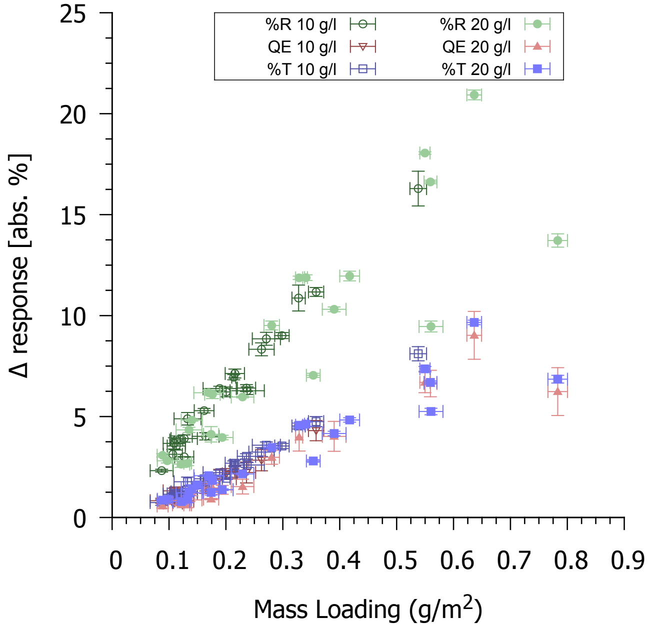


Fig. 2. Change in measured J_{SC} for low mass loadings. Reflectance measurements are shown as an absolute value. Points with $\sigma > 25\%$ are shown as a shaded area.

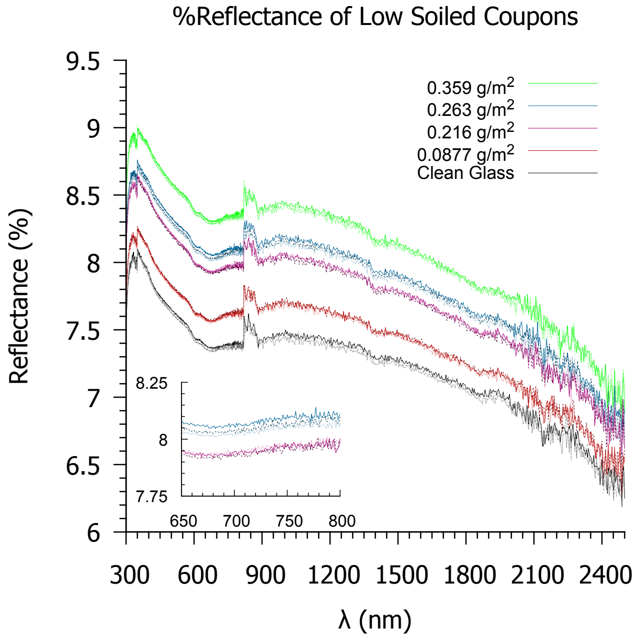


Fig. 3. Reflectance measurements provided the most distinct delineation between each sample. Each data set shows triplicate measurements (higher resolution inset).

not directly correlated to mass loading; however, the authors reported a particle composition effect in later work [9]. The authors emphasized composition rather than particle size as the primary property.

In the present work, we have demonstrated that reflectometry can be a useful measurement proxy for the effects of soil accumulation. The reflectance correlates to transmission and quantum efficiency measurements in Fig. 4. In the figure, a linear fit was applied to each data set for both the individual (10 and 20 g/l) and combined application techniques. The fit to transmission response agrees very well between the two sets, indicated as dashed blue lines. The overall fit, shown as a solid line, is overlapped by both individual curves. In contrast, the linear fits for quantum efficiency measurements diverge significantly between the two application techniques. Since data points with excessively large uncertainty were not included, the quantum efficiency data consists of fewer points, thus limiting the quality of the fit.

We have investigated agglomerate size effects in the as-deposited soil; looking specifically at the arrangement of particulate clusters rather than the size of individual particles. Application of very dense grime suspension was found to cause a non-uniform deposition pattern on the glass coupon. The suspension density was used to produce a range of soil patterns with a similar total mass loading. Dilute suspensions (10 g/l) produced highly uniform samples with a consistent measured area fraction. The grime patterning appeared visually uniform for the coupons prepared with the 10 g/l grime suspension. Microscopic inspection (Fig. 5a) indicated a homogenous distribution of particles. The uniformity of the applied particle film decreased with increasing mass loading (Fig. 5b), as illustrated by the error bars in Fig. 6. Very lightly coated coupons exhibit a similar mass loading and reflectance with a similar obscured area fraction. More heavily coated coupons follow an increasing trend; however, the uncertainty

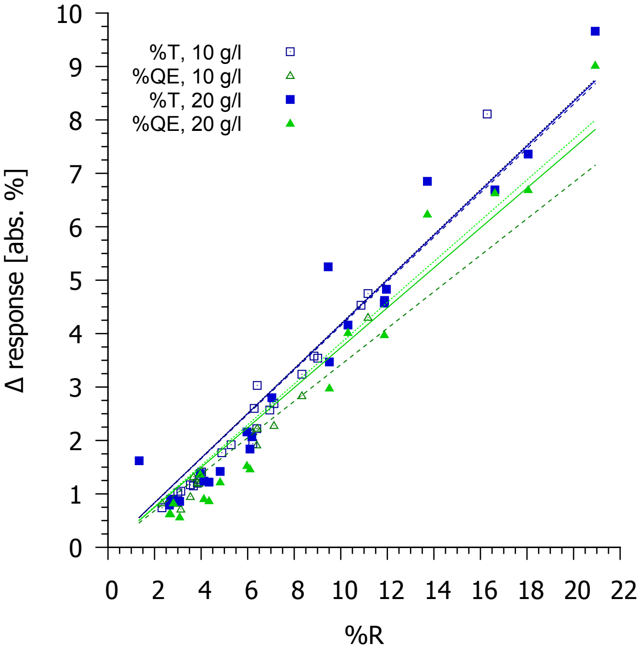
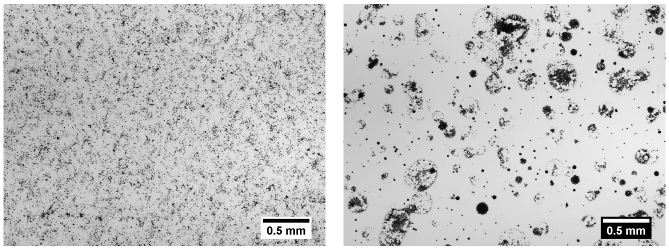


Fig. 4. Correlation between reflectance and transmission and QE, respectively.



(a) 0.537976 g/m^2, 13.8% area (b) 0.783093 g/m^2, 7.3% area

Fig. 5. Images of maximum mass loading coupons for uniform (a) and patterned (b) grime application at 2.52x magnification.

associated with these measurements also increases. The greater uncertainty indicates that heavily loaded coupons tend to have a less uniform coverage. Increasing uncertainty was likewise observed for measurements made with the QE, which uses a smaller probe spot and is therefore more sensitive to sample inhomogeneity.

When the grime solution density was increased to 20 g/l, the grime tended to aggregate in distinct droplets (Fig. 5b) The more dense solution was difficult to apply in a consistent manner. As a result, the range of mass loadings and measured optical responses was greater than the corresponding range for samples prepared with 10 g/l solution. The data did follow the same general trend.

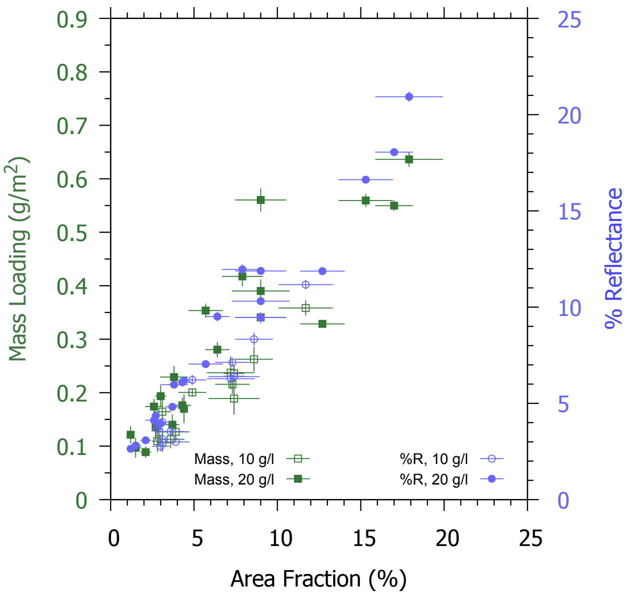


Fig. 6. Correlation between mass density, area fraction and measured reflectance.

When all of the samples are evaluated collectively (Fig. 2), a strong linear trend can be seen for the transmission measurements with a mass loading less than 0.5 g/m^2. The trend is weaker for greater mass loadings.

IV. CONCLUSION

Mass measurement precision and accuracy is the primary limiting factor in determining a minimum level of loss due to soil accumulation. Sufficiently reliable measurements of grime mass loading could not be determined for a mass loading less than 0.1 g/m^2. However, the sensitivity of both reflection and transmission measurements appear to be adequate to detect optical changes below this level of soiling. This mass loading can be expected to cause a transmission loss less than 1%. This decrease in output corresponds to average daily losses under heavy soiling conditions reported by [13]. Slightly greater mass loadings contributed to a 1-2.5% reduction in J_{SC}, which correlates to previous measurements [11].

The UV/vis transmission data closely followed the measured QE response. Reflectance measurements followed a steeper trend, and were used to readily distinguish the lightest grime coatings from clean glass. A linear trend was noted between the reflectance, transmission and quantum efficiency responses, respectively. Reflectance measurements could be used as a proxy for mass loading when making measurements on fielded systems. This indicates that reflectance may be promising for field studies.

The overall effect of soil accumulation on PV surfaces is a reduction in the light available to generate electron/hole pairs. Determining the most consistent technique to measure soil on a surface for comparison to other systems has been challenging. Many of studies in the literature use different techniques, making comparisons between systems difficult. Mass loading has been a convenient metric to use for laboratory-based tests; however, determining the mass of soil on large arrays is cumbersome. We have shown a good correlation between deposited mass and the obscured area of test coupons for non-spectrally responsive test grime. Measured responses overlapped between 0.1 and 0.2 g/m^2 and 1-5% area fraction. Greater mass loading and area fraction resulted in a wider spread between data points. Due to the variation in particulate patterning, quantitative comparisons between mass loading, obscured area and change in transmission were not feasible. However; qualitative evaluation of fielded systems should be possible.

Ultimately, when determining a minimum soiling level, PV instrumental sensitivity is a potential limiting factor. An appropriate test method must be selected to ensure that losses due to soil are outside the instrumental error. Surface reflectance may be a useful method to evaluate module soiling in the field. This level of detail will be useful to high performance CPV systems and large utility installations.

ACKNOWLEDGEMENT

SAND2014-4402C This work was supported by the U.S. Department of Energy SunShot Initiative. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

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