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Outdoor soiling microscope for measuring particle deposition and resuspension

Benjamin Figgis[a,b,*], Ahmed Ennaoui[a], Bing Guo[c], Wasim Javed[c], Eugene Chen[c]

[a] *Qatar Environment & Energy Research Institute, HBKU, PO Box 5825, Doha, Qatar*
[b] *ICube Laboratory, University of Strasbourg–CNRS, Strasbourg, France*
[c] *Texas A&M University at Qatar, PO Box 23874, Doha, Qatar*

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ABSTRACT

The rate of soiling of photovoltaic modules depends on environmental parameters such as aerosol concentration, humidity and wind speed. Previously we found low correlations between daily averages of these values and the daily soiling rate of a PV system. In this study we aimed to achieve stronger correlations by increasing the measurement frequency, with a simple device able to quantify soiling in outdoor conditions in real time. The so-called outdoor soiling microscope developed could measure the deposit and removal of individual dust particles larger than 10 μm^2 every few seconds, and could detect the onset and disappearance of condensation. In an initial trial the device revealed qualitative relations between the parameters not seen with 24-h data. However most linear correlation coefficients remained low, suggesting the need for a more sophisticated model of outdoor soiling.

1. Introduction

Soiling of photovoltaic (PV) modules has become important as countries with desert climates pursue large PV projects. Reviews show that soiling can seriously degrade the performance of PV systems in desert climates (Sarver et al., 2013; Mani and Pillai, 2010; Costa et al., 2016). It would be useful to be able to predict (i) the long-term soiling rate at a location from atmospheric measurements, and (ii) the short-term soiling rate in outdoor conditions, which would demonstrate an accurate understanding of ambient soiling mechanics. Soiling models have not yet met these goals although progress is being made (Boyle et al., 2016; Guo et al., 2015).

Soiling is commonly measured by exposing either small collection coupons or full-size operating PV modules in the field. Coupons are typically characterized by light transmission loss or accumulated soil mass, while modules are characterized by their short-circuit current (I_{sc}) or energy yield. Common to all these approaches is that soiling is measured daily or less frequently. Weather conditions vary continually, of course, which obscures their relations to soiling.

This shortcoming is exemplified in two recent studies. In Colorado, Boyle et al. (2016) collected and weighed dust from coupons at two sites every 2–4 weeks. They attributed two-thirds of their model's error to the long measurement period and measurement error. In Doha, Qatar, some of us (Guo et al., 2015) used an eight-module operating PV system as the collection surface, and characterized soiling rate by the daily decrease in its normalized energy yield. We found low correlations between the daily soiling rate and daily averages of relative humidity (RH), wind speed (WS), and 10 μm airborne particulate matter (PM10).

Clearly, correlation of soiling to environmental parameters might be improved by reducing the soiling measurement period, from days to hours or minutes. This appears to rule out traditional methods mentioned above (e.g. soil mass, light transmission, PV module response) because their values would not change appreciably with the amount dust that settles in such a short time. We therefore aimed to develop an optical method using a portable, outdoor, low-power microscope coupled with automated image-processing software.

Photography and videography with microscopes have been used previously to study particle deposition and removal. Kassab et al. (2013) used a high-speed camera in a wind tunnel to measure the effect of surface roughness on adhesion of 10–100 μm glass beads. Also in wind tunnels, Ibrahim et al. (2004) used a video

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[*] Corresponding author at: Qatar Environment & Energy Research Institute, HBKU, PO Box 5825, Doha, Qatar.

E-mail addresses: bfiggis@qf.org.qa (B. Figgis), aennaoui@qf.org.qa (A. Ennaoui), bing.guo@qatar.tamu.edu (B. Guo), wasim.javed@qatar.tamu.edu (W. Javed), eugne.chen@qatar.tamu.edu (E. Chen).

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camera to measure removal of 70 μm stainless steel spheres from a surface in varying RH, and Wu et al. (1992) used one to observe rebound and resuspension of several organic particles from a variety of surfaces. Lin et al. (1994) exposed greased plates outdoors for 8 and 16 h, and then used a microscope and computer to analyze the particles.

These wind tunnel studies used a single type of particle in each experiment, while the outdoor study did not account for resuspension and had a relatively long measurement period. A device to measure particle deposition and re-suspension, with natural weather and particles, in short time intervals, appears to be a novel approach.

2. Outdoor soiling microscope

We developed a simple "outdoor soiling microscope" comprising a small, low-power digital microscope (Celestron® Handheld Digital Microscope Pro) connected to a computer. A borosilicate glass microscope slide, 5 cm square and 1.6 mm thick, was glued to the shroud protecting the front of the microscope. The microscope and attached slide were inverted, so that dust settles on the slide and is visible through the slide by the microscope (Fig. 1). In this configuration a surface area of 2.42 × 1.82 mm was captured as an image of 2592 × 1944 pixels, giving a resolution of 0.935 μm/pixel.

In order to maximize contrast of dust particles against the background, and achieve consistent lighting during day and night, a 10 W LED lamp was positioned over the device such that the microscope was "looking into" the lamp (Fig. 2). A sheet of translucent paper was placed over the lamp to make the background lighting more uniform. The built-in LEDs of the microscope were turned off. Dust particles appeared as dark areas against a bright yellow background, both day and night (Fig. 3, right image). A program was written to capture images at any desired time interval. This could be as short as a few seconds—effectively real time—although we found that 10 min worked well for the rate of soiling in Doha. Images from the microscope were analyzed with imageJ software and custom macros, described further later.

In light wind the lamp might interfere with deposition of large particles, which settle vertically under the action of gravity. The distance between lamp and microscope was made as large as possible while preserving image quality, resulting in a spacing of roughly 10 cm. In the trial reported herein, the device was also tilted to 22° (latitude tilt) which reduced obstruction vertically above the collector surface. In future a smaller, brighter lamp may allow greater spacing and reduce such interference.

Fig. 1. Outdoor soiling microscope with glass slide as soiling collection surface.

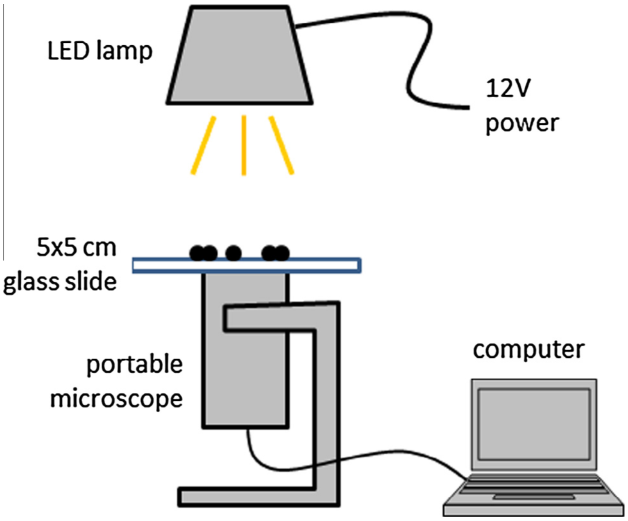

Fig. 2. Schematic set-up of outdoor soiling microscope.

2.1. Particle resolution and size measurement

What is the smallest particle the outdoor soiling microscope can reliably measure? Dark areas 2–3 pixels across (i.e. particles 2–3 μm in diameter) could be clearly seen against the bright background. However such small particles were relatively faint and detection of their edges was sensitive to slight changes in lighting, making measurements of their sizes unreliable. Also, light transmission loss is overwhelmingly governed by large particles: studies using greased plates near Chicago found that 99% of mass collected was particles larger than 10 μm (Lin et al., 1994) or 2 μm (Aluko and Noll, 2006). For these reasons we decided to ignore dark image areas smaller than a certain size.

To determine this size limit we compared images of the same soiled coupon using the outdoor soiling microscope and a laboratory optical microscope (Leica DM2700M RL/TL, 5X objective lens). The resolution of the lab microscope image was 0.332 μm/pixel, and as mentioned the outdoor images were 0.935 μm/pixel. A sample pair of images is shown (Fig. 3). As expected the lab microscope had greater resolution, i.e. it revealed small particles that the outdoor microscope did not. (The "cost" of high resolution is surface area surveyed: the outdoor microscope captured 4.39 mm^2 of the surface, while the lab microscope captured 1.30 mm^2. Soiling rate measurement with a larger surface would be less skewed by an occasional very large particle.)

ImageJ software was used to measure the projected area of deposited particles. The steps were: (1) convert the image to 8-bit greyscale, (2) set the scale (μm/pixel), (3) determine the image average light intensity (range 0–255), (4) select image segments that were 50 units darker than the average (threshold function), (5) measure the sizes of each such segment. The backing LED lamp allowed this method to be used day and night. The lab and outdoor microscopes were used to photograph the same patch of soiling, and the measured particles areas were sorted large to small and summed (Fig. 4). Compared to the lab microscope, the outdoor soiling microscope tended to generate images that understated the areas of large particles, i.e. the sum of areas measured by the outdoor device (red points) was less than that by the lab microscope (blue points) toward to left of the chart. Conversely, it overstated the size of small particles (the sums cross and diverge going right). The point at which the under- and over-measurement errors cancel