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DESIGN AND INDOOR VALIDATION OF “DUSST”: A NOVEL LOW-MAINTENANCE SOILING STATION

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ABSTRACT: Soiling can cause significant losses to photovoltaic systems, and therefore it has to be carefully monitored. Currently, the most common soiling monitoring technologies are soiling stations that use the electrical outputs of a regularly cleaned PV device and of a naturally soiled PV device to quantify soiling. A new class of low-maintenance soiling stations has now been launched in the market to lower the cost and increase the reliability of soiling monitoring. In this work, the design, and the indoor validation of “DUSST” (Detector Unit for Soiling Spectral Transmittance), a new low-maintenance soiling station, are presented. DUSST projects a collimated monochromatic light through a glass surface and on to a light detector to measure the intensity of the transmitted light. As the glass surface naturally soils, the losses are quantified by comparing this soiled reading with a calibrated reading in the baseline clean condition.

Keywords: Soiling, Detector, Reliability, Monitoring, Optical Losses

1 INTRODUCTION

The accumulation of contaminants on the surface of photovoltaic (PV) modules (i.e. soiling) is an issue affecting PV systems worldwide, where it can decrease the annual energy yield by up to 7% [1–3]. In some regions, soiling can cause power drops as high as 70% [4]. Soiling can cause significant economic losses because it lowers the energy yield of PV systems, raises the operations and maintenance costs, and increases the uncertainty on PV performance, which can lead to higher finance rates from the investors. Therefore, it is important to monitor soiling, in order to plan the most accurate cleaning schedule for a system, i.e. only executing cleanings when the associated expenses are justified by the economics of the projected energy gains [5].

So far, the community has been monitoring soiling at PV sites mainly by using soiling stations [6,7]. These systems are generally made of two PV devices (cells or modules), one of which is left to soil naturally, while the other is regularly cleaned. Soiling is quantified by comparing the electrical outputs of the two PV devices. Soiling stations are cleaned either by an operator or through an automated rotating brush or high-pressurized water spray. As discussed in [8], soiling stations require frequent cleanings and careful maintenance in order to produce low uncertainty and reliable data. For example, in the right location one missed cleaning can result in uncertainties ballooning to values that are greater than the reported soiling loss. In this light, we propose an innovative cleaning-less soiling station, named DUSST (*Detector Unit for Soiling Spectral Transmittance*), designed to monitor soiling without moving parts and the need of water [9].

In the present work, the design, and the measurement procedure of DUSST are detailed followed by the results of an indoor validation conducted using artificially soiled coupons.

2 DUSST

2.1 Design

A 2D drawing of the DUSST design, described in the provisional patent submitted to the U.S. Patent and Trademark Office [9], is shown in Figure 1. A collimated light source is used to emit a monochromatic light perpendicularly onto a glass coupon where soiling is collected. The glass coupon is exposed to the same conditions and mounted at the same tilt, azimuth, and height as the PV modules to be monitored. The intensity of the light transmitted through the soiled glass is measured using a light detector and compared to the intensity of the light transmitted through the glass in clean reference conditions. The ratio between the two intensities (*Light Intensity Ratio*) can be used to estimate the *Soiling Ratio*, the most common metric to quantify the impact of soiling on the PV performance, defined as the ratio between the electrical output of a soiled PV module and the same electrical output of the module in clean conditions [10].

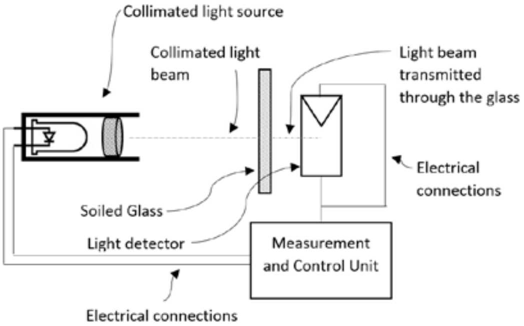

Figure 1: 2D schematic of DUSST.

2.2 Measurement

DUSST follows the soiling monitoring procedure described in Figure 2. It quantifies the daily soiling losses by averaging the soiling ratios measured at different moments each night, when the external light noise is at a minimum. Multiple measurements serve to minimize the impact of noise that may occur due to varying external light sources in the vicinity of measurement sensor. Each measurement consists of five steps:

1. **Zero Measurement**: the reading of the light detector is recorded while the collimated light source is turned off. This way, potential external light sources, which might affect the soiling measurement, are quantified.
2. **Soiling Measurement**: the collimated light source is switched on. Once the signal is stable, the intensity of the light measured by the light detector is recorded. A second zero measurement can be conducted to re-check the absence of

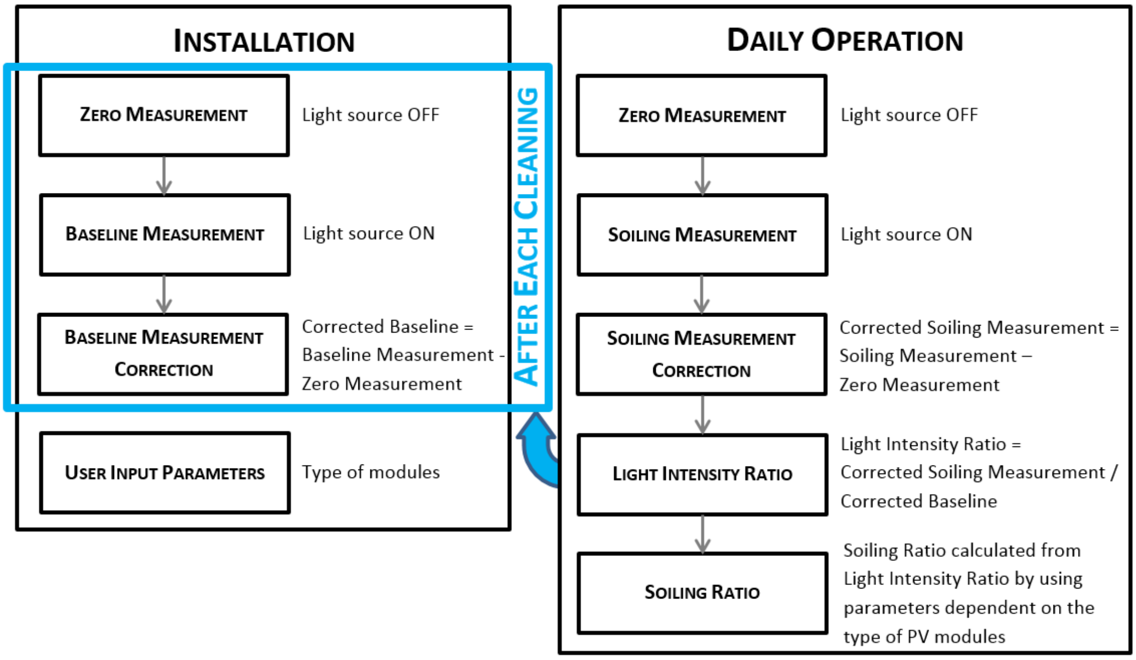

Figure 2: Schematic of the measurement process steps and of the calibration process required after the first installation and after each cleaning.

external light sources and/or to verify the same signal obtained when performing the initial zero measurement.

3. **Soiling Measurement Correction**: the soiling measurement is corrected by subtracting the zero-measurement to remove part of the light signal due to external sources.
4. **Light Intensity Ratio**: the ratio between the intensity of the light transmitted through the soiled glass and its *baseline* (intensity of the light transmitted through the clean glass) is determined.
5. **Soiling Ratio**: the soiling ratio is calculated by correcting the light intensity ratio according to *pre-determined coefficients* that take into account the type of modules under investigation [11].

DUSST should be cleaned at the same time as the PV array. The baseline value of the light intensity, representing the intensity of the light transmitted through the glass in clean condition, is determined (i) at the moment the device is installed, and (ii) after each cleaning. The baseline is measured following steps 1 to 3 of the procedure above.

2.3 Advantages

When light hits soiling particles or a soil layer, part of it is transmitted and reaches the PV material, while part of it is either absorbed or reflected. DUSST replicates the behavior of the solar cell, where the sunlight is replaced by a beam of known intensity, converting the photons into a signal. It measures the transmitted component of the light: transmittance is often larger than the sum of absorbance and reflectance, and its measurement is generally less noisy than a reflectance signal, meaning that DUSST is expected to achieve an excellent signal-to-noise ratio.

DUSST uses a stable monochromatic light source to quantify soiling, instead of the constantly varying sunlight used for typical soiling stations. The need of determining the intensity of the sunlight makes it necessary to regularly clean the reference cells in a typical soiling station. In DUSST, the intensity of the incoming light is known due to the stable monochromatic light source used, thus eliminating the need for cleaning. In addition, the lack of movable parts and the employment of standard components make DUSST reliable, durable, and a low-cost option. The re-calibration, automatically conducted after each cleaning, reduces the potential effects of component aging and degradation on the soiling measurement.

3 INDOOR VALIDATION

3.1 Prototype

The choice of the monochromatic light emitter's wavelength is based on the analysis presented in [11]. A monochromatic diode emitting light at 530 nm (green light) has been chosen for the prototype, because within the waveband that returned the best soiling estimation for any of the PV technologies investigated in [11]. An optical structure has been used to collimate the light onto the light detector.

An encapsulated solar cell has been employed as light detector and a Fluke 289 multimeter has been used to measure the current generated by the cell. In the fielded prototype, a data logger will replace the Fluke multimeter. The on/off switching of the diode is controlled by a timer. Power for the entire station is supplied by a Li-ion USB power bank.

3.2 Artificially Soiled Coupons

Five 4cm × 4cm sized and 3mm thick Diamant low-iron glass coupons have been artificially soiled by using different amounts of Kaolinite. The deposition was performed by using a deposition chamber developed at NREL. The hemispherical transmittances of the coupons were measured between 250 and 1300 nm, at 1-nm steps, using a Cary 5000 dual-beam ultraviolet-visible-near infrared (UV-VIS-NIR) spectrophotometer (Agilent Technologies Inc.) equipped with a DRA-2500 integrating sphere (Agilent Technologies Inc.).

Figure 3: Picture of the prototype built for the indoor validation process.

3.3 Indoor Validation

The validation of the prototype has been conducted by powering the green diode at 510 mA and 3.025 V. The measurements started 30 minutes after the light source had been switched on to let the light beam stabilize. In order to minimize the impact of external light sources, the test was conducted in the dark and a zero calibration was performed (zero reading of the detector: 0.011 mA).

The intensity of the light emitted by the diode and recorded by the light detector under a clean glass resulted in a *baseline* of 5.127 mA. The intensities of the light transmitted through each soiled glass coupon were measured and, along with the baseline, corrected according to the zero measurement. The readings of the multimeter (*soiling measurements*) were compared with the hemispherical transmittance of the same glass at 530 nm, previously measured using the spectrophotometer. The results of the test are shown in Figure 4: the two measurements have a coefficient of determination (R^2) of 97.6%, proving a strong linear correlation between the measurement of DUSST and the actual hemispherical transmittance of the glass coupons.

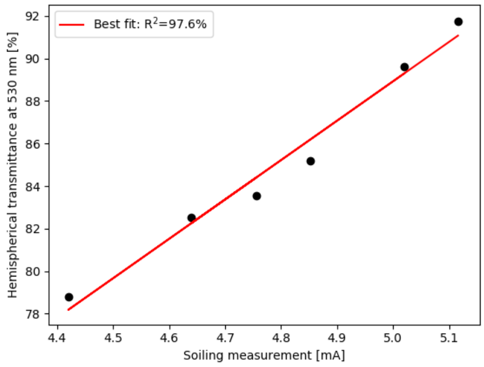

Figure 4: The readings of DUSST (x-axis) compared to the hemispherical transmittance at 530 nm, measured with the spectrophotometer, of the soiled and clean PV glass coupons.

When measuring the intensity of the light transmitted through by each soiled glass coupon and comparing it with the baseline measurement, DUSST functions in a similar manner as a spectrophotometer. Therefore, the quality of the measurement can be determined as shown in Figure 5 by comparing the *Light Intensity Ratio* (ratio of the intensity of the light transmitted by a soiled glass coupon to the intensity of the baseline measurement) with the *Soiling Relative Transmittance* (ratio of the hemispherical transmittance at 530 nm of the soiled glass coupon to the clean glass coupon). Similar to the soiling ratio, the *Soiling Relative Transmittance* and the *Light Intensity Ratio* have values of 100% in clean conditions and decrease with soiling. In ideal conditions, the *Light Intensity Ratio* for a monochromatic light and the *Soiling Relative Transmittance* at that same wavelength should be the same. In our test, the best fit between *Light Intensity Ratio* and the *Soiling Relative Transmittance* (blue dashed line in Figure 5) demonstrates the excellent linear correlation between the two measurements and proves therefore the reliability of the DUSST prototype.

Soiling has a non-linear impact on the irradiance spectra, with the blue region of the light being more affected than the red region [12,13]. This means that the *Soiling Ratio* is the result of a complex interaction among the irradiance spectrum, the soiling transmittance spectrum, and the spectral response of the photovoltaic material. This interaction can modeled for reference conditions as follows [11]:

$$r_s = \frac{\int_{\lambda 1}^{\lambda 2} E_G(\lambda, t)\tau_{soiling}(\lambda, t)SR(\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_G(\lambda, t)SR(\lambda)d\lambda} \qquad (1)$$

where E_g is the spectral distribution of the incident global irradiance, $\tau_{soiling}$ is the hemispherical transmittance of soiling, SR is the spectral response, and λ_1 and λ_1 are the lower and the upper limits of the absorption band of the cell. In this work, the spectral response and the absorption band of a mono-crystalline silicon cell are considered. The global reference spectrum reported in [14] has been considered in this study.

The green continuous line in Figure 5 shows the relation between the *Light Intensity Ratio* and the *Soiling Ratio* (modeled per eq. 1) for the glass coupons under investigation. The slope is substantially less than 1 due to the fact that DUSST measures only a single wavelength, while the *Soiling Ratio* is calculated over the whole absorption band of the cell. This discrepancy can be corrected by applying a calibration to the light intensity ratio, in order to consider the spectral response of each PV material.

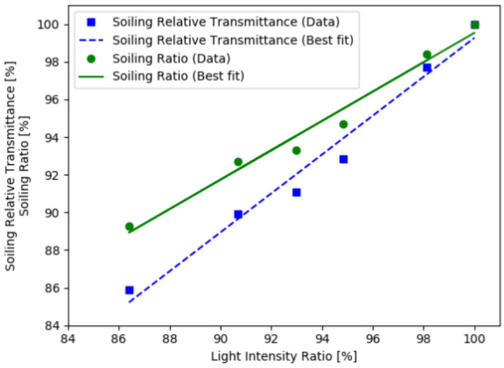

Figure 5: Blue data compare the l*ight intensity ratio* per DUSST against the *Soiling Relative Transmittance* at 530 nm. Green data compare the *Light Intensity Ratio* per

DUSST against the *Soiling Ratio* of a mono-crystalline cell placed behind each glass, modelled according to eq. 1, under a reference global irradiance spectrum [13]

Applying a calibration factor for mono crystalline cells determined per the line of best fit in Figure 5 (green continuous line) results in accurate DUSST Soiling Ratios. Overall, a mean absolute percentage error (MAPE) of 0.6% is found between the actual soiling ratios and the values of the best fit line calculated at the DUSST Soiling Ratios (see Figure 6). The MAPE expresses the average absolute error between actual *Soiling Ratios* and best fit line. This error is within the uncertainty ranges of the spectrophotometer and is lower than the expected errors of irregularly cleaned traditional soiling stations [8].

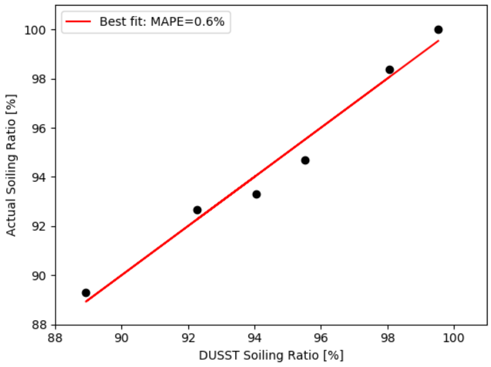

Figure 6: Comparing the *Soiling Ratios* calculated by DUSST (DUSST Soiling Ratio) and the *Soiling Ratios* of a mono-crystalline cell placed behind each glass, modelled according to eq. 1, under a reference global irradiance spectrum [14].

4 CONCLUSIONS AND FUTURE WORK

This work presents the design and the indoor validation of DUSST ("Detector Unit for Soiling Spectral Transmittance"), a novel soiling station that does not need to be cleaned. DUSST, which does not require water to operate and has no movable components, measures monochromatic light emitted by a known collimated source and transmitted through a naturally soiled glass coupon to quantify the soiling ratio of a PV array. The measurements are taken each night, under conditions with minimal external light. DUSST is re-calibrated after each cleaning to take into account any potential degradation of the components.

The indoor validation of a first prototype of DUSST is presented in this work. The analysis shows that DUSST measures the transmittance of soiled glass with extreme accuracy (R^2=97.6%) and that it can calculate the *Soiling Ratio* of a silicon cell with a MAPE of 0.6%, in line with the current soiling monitoring technologies.

The indoor validation will be continued by using different types of dusts and by comparing the DUSST measurements with the soiling losses of actual cells. In addition, more prototypes are now being deployed in outdoor conditions to validate the reliability of DUSST in natural soiling conditions and to test the durability of its components.

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